PB95-242145

Publication No. FHWA-RD-94-114
July 1995

Human Factors Aspects of the Transfer of Control from the Automated Highway System to the Driver

U.S. Department of Transportation
Federal Highway Administration

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

REPRODUCED BY: NTIS
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

FOREWORD

This report presents the results of two initial experiments which investigated driver performance in a generic Automated Highway System configuration. The experimental research was conducted in an advanced driving simulator and involved younger and older drivers transitioning from an automated lane to a manual lane. Driver performance data as well as subjective 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.

Lyle Saxton, 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.

Technical Report Documentation Page

1. Report No. FHWA-RD-94-114	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
HUMAN FACTORS ASPECTS OF THE TRANSFER OF CONTROL FROM THE AUTOMATED HIGHWAY SYSTEM TO THE DRIVER

5. Report Date
July 1995

6. Performing Organization Code

7. Author(s)
Bloomfield, J.R., Buck, J.R., Carroll, S.A., Booth, M.S., Romano, R.A., McGehee, D.V., and North, R.A.

8. Performing Organization Report No.

9. Performing Organization Name and Address
Honeywell Inc.
3660 Technology Drive
Minneapolis, MN 55418

10. Work Unit No. (TRAIS)
3B4d1012

11. Contract or Grant No.
DTFH61-92-C-00100

12. Sponsoring Agency Name and Address
Office of Safety and Traffic Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

13. Type of Report and Period Covered
Working Paper
10/93-9/94

14. Sponsoring Agency Code

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

16. Abstract

The first two experiments in a series exploring human factors issues related to the Automated Highway System (AHS) used a generic AHS configuration—the left lane reserved for automated vehicles, the center and right lanes containing unautomated vehicles, no transition lane, and no barriers between the automated and unautomated lanes—that was simulated in the Iowa Driving Simulator (IDS). The IDS has a moving base hexapod platform containing a mid-sized sedan. Imagery was projected onto a 3.35-rad (180°) screen in front of the driver, and onto a 1.13-rad (60°) screen to the rear. Thirty-six drivers between the ages of 25 and 34 years participated in the first experiment; 24 drivers who were age 65 or older took part in the second. Both experiments explored the transfer of control from the AHS to the driver when the driver's task was to leave the automated lane. The driver, who was traveling under automated control in a string of vehicles in the automated lane, had to take control, drive from the automated lane into the center lane, then leave the freeway.

Results: (1) The mean time to respond to an *Exit* advisory decreased from 13.41 s to 10.16 s as the design velocity increased from 104.7 km/h (65 mi/h) to 153.0 km/h (95 mi/h). (2) After the transfer of control, the driver remained in the automated lane, decelerating until the velocity was slow enough to allow a safe transition into the slower traffic in the unautomated lanes. It took longer to decelerate (13.19 s vs. 10.26 s) and the exit velocity dropped [105.30 km/h (65.40 mi/h) vs. 99.54 km/h (61.83 mi/h)] as the unautomated traffic density decreased from 12.42 v/km/ln (20 v/mi/ln) to 6.21 v/km/ln (10 v/mi/ln). It also took longer to decelerate (15.23 s vs. 8.62 s) and the extent of the deceleration decreased [42.7 km/h (26.49 mi/h) vs. 13.18 km/h (8.16 mi/h)] as the design velocity decreased from 153.0 km/h (95 mi/h) to 104.7 km/h (65 mi/h). (3) Once in the unautomated lanes, the younger drivers were in the center lane 70 percent longer than the older drivers. (4) The vehicle immediately behind the driver's vehicle in the automated lane was delayed after control was transferred—the delay increased from 1.36 s to 6.70 s as the design velocity increased from 104.7 km/h (65 mi/h) to 153 km/h (95 mi/h). (5) Allowing for the delay times obtained in these experiments, it was determined that the potential capacity of an automated lane should increase from 634.6 v/h to 2087.8 v/h as the design velocity decreases from 153.0 km/h (95 mi/h) to 104.7 km/h (65 mi/h). (6) Collisions and incursions occurred at unacceptably high rates. (7) The responses to the questionnaire suggest that the drivers were receptive to the AHS concept.

17. Key Words
Automated highway system, human performance, driving simulation, traffic flow, 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 145	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^2	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 FIGURES
(concluded)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (concluded)

SECTION 1: INTRODUCTION

Currently, a great deal of attention is being focused on the possibility of using advanced technologies to develop an Automated Highway System (AHS). Several possible AHS configurations are under consideration—for example, Zhang, Shladover, Hall, Levitan, Plocher, and Bloomfield describe seven different possible configurations.(1) Various human factors issues related to these configurations are being explored in an on-going Federal Highway Administration (FHWA) program. As part of this program, a series of experiments is being conducted using the Iowa Driving Simulator.

The two experiments reported here were the first in this series—they investigated human factors aspects of the AHS configuration that requires the least structural alteration to the roadways. This configuration utilizes a three-lane expressway, with the vehicles that are controlled by the AHS traveling in strings of three or four in the left lane, while the vehicles that remain under the control of the driver travel in the center and right lanes. In addition, there is no transition lane and no barrier between the automated and unautomated lanes.

Other than some minor changes in procedure, which will be discussed in the Method section of this report, the main difference between the two experiments was that in the first experiment, there were 36 drivers who were relatively young—they were between the ages of 25 and 34 years—while in the second, there were 24 relatively older drivers—they were age 65 or older. Because of the similarities in the experiments, they are reported together in this document.

Both experiments focused on the transfer of control from the AHS to the driver that is necessary when the driver leaves the automated lane. In both studies, at the start of each experimental trial, the driver's vehicle was traveling, under automated control, in a string of vehicles in the automated lane. The driver's task was to take control of the vehicle, drive from the automated lane into the center lane, move to the right lane, and then leave the freeway at a specified exit. Both experiments investigated the effect on the driver's performance of manipulating the following variables:

- Design velocity of the automated lane.
- Size of the gap between the vehicles within the strings of automated vehicles.
- Density of the vehicles in the unautomated lanes.

In addition, the effect of a fourth variable—driver's age—could be determined by comparing the data obtained in experiment #1 with drivers between the ages of 25 and 34, with the data obtained in experiment #2 with drivers who were age 65 or older.

The objective of these two experiments was to determine the conditions under which control can be transferred from the AHS to the driver, when the latter leaves the automated lane, with due regard to safety and with the minimum of interference to the flow of traffic in the automated lane. It was necessary to determine the answers to the following questions:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the driver's* ***Response Time*** *(i.e., the time between the moment the AHS issues the* Exit *advisory and the moment the driver takes control of the vehicle)?*
- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Exposure Time*** *(i.e., the length of time that the driver stays in the automated lane after taking control of the vehicle)?*
- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Lane-Change Time*** *(i.e., the length of time it takes to drive from the automated lane into the center lane)?*
- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Center Lane Time*** *(i.e., the time the driver spends in the center lane after leaving the automated lane)?*
- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Delay Time*** *experienced by the vehicle immediately behind the driver's vehicle in the automated lane?*
- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the driver's ability to avoid* ***Collisions*** *with other vehicles or* ***Lane Incursions*** *(i.e., incomplete lane changes)?*

SECTION 2: METHOD

SUBJECTS

The following guidelines were used in selecting the drivers who took part in experiment #1 and experiment #2:

- The drivers had no licensing restrictions, other than wearing eyeglasses for vision correction during driving.
- The drivers did not require special driving devices—the simulator is not equipped to accommodate such devices.
- In experiment #1, there were 36 drivers—half male and half female—between the ages of 25 and 34.
- In experiment #2, there were 24 drivers who were at least 65 years old—of these, six were males between the ages of 65 and 69, six were females between the ages of 65 and 69, six were males age 70 or older, and six were females age 70 or older.

All 60 drivers who took part in experiment #1 or experiment #2 were volunteers, who replied to advertisements in the Iowa City and University of Iowa daily newspapers, and met the selection criteria.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator is located in the Center for Computer Aided Design, University of Iowa, Iowa City.(2) It is shown in figure 1. The simulator has a moving base hexapod platform that is covered with a projection dome. For the two experiments reported here, a mid-sized Ford sedan was placed on the platform. The simulator was controlled by a computer complex consisting of a Harris Nighthawk 4400, an Alliant FX/2800, and an Evans and Sutherland CT-6 Image Generator. A simulator operating system operated simultaneously on the Harris Nighthawk and Alliant systems.(3) 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.

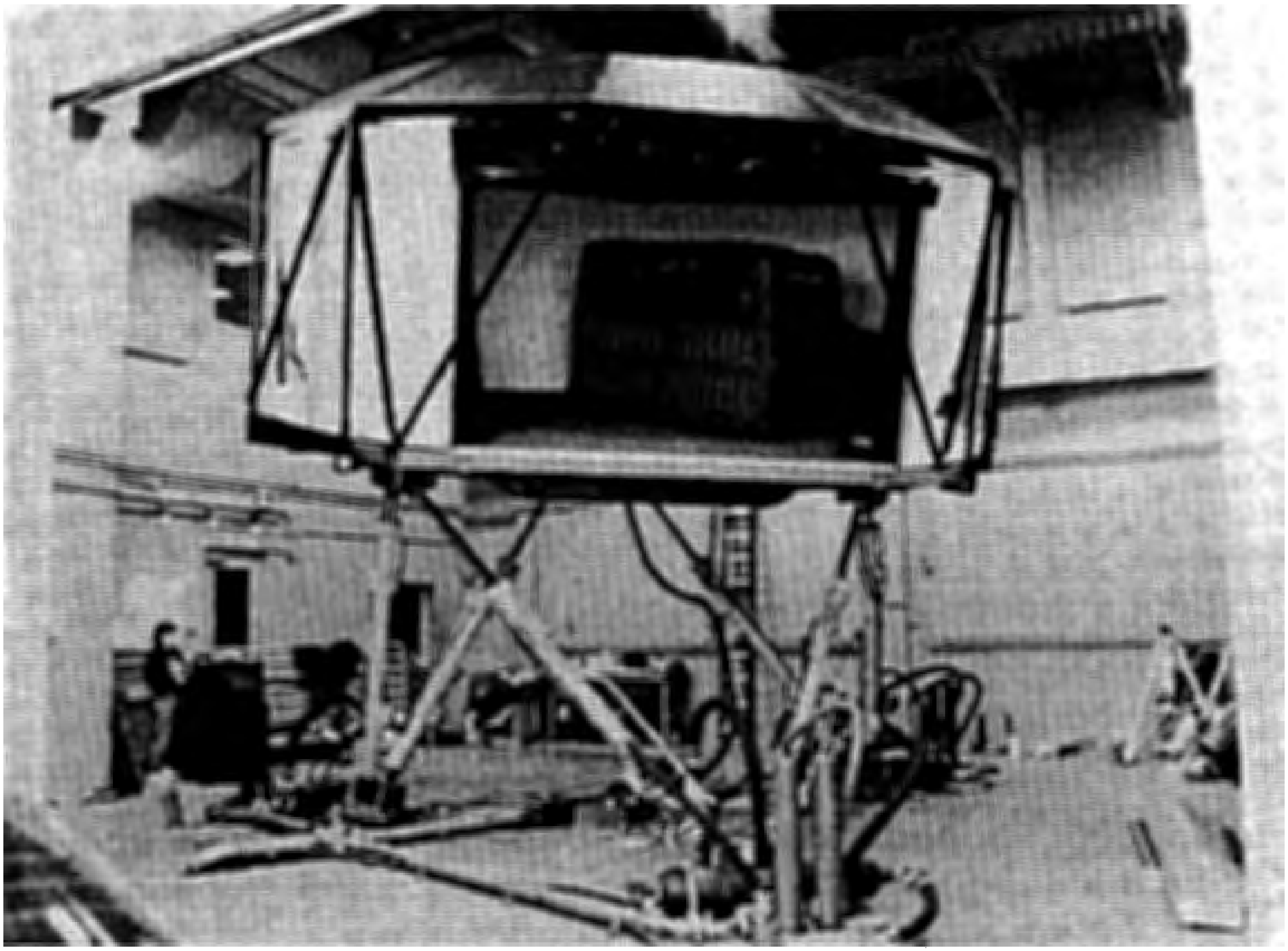


Figure 1. The Iowa Driving Simulator.

The inner walls of the simulator act as a screen onto which imagery can be projected by the CT6 visual projection system. For both experiments, the CT6 system projected correlated imagery onto a 3.35-rad (192°) section of the inner wall in front of the simulator vehicle, and onto a 1.13-rad (60°) section to its rear. The driver of the simulator vehicle viewed the 3.35-rad (192°) section through the windshield and side windows, and the 1.13-rad (60°) section to the rear either by turning around or by using an interior driving mirror and a left-hand side driving mirror mounted outside the vehicle.

DRIVING SCENARIO

In each experimental trial in both experiments, the subject sat in the driver's seat of the simulator vehicle. At the start of each trial, the driver's vehicle was in the automated lane of a three-lane freeway. After traveling under automated control for 2 to 4 min, an *Exit* advisory was given 60 s before the driver would arrive at a selected exit if the vehicle continued traveling at the design velocity. On hearing the advisory, the driver's task was to take control of the vehicle, maneuver it out of the automated lane, and leave the freeway at the specified exit.

A simulated roadway, known as Orchids, was produced for an earlier study using the Iowa Driving Simulator. The Orchids roadway was modified so that it could be used for experiment #1 and experiment #2. The first modification was to extend the three-lane freeway section of this roadway. Eight different routes, using four different exits, were selected from the modified freeway section, with the driver's vehicle traveling east on some and west on others. The time from the start of each of these routes until the point at which the driver received the *Exit* advisory was varied—the time for the shortest route was 120 s, while for the longest it was 225 s, with the intermediate steps being 15 or 20 s. There were three start points for each route—one for each design velocity condition. The second modification was to reconfigure the Orchids roadway as an automated highway with:

- Left lane reserved for vehicles under automated control.
- Center and right lanes occupied by unautomated vehicles.
- No transition lane between the automated and unautomated lanes.
- No barrier between the automated and unautomated lanes.

DRIVING SITUATION

In investigating the transfer of control from the AHS to the driver, many different variables must be taken into consideration, either as variables to manipulate, variables to control, or variables to measure. A preliminary taxonomy of these variables appears as appendix 1 of this document. This taxonomy was used as a guide in selecting the driving situation simulated in experiments #1 and #2.

This driving situation can be characterized as follows:

Each driver drove in dry weather conditions, at midday, on a three-lane freeway with the left lane automated, and the center and right lanes unautomated—there was no transition lane and no barriers between the automated and unautomated lanes. The lane widths were the current standard 3.67-m (12-ft) freeway width. The driver drove on sections of freeway that were modified segments of the current Iowa Driving Simulator Orchids scenario. These freeway sections had a standard road surface.

All of the automated vehicles involved in the experiment were directly controlled by the AHS.

The driver's steering wheel was locked firm when the simulator vehicle was in the automated lane; the accelerator pedal reflected the vehicle behavior; and the brake pedal was disconnected.

The health and driving history of the 36 drivers who participated in experiment #1 and the 24 drivers who participated in experiment #2 were recorded. In addition, the visual capabilities of all 60 drivers were measured—before the simulation trials began, for the drivers in experiment #1, and after they were completed, for the drivers in experiment #2.

The length of time the driver was in the automated lane, and the distance traveled in the automated lane before control was transferred from the AHS to the driver, were varied from trial to trial.

The average velocity of the unautomated vehicles was fixed at 88.6 km/h (55 mi/h). The mean headway time for vehicles in the unautomated lanes was:

- 6.55 s for the lower traffic density condition, which was 6.21 v/km/ln (10 v/mi/ln).
- 2.62 s for the higher density condition, which was 12.42 v/km/ln (20 v/mi/ln).

[Note: the mean headway time is the average difference in arrival time of two consecutive vehicles at a particular observation point on the highway. The mean headway time includes both the length of the first vehicle and the gap between it and the following vehicle.] The distribution of the velocities of the unautomated vehicles was normal, while a Pearson Type III distribution was used to generate the time headways. The parameters used in the equations defining both the normal distribution of velocities and the Pearson Type III distribution were derived using the procedure described by May and using the data provided by May.(4,5) This procedure is described in detail in appendix 2.

In each trial, an auditory *Exit* advisory was given. It consisted of a tone that was followed immediately by a verbal advisory. The tone was given 60 s before the exit would have occurred if the driver's vehicle were to continue traveling at the design velocity. The driver took control of the vehicle when all three of the following conditions were satisfied:

1. *Exit* advisory had been issued by the AHS.
2. Driver was holding the steering wheel.
3. Driver pressed either the accelerator or the brake pedal.

EXPERIMENTAL DESIGN

Conventional factorial experimental designs were used in both experiments—with the design velocity of the automated vehicles as a between-subjects factor, and the size of the intra-string gap between the automated vehicles and the density of the unautomated vehicles as within-subjects variables.

In addition, by comparing the data obtained in experiment #1 (from drivers between the ages of 25 and 34) with the data obtained in experiment #2 (from drivers who were age 65 or older), the effect of a fourth variable—driver's age—could be determined. Details of the independent variables varied in experiment #1 and experiment #2 are given below.

Design Velocity

Design velocity was varied as a between-subjects factor. The following three design velocities were used: (1) 104.7 km/h (65 mi/h); (2) 128.8 km/h (80 mi/h); and (3) 153.0 km/h (95 mi/h).

Intra-String Gap

While under automated control, the driver's vehicle was the second in a string of three vehicles that were traveling in the automated lane. The intra-string gap is the distance (in time) between the rear bumper of the vehicle immediately ahead of the driver's vehicle and the front bumper of the driver's vehicle, and between the rear bumper of the driver's vehicle and the front bumper of the vehicle immediately behind the driver's vehicle. The intra-string gap was a within-subjects variable. Three different gap times were used in both experiments: (1) 1.0 s, (2) 0.25 s, and (3) 0.0625 s.

Traffic Density

The traffic density of the vehicles in the unautomated lanes took one of the following two values:

- The lower traffic density was 6.21 v/km/ln (10 v/mi/ln)—this low traffic density level is close to the upper boundary of the Transportation Research Board Level of Service A (LOS A).(6) At this density, traffic flows freely.

- The higher density was 12.42 v/km/ln (20 v/mi/ln)—this density level is right at the upper boundary of LOS B. This density is in the range of stable flow, but the presence of other users is noticeable, and there is a slight decline in the freedom to maneuver.

Table 1. The gap [in meters (and feet)] between the back of the vehicle immediately ahead of the driver and the front of the driver's own vehicle for the six combinations of gap time and design velocity.

Design Velocity	Gap Times		
	1.0 s [m (ft)]	0.25 s [m (ft)]	0.0625 s [m (ft)]
104.7 km/h (65 mi/h)	29.06 (95.33)	7.26 (23.83)	1.82 (5.96)
128.8 km/h (80 mi/h)	35.76 (117.33)	8.94 (29.33)	2.24 (7.33)
153.0 km/h (95 mi/h)	42.47 (139.33)	10.62 (34.83)	2.65 (8.71)

Interaction Between Design Velocity and Intra-String Gap

The first two of these variables—the design velocity of the automated lane and the intra-string gap time between the automated vehicles—interact to produce the gaps shown in table 1.

Assignment and Counterbalancing of Experimental Conditions

In both experiments, the drivers were assigned to 3 groups—with 12 drivers per group in experiment #1, and 8 per group in experiment #2. As table 2 shows, each of the three groups drove all six combinations of gap time and traffic density with different design velocities: group 1 drove the combinations at 104.7 km/h (65 mi/h); group 2 drove them at 128.8 km/h (80 mi/h); and group 3 drove them at 153.0 km/h (95 mi/h).

Table 2. The experimental conditions received by the three groups of drivers in experiments #1 and #2.

Design velocity [km/h (mi/h)]	Intra-string gap (s)	Unautomated traffic density (v/km/ln) 6.21	12.42
104.7 (65)	1.0 0.25 0.0625	Group 1 Group 1 Group 1	Group 1 Group 1 Group 1
128.8 (80)	1.0 0.25 0.0625	Group 2 Group 2 Group 2	Group 2 Group 2 Group 2
153.0 (95)	1.0 0.25 0.0625	Group 3 Group 3 Group 3	Group 3 Group 3 Group 3

In order to completely counterbalance the order of presentation across both conditions and drivers within the three groups of drivers, the number of drivers had to be a multiple of six. Since 12 drivers were used in experiment #1, counterbalancing was possible, and it was achieved using 2 Latin squares—the counterbalanced order used for group 1 is shown, as an example of this procedure, in table 3.

Table 3. The counterbalanced order in which the 12 drivers in group 1 received the 6 combinations of gap time and unautomated traffic density.

	Driver	Counterbalanced order					
Latin square 1	D1	1	5	3	4	2	6
	D2	6	2	4	3	1	5
	D3	2	4	1	5	6	3
	D4	4	3	6	2	5	1
	D5	3	6	5	1	4	2
	D6	5	1	2	6	3	4
Latin square 2	D7	1	6	5	2	4	3
	D8	3	5	2	6	1	4
	D9	4	1	6	3	2	5
	D10	2	3	4	5	6	1
	D11	5	2	1	4	3	6
	D12	6	4	3	1	5	2

Key: 1. — 1.0 s & 6.21 v/km/ln
2. — 0.25 s & 6.21 v/km/ln
3. — 0.0625 s & 6.21 v/km/ln
4. — 1.0 s & 12.42 v/km/ln
5. — 0.25 s & 12.42 v/km/ln
6. — 0.0625 s & 12.42 v/km/ln

However, since there were eight drivers per group in experiment #2, it was not possible to counterbalance completely within the groups. Instead, the conditions were counterbalanced over blocks of six drivers—the first six drivers in group 1 formed the first block of six; the last two drivers in group 1 and the first four in group 2 formed the second block of six; the last four drivers in group 2 and the first two in group 3 formed the third block; and the last six drivers in group 3 formed the fourth block.

In addition to counterbalancing across all six of the combined conditions, a further restriction was imposed on the order of presentation to prevent any driver from receiving three consecutive trials with the same traffic density: in the first three trials, there was always at least one high-density condition and at least one low-density condition—this also ensured that the driver received at least one low- and one high-density condition in the second block of three trials.

EXPERIMENTAL PROCEDURE

Initial Procedure

First, the driver was introduced to the experiment and the type of testing that would be carried out (i.e., that several tests would be given to assess the driver's vision before the experimental trials in the simulator were conducted). The driver was informed that the experiment was part of an on-going FHWA program that is exploring ways of designing an AHS, determining how it might work, and determining 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 complete text for this introductory information is presented along with a complete description of the experimental protocol in appendix 3.

In experiment #1, this introductory material was followed by the administration of a series of tests in which aspects of the driver's vision were assessed. A Titmus Vision Tester was used to test:

(1) Far foveal acuity.
(2) Near foveal acuity.
(3) Stereo depth perception.
(4) Color deficiencies.
(5) Lateral misalignment.
(6) Vertical misalignment.

These vision tests were administered to discover whether any of the drivers who participated in either experiment had any visual anomalies—if any did, the data obtained from that driver in the main part of the experiment would be examined to discover whether there was any corresponding decrement in driving performance.

Then, two newly developed perimetry tests of static peripheral sensitivity and dynamic peripheral sensitivity were administered.(7) Data from these tests were to be used to determine whether there were any correlations between static or dynamic peripheral vision and driving performance.

Experiment #2 differed from experiment #1 in that both the Titmus vision tests and the perimetry tests were delayed until after the driver had driven in the simulator.

Pre-Experimental Simulator Procedure

The driver sat in the driver's seat of the simulator vehicle, put on the seat belt, adjusted the seat and mirrors, and was shown and instructed on the use of the simulator emergency button.

Then the driver drove the simulator vehicle in two familiarization trials—first on a segment of country road with no other traffic present; then on a segment of freeway in the presence of low-density traffic. While driving the freeway segment, the driver was asked to change from the right lane to the center lane, and then back again from the center lane to the right lane. Driving in these trials, each of which lasted 2 or 3 min, gave the driver an opportunity to become familiar with the simulator.

Experimental Procedure and Instructions

After the familiarization trials, the driver heard the taped instructions for the experimental trials. These instructions, which are given in full in appendix 3, gave an account of the sequence of events throughout the trial. In brief, they provided the following information:

- At the start of each experimental trial, the driver's vehicle would be in the middle of a string of three vehicles.
- If the vehicle ahead were to slow down, the AHS would reduce the speed of the driver's vehicle to maintain the gap between the vehicles; similarly, if the driver's vehicle were to slow down, the AHS would reduce the speed of the vehicle behind, so that the distance between them would remain constant.
- The driver's vehicle would travel along under the control of the AHS for a few minutes.
- An *Exit* advisory would be given when the vehicle was 60 s away from the specified exit; and since the tone would be given 60 s before the exit, the driver would not have to take control immediately.
- On hearing the *Exit* advisory, the driver could take control of the vehicle—but, in order to take control, the following three conditions would have to be satisfied: (1) the *Exit* advisory would have to have been given; (2) the driver would have to be holding the steering wheel; and (3) the driver would have to press either the accelerator or the brake pedal.
- After the transfer of control, the AHS would issue a second message to confirm that the driver had control of the vehicle.

- The vehicles in the center and right lanes would not be under automated control and would behave the way that traffic usually behaves on a freeway.
- At the moment that control was transferred from the AHS to the driver, the driver's vehicle would be traveling faster than the traffic in the unautomated lanes.
- The speed limit in the unautomated lanes was 88.6 km/h (55 mi/h).
- It would be necessary for the driver to slow down in order to drive in a normal way in the unautomated lanes.
- The driver would drive out of the automated lane, move from the center lane to the right lane, then leave the freeway at the specified exit.

The driver took part in six experimental trials, each of which took 3 to 5 min to complete. There was a brief break between trials while the simulator was reset.

Post-Simulator Procedure

As mentioned earlier, the presentation of both the Titmus vision tests and the perimetry tests that occurred as part of the initial procedure in experiment #1, was delayed in experiment #2 until this point. Then, each driver was debriefed and asked to complete a questionnaire. The drivers who took part in experiment #1 went straight to the debriefing and questionnaire. The questionnaire was designed to elicit the driver's opinion of the driving simulator, the experiment, and the AHS. A copy of this questionnaire is presented in appendix 4.

SECTION 3: RESULTS

FOCUS OF DATA ANALYSIS

Objective

The objective of these two experiments was to determine the conditions under which control can be transferred from the AHS to the driver, when the driver leaves the automated lane, with due regard to safety and with a minimum of interference to the flow of traffic in both the automated and unautomated lanes. The data analysis focused on:

- The moment that control was transferred to the driver from the AHS, and on the periods of time just before and just after this moment.
- The actions carried out by the driver, their effect on the driver's vehicle and on nearby vehicles, and whether these actions had any effect on the safety and/or efficiency of the AHS.

Critical Moments and Time Periods

In the time around the moment that control was transferred to the driver from the AHS, four distinct time periods can be identified. The beginning and end points of these time periods are marked by the following five critical moments:

(1) The moment that the *Exit* advisory was issued.
(2) The moment that the driver took control of the vehicle.
(3) The moment that the lane change from the automated lane to the center lane began.
(4) The moment that the lane change from the automated lane to the center lane was completed.
(5) The moment that the lane change from the center lane to the right lane began.

The time periods between these critical moments are illustrated in figure 2.

Preceding page blank

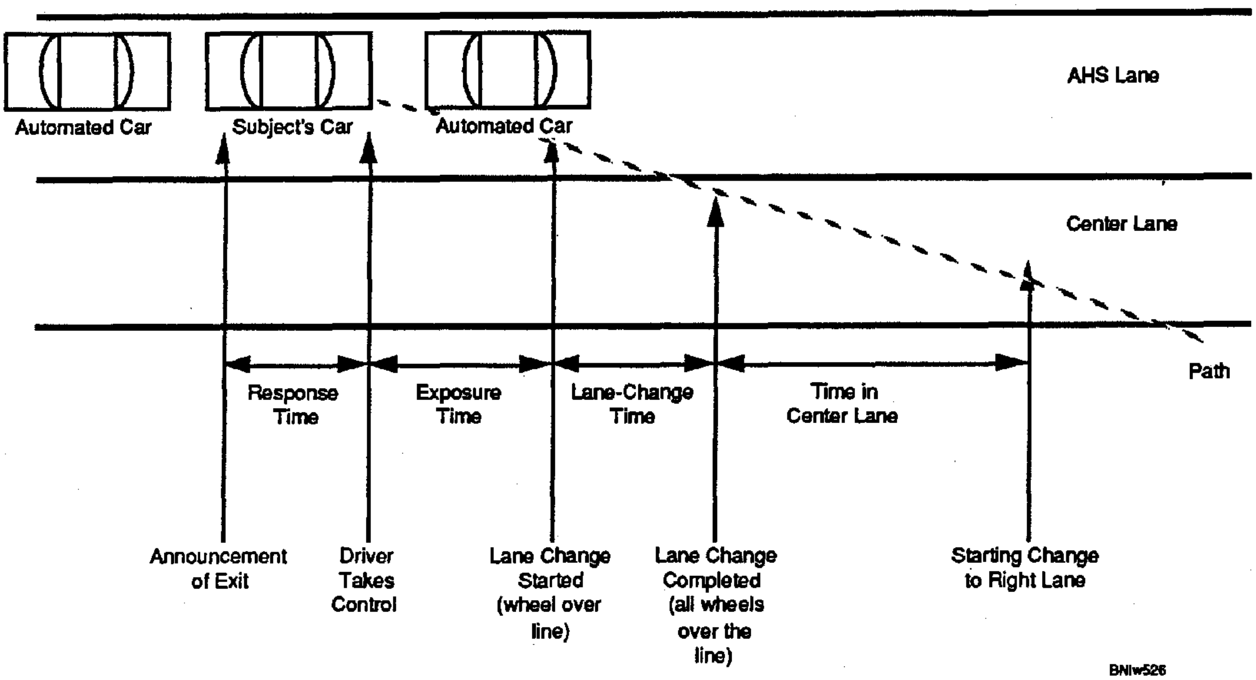


Figure 2. Critical moments and time periods when control was transferred to the driver from the AHS.

The four time periods are described below:

(1) Response Time Period occurred between the moment that the *Exit* advisory was issued and the moment that the driver took control of the vehicle.

(2) Exposure Time Period occurred between the moment that the driver took control of the vehicle and the moment that the first wheel touched the line between the automated and center lanes.

(3) Lane-Change Time Period occurred between the moment that the first wheel touched the line between the automated and center lanes and the moment that the fourth wheel crossed that same line.

(4) Center Lane Time Period occurred between the moment that the fourth wheel of the driver's vehicle had crossed the line between the automated lane and the center lane, and the moment that the first wheel of the driver's vehicle touched the line between the center lane and the right lane on a completed lane change.

Before the first of these four time periods, the driver's vehicle was in the automated lane under automated control traveling at the design velocity. During the response time period, the vehicle remained under the control of the AHS. During the exposure time period, the vehicle remained in the automated lane, but was under the control of the driver, who could chose whether and how to control velocity. During the lane-change time period, the vehicle moved from the automated to the center lane. And during the center lane time period, the driver adjusted to driving among unautomated traffic with a speed limit of 88.6 km/h (55 mi/h).

Delay Time

It is also necessary to consider another time period—that is defined here as delay time. When the driver's vehicle was in the automated lane and under the control of the driver, the AHS was not in complete control of the automated lane: if the driver decided to reduce speed, the automated vehicle traveling immediately behind the driver's vehicle had to respond by decelerating. Then, in turn, the string of vehicles behind the vehicle immediately following the driver's vehicle would also have to slow down—and then the string behind that, and so on. The time period in which the driver's vehicle might have influenced the vehicles behind it began when the exposure time started—i.e., it began the moment the driver took control of the vehicle—and it continued until the driver's vehicle had moved out of the way and the AHS had increased the velocity of the automated vehicle traveling behind the driver's vehicle until it reached design speed. Two measures of delay time were used.

(1) Measured delay time, which was directly obtained in experiments #1 and #2, occurred during the period that the driver's vehicle was decelerating while it was in the path of the automated vehicle that was following it. The measured delay time was dependent on the way in which the driver carried out the task of regaining control of the vehicle while it was still in the automated lane.

(2) Total delay time was the sum of the measured delay time and a second component that was not directly measured but was inferred. The added inferred component occurred during the period that the vehicle immediately following the driver's vehicle was accelerating back to the design velocity after the driver's vehicle had moved out of its path. It was computed using the empirically determined acceleration characteristics of the simulator vehicle. The inferred component was dependent on the driver's behavior and on the simulator vehicle's acceleration characteristics.

For the analysis conducted for this report, it was assumed that the AHS would use the moment that the driver's vehicle had completely moved out of the automated lane—i.e., the moment that the fourth wheel of the driver's vehicle had crossed the white line between the automated lane and the center lane—as the dividing point marking the end of the measured delay time and the beginning of the inferred component of the total delay time.

The AHS could use other, less conservative, dividing points. To decide which dividing point should be used in operating the AHS, it will be necessary to conduct a trade-off between efficiency and safety. If it were decided that the emphasis should be placed on efficiency, the choice should be to use an earlier dividing point, such as the moment that the first wheel of the driver's vehicle touches the white line between the automated and center lanes: this would minimize the delay time and increase the system efficiency by maximizing the traffic flow. However, along with the increased system efficiency would come greater risk. Once the driver had selected a particular space between two unautomated vehicles in the center lane and had begun to change lanes, the AHS would start to increase the velocity of the vehicle behind the driver's vehicle. But, then if the driver were to reconsider—because of a misjudgment or because the space in the unautomated lane had decreased in size—and were to attempt to abort the lane change, it would be difficult to avoid a collision with the now accelerating vehicle immediately following the driver's vehicle. By choosing to minimize the delay time, the margin of safety would be reduced.

On the other hand, if safety were to be emphasized, the choice should be to use a later dividing point—like that selected for the analysis conducted for this report. With the moment that the fourth wheel of the driver's vehicle crosses the white line between the automated and the center lanes as the dividing point, safety would not be compromised if, while in the process of changing lanes, the driver were to reconsider an already-selected space between two unautomated vehicles in the center lane and were to abort the lane change. Safety would not be compromised in this situation, because the AHS would not have already started to accelerate the automated vehicle following the driver's vehicle. However, while improving safety, the use of this later dividing point would also reduce the efficiency of the automated lane—the automated vehicle immediately following the driver's vehicle would be slowed down for a longer time, and the effects of that slowdown would propagate back to other vehicles in the automated lane. As mentioned above, this conservative dividing point was used as the dividing point marking the end of the measured delay time and the beginning of the inferred component in the analysis that follows.

Once a dividing point has been selected, the delay time itself can be calculated using the following equation:

$$T_d \quad = \quad (d_1 - d_2)) / V$$

where:

T_d — was the delay time (which was the measured delay time in the first part of the analysis, and was the total delay time in the second part).

d_1 — was the distance traveled by the string of vehicles following the driver's vehicle in T_d.

d_2 — was the distance that would have been traveled by the string of vehicles following the driver's vehicle, in T_d, if the driver had not, in fact, taken control of the vehicle.

V — was the design velocity.

Conflict Between Safety and Traffic Flow

Experiments #1 and #2 were designed to determine the conditions under which control can be transferred from the AHS to the driver with due regard to safety, with the minimum of interference to the flow of traffic in the unautomated lanes, and with the minimum of interference to the flow of traffic in the automated lane. Unfortunately, the first and second of these concerns are at odds with the third.

If safety and the flow of traffic in the unautomated lanes were of prime concern, it would be preferable if, after taking control of the vehicle, the driver would decelerate down to a speed close to 88.6 km/h (55 mi/h) while still in the automated lane, and then change lanes when there is an appropriate gap in the traffic in the center lane. The lane change would be smooth and the adjustment to the driving conditions in the center lane would be effortless. However, since the velocity of the automated vehicles immediately following the driver's vehicle would have to be reduced to the same extent as that of the driver's vehicle, and the resultant slowdown would cascade back through the successive strings of automated vehicles—with the cascading effect being greater the higher the density of the automated lane—the efficiency of the automated lane could be greatly reduced.

In contrast, if the efficiency of the AHS were of prime concern, it would be preferable if, after taking control of the vehicle, the driver left the automated lane as soon as possible, since then the vehicles immediately behind the driver's vehicle would experience the minimum interference. However, since to do this the driver's vehicle would have to move into the center lane at high speed, the lane change might be risky and, since the driver's vehicle would have to slow down rapidly to 88.6 km/h (55 mi/h) when it arrived in the center lane, the possibility of a rear-end collision with the unautomated vehicle ahead would be greatly increased—as a result, the safety of the driver's vehicle and the vehicles in the unautomated lanes could be severely compromised.

These goals are incompatible. The way the drivers in the two experiments reported here chose to resolve these issues is revealed by considering how long the driver's vehicle remained in each of the time periods—i.e., in the response, exposure, lane-change, and the center lane time periods—and how much delay was caused for the vehicle immediately behind the driver's vehicle. In part, the driver's choice may have been affected by the availability of gaps in the traffic in the center lane—which, in turn, may be affected by the traffic density—as well as by the driver's ability to see and take advantage of those gaps.

Data Items

For each of these critical moments defined in the previous subsection, the time that it occurred and the velocity of the driver's vehicle when it occurred were recorded. Then, the length of time between the critical moments and the changes in the velocity of the driver's vehicle from one critical moment to the next were calculated. The resultant data were the primary measures used in the analysis. The full list of the data items that were recorded or calculated in both experiments is as follows. [Note the numbered items are the five critical moments identified above.]

- Track of the vehicle relative to the roadway.
- (1) Moment that the *Exit* advisory was issued.
- (2) Moment that the driver took control of the vehicle
  —i.e., when all three of the following conditions were satisfied:
  - (a) *Exit* advisory had been issued.
  - (b) Driver was holding the steering wheel.
  - (c) Driver had pressed either the accelerator or the brake pedal.
- Driver's response time
  —i.e., time between (1) the moment that the *Exit* advisory was issued and (2) the moment that the driver took control of the vehicle.

(3) Moment that the lane change from the automated lane to the center lane began.

—i.e., moment at which the first wheel touched the line between the automated lane and the center lane on a completed lane change.

(4) Moment that the lane change from the automated lane to the center lane was completed

—i.e., moment at which the fourth wheel crossed the line between the automated lane and the center lane.

- Influence time

  —i.e., time spent in the automated lane from (2) the moment that the driver took control of the vehicle until (4) the moment that the lane change was completed.
- Time to change lanes from the automated lane to the center lane

  —i.e., time between (3) and (4).
- Velocity of the driver's vehicle at the moment that the lane change from the automated lane to the center lane began

  —i.e., velocity at (3).
- Velocity of the driver's vehicle at the moment that the lane change from the automated lane to the center lane was completed

  —i.e., velocity at (4).

(5) Moment that the lane change from the center lane to the right lane began

—i.e., moment at which the first wheel touched the lane marker on a completed lane change from the center to the right lane.

- Velocity of the driver's vehicle at the moment that the lane change from the center lane to the right lane began

  —i.e., velocity at (5).
- Time spent in the center lane

  —i.e., time between (4) and (5).
- Whether the driver was able to leave the freeway at the designated exit.
- Number of inappropriate lane incursions

  —i.e., number of times that the first wheel crossed the lane marker on an incomplete lane change.
- Whether the driver's actions while controlling the vehicle in the automated lane caused the automated vehicle behind the driver to slow down.
- Whether the driver's actions caused the vehicle to collide with any other vehicles.

Sequential Effects

Initial inspection of the experimental data indicated that it was possible that, for the response time data and exposure time data, the responses made by the drivers to the first trial may have been somewhat different than the responses that they made in subsequent trials. Two sequential, trial-by-trial analyses were conducted to determine whether there were any consistent trends within the sequence of trials for either the response time data or the exposure time data.

Sequential Effects with the Response Time Data. To determine whether the responses made by the drivers to the first trial may have been somewhat different than the responses that they made in subsequent trials, during the response time period, two analyses of variance (ANOVAs) were conducted. In each, the mean response times in the first, second, third, fourth, fifth, and sixth trials were compared, both for the younger drivers in experiment #1 and for the older drivers in experiment #2—the data used in these comparisons were collapsed across the design velocities, gap sizes, densities, and drivers, within each experiment. As table 4 indicates, these ANOVAs showed that there were significant differences between response times that could be attributed to the sequence of trials.

Table 4. Summary of the ANOVAs determining whether there were sequential effects within the response time data of the younger and older drivers (data from experiments #1 and #2).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	p-value
Experiment #1 (Younger Drivers):					
Trials	5	1538.43	307.69	7.96	0.0001
Trials x Subjects	166	6415.28	38.64		
Experiment #2 (Older Drivers):					
Trials	5	1517.03	303.41	6.04	0.0001
Trials x Subjects	99	4974.85	50.25		

To explore these differences further, the Tukey Studentized Range post hoc test was used to compare the mean response times that were obtained for each trial. For the younger drivers, the mean response time for the first trial was significantly longer than the mean response times for the remaining five trials, and there were no other differences between the trials. The trial 1 mean response time was 17.00 s—it was approximately 60 percent longer than the remaining five trials, which averaged 10.44 s.

When the Tukey test was used to compare the mean response times for the older drivers, the findings were similar. The mean response time for the first trial was significantly longer than the mean response times for trials 3, 4, 5, and 6—in addition, trial 2 was significantly longer than trials 5 and 6. The trial 1 mean response time was 17.34 s—approximately 90 percent longer than the remaining five trials, which averaged 9.04 s. The sequential effect of trials on response times is shown graphically in figure 3.

Sequential Effects with the Exposure Time Data. The exposure time data were treated in the same way as the response time data. Again, two ANOVAs were conducted—this time comparing the mean exposure times obtained in the six experimental trials from both the younger drivers (experiment #1) and the older drivers (experiment #2). The data used in these comparisons were collapsed across the design velocities, gap sizes, densities, and drivers. The results of these analyses are shown in table 5.

Table 5. Summary of the ANOVAs determining whether there were sequential effects within the exposure time data of the younger and older drivers (data from experiments #1 and #2).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	p-value
Experiment #1 (Younger Drivers):					
Trials	5	525.35	105.07	2.40	0.0395
Trials x Subjects	165	7231.80	43.83		
Experiment #2 (Older Drivers):					
Trials	5	497.51	99.50	1.85	0.1101
Trials x Subjects	99	5326.05	53.80		

When the t-test was used, post hoc, to examine the differences in the mean exposure times for the younger drivers, it indicated that the mean exposure time for trial 1 was significantly shorter than the means for trials 4 and 6. Inspection of figure 4, which shows the sequential effect of trials on exposure times for both the younger and older drivers, indicates that there may have been a similar tendency for the mean exposure times for the older drivers to increase as the number of trials increased.

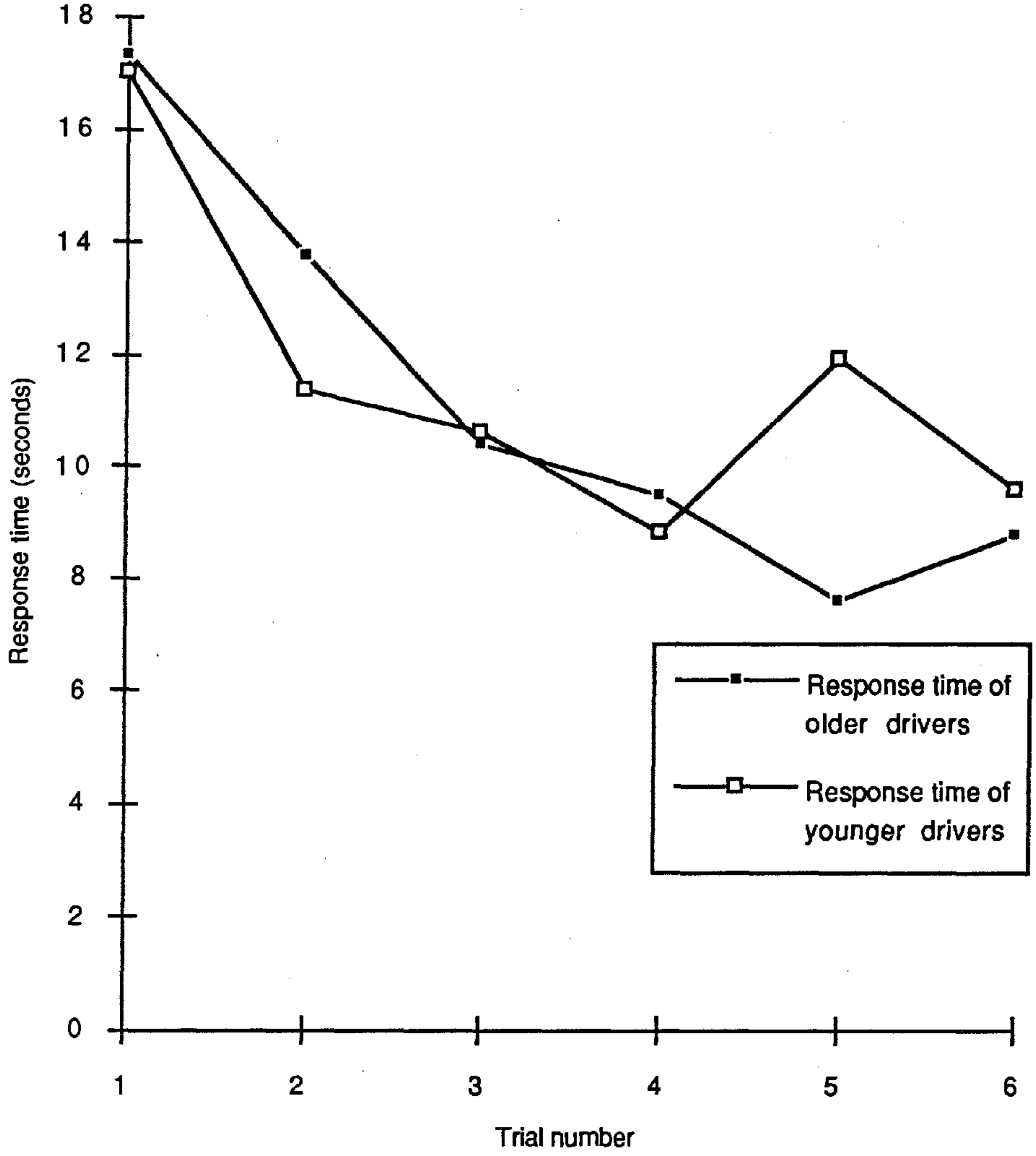


Figure 3. Response time from trial to trial for younger and older drivers.

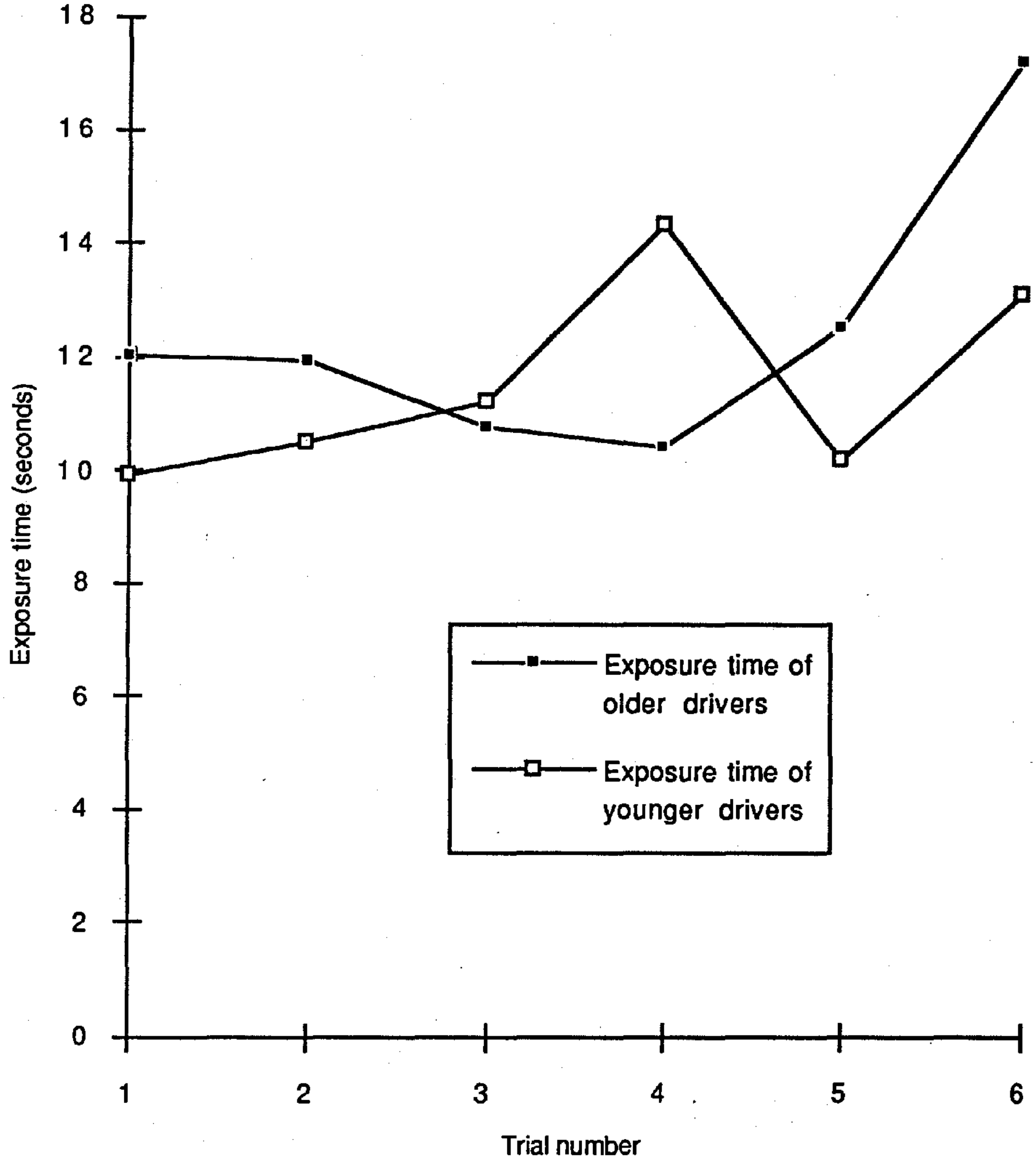


Figure 4. Exposure time from trial to trial for younger and older drivers.

Dealing with Sequential Effects. All the data analyses that follow examine four experimental variables. Of these, one—driver's age—was a between-experiments variable, another—the design velocity of the automated vehicles—was a between-subjects variable. The remaining two—the size of the intra-string gap and the density of the unautomated vehicles—although within-subjects variables, were completely counterbalanced. Because of all this, sequential effects like those demonstrated above are unlikely to have distorted the analyses of the four experimental variables.

Visual Capabilities Testing

The Titmus Vision Tester was used to administer a series of standard visual tests. In experiment #1, these tests were administered before the simulation trials, while in experiment #2, they were administered after the simulation trials. None of the drivers were found to have any uncorrected visual problems.

Each driver was also given two newly developed tests—they used a perimeter that explored static and dynamic peripheral sensitivity out to 21° of eccentricity, under binocular viewing. As with the Titmus test, these tests were administered prior to the simulation trials for the drivers who took part in experiment #1, and after the simulation trials for the older drivers who participated in experiment #2. In an initial comparison of the data from the drivers who took part in experiments #1 and #2 with data from ophthalmic patients examined in the University of Iowa Hospitals and Clinics, Dr. Michael Wall, Associate Professor of Neurology and Ophthalmology, states that the results from the drivers in experiment #1 were typical of normal subjects drawn from the population aged between 25 and 34, while the data from the drivers in experiment #2 were typical of data from people who were 65 or older, who have normal vision.

DATA ANALYSIS: THE EFFECTS OF DESIGN VELOCITY, INTRA-STRING GAP, TRAFFIC DENSITY, AND DRIVER'S AGE

The effects of the four independent variables—the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver—on the duration of each of the critical periods and on the measured and total delay times were assessed. In each case, three separate ANOVAs were carried out: the first using data from the younger drivers who took part in experiment #1; the second using data from the older drivers who took part in experiment #2; and the third comparing the data from both experiments to determine whether there were any differences between the younger drivers and the older drivers.

Organization

The first two subsections that follow deal with the response and exposure time periods—their data analyses focus on the duration of the time periods. The third subsection presents exit velocity data. Then, in the fourth and fifth subsections, which deal with the lane-change and center lane time periods, the data analyses again focus on the duration of the time periods. In the sixth subsection, dealing with both the measured and total delay times, the analyses explore how the velocity changes made by the driver's vehicle influenced the traffic in the automated lanes. In all six of these subsections, a summary table is presented first—it shows which, if any, of the independent variables were found from the three ANOVAs to have had a significant effect. Then in the rest of the subsection, the nature of any such effects is discussed. [Detailed summaries of the ANOVAs can be found in appendix 5.] In the seventh subsection, collision and incursion data are presented, and finally, in the eighth subsection, the results of analyzing the questionnaire data are given.

Response Time

The first experimental question asked was:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the driver's* **Response Time** *(i.e., the time between the moment the AHS issues the* Exit *advisory and the moment the driver takes control of the vehicle)?*

In order to answer these questions, three separate ANOVAs were carried out on the data from experiment #1, the data from experiment #2, and then on the combined data from both experiments. Table 6 summarizes the findings of these three ANOVAs.

As table 6 shows, there was no evidence that variations in the three independent variables or the interactions between them had any effect on the response times of the younger drivers in experiment #1. However, the table does show that for the older drivers in experiment #2, one of the variables—design velocity—did have a statistically significant effect. And the table shows that design velocity also had a statistically significant effect when the data from the two experiments were analyzed together.

Table 6. Summary of the ANOVAs determining whether response times were affected by variations in the design velocity, intra-string gap, traffic density, or the driver's age.

	Experiment #1 Younger Drivers	Experiment #2 Older Drivers	Combined Data Younger vs. Older
Age			—
Velocity	—	0.0201	0.0224
Gap	—	—	—
Density	—	—	—
Interactions	—	—	—

The Effect of Design Velocity on Response Time. There are three ways in which it would be possible to obtain a significant effect of design velocity for the older drivers and for the combined data, but not for the younger drivers—there would have to be an effect of age, or a significant interaction of design velocity and age, or the plot of mean response times against design velocity for the younger drivers should show a similar pattern to that of the older drivers. The first and second possibilities did not occur—as table 6 shows, there was no effect of age, and the interaction between age and design velocity was not significant. However, the third did occur—figure 5 shows that when mean response time was plotted as a function of design velocity, the pattern for the younger drivers was similar to that of the older drivers.

The t-test was used as a post hoc test to examine further the effect of design velocity on the response times of the older drivers and on the combined data. For the older drivers, the mean response time for the slowest of the three design velocities, 104.7 km/h (65 mi/h), was 14.30 s. This was almost 5 s longer than the mean response time for the 128.8-km/h (80-mi/h) design velocity (which was 9.36 s). For the combined data of both the younger and older drivers, the mean response time of 13.41 s for the 104.7-km/h (65-mi/h) velocity dropped to 10.16 s for the 128.8-km/h (80-mi/h) design velocity.

Exposure Time

The second experimental question was:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Exposure Time*** *(i.e., the length of time that the driver stays in the automated lane after taking control of the vehicle)?*

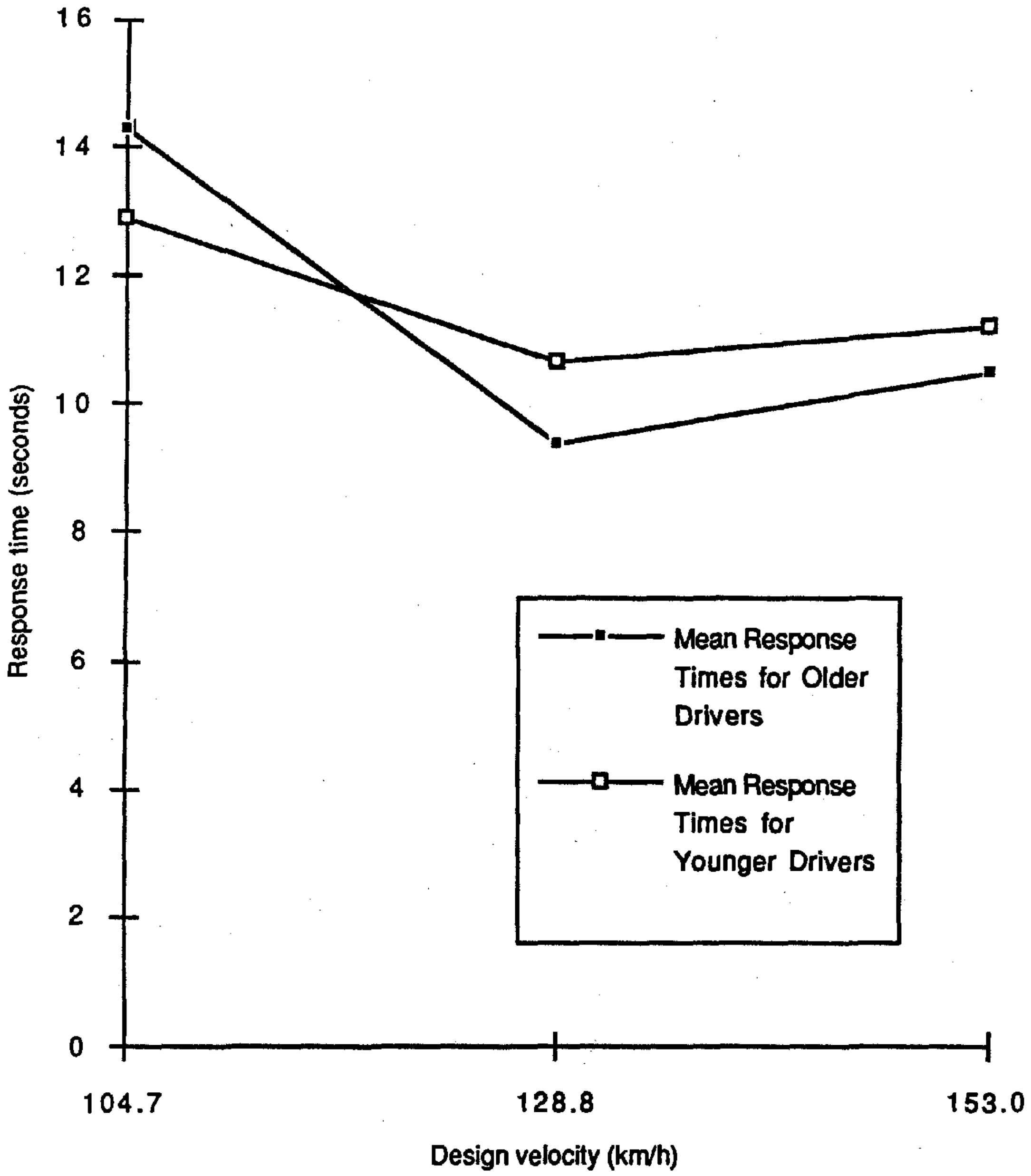


Figure 5. Response time as a function of design velocity for younger and older drivers.

The exposure time is the time between the moment that the driver took control of the vehicle and the moment that the first wheel touched the line between the automated and center lanes as the driver left the automated lane.

As with the response time data, three separate ANOVAs were carried out on the exposure time data from experiment #1, from experiment #2, and from both experiments combined. Table 7 summarizes the findings of these three ANOVAs.

Table 7. Summary of the ANOVAs determining whether exposure times were affected by variations in the design velocity, intra-string gap, traffic density, or the driver's age.

	Experiment #1 Younger Drivers	Experiment #2 Older Drivers	Combined Data Younger vs. Older
Age			—
Velocity	0.0044	—	0.0067
Gap	0.0124	—	0.0051
Density	0.0021	0.0037	0.0001
Interactions			
G x D	—	—	0.0205
A x V x D			0.0052

As table 7 shows, all three independent variables affected the mean exposure time for the younger drivers in experiment #1.

Exposure Time, Design Velocity, and the Younger Driver. The effect of variations in design velocity was significant at the p = 0.0044 level. The t-test was used, post hoc, to examine this effect in more detail: it showed that the mean exposure time of 15.98 s obtained for the fastest design velocity—153.0 km/h (95 mi/h)—was significantly greater than the exposure times for both the 128.8-km/h (80-mi/h) and 104.7-km/h (65-mi/h) design velocities, which were 10.65 s and 7.31 s, respectively. The latter two design velocities were not significantly different from each other—however, as can be seen from figure 6, it is clear that as the design velocity decreased from 153.0 km/h (95 mi/h) to 104.7 km/h (65 mi/h), the exposure time progressively decreased.

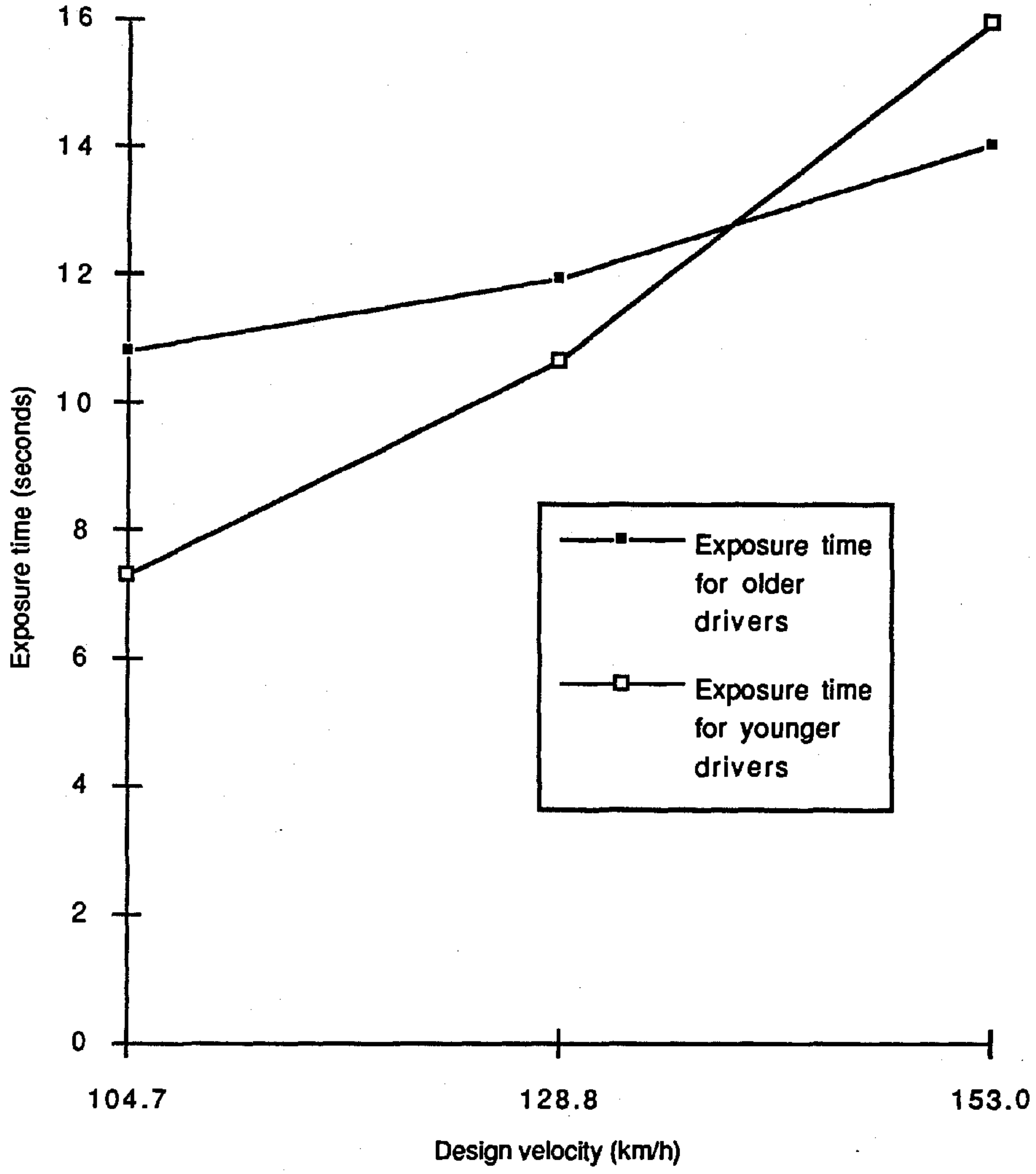


Figure 6. Exposure time as a function of design velocity for younger and older drivers.

Exposure Time, Intra-String Gap, and the Younger Driver. Table 7 also indicates that the mean exposure time for the younger drivers was affected by variations in the size of the intra-string gap (p = 0.0124). Post hoc testing showed that the exposure time of 13.5 s obtained for the smallest intra-string gap—0.0625 s—was significantly longer than the 9.49-s mean exposure time obtained with the 0.25-s intra-string gap. Given this result, it might have been expected that the mean exposure time for the 1.00-s gap would be even shorter than the 0.25-s gap: it was not—and, at 11.52 s, it was not significantly different from the other two means.

Exposure Time, Unautomated Traffic Density, and the Younger Driver. In addition, table 7 indicates that the mean exposure time for the younger drivers was significantly affected (with p = 0.0021) by the change in the density of the unautomated traffic. When the density doubled from 6.21 v/km/ln (10 v/mi/ln) to 12.42 v/km/ln (20 v/mi/ln), the exposure time increased from 9.98 s to 12.70 s.

Exposure Time and the Older Driver. As table 7 shows, variations in the design velocity and in the size of the intra-string gap did not affect the exposure times of the older drivers in experiment #2. Only the density of the unautomated traffic had a significant effect on the mean exposure time—for the older drivers, when the density doubled from 6.21 v/km/ln (10 v/mi/ln) to 12.42 v/km/ln (20 v/mi/ln), the exposure time increased from 10.70 s to 14.03 s.

Combined Data—Main Effects on Exposure Time: (a) Design Velocity. As can be seen from table 7, all three independent variables affected the mean exposure time when an ANOVA was conducted on the combined data of experiments #1 and #2.

There were significant differences in the exposure times related to variations in design velocity for the combined data (p = 0.0067). When the t-test was used, post hoc, the mean exposure time of 15.23 s obtained with the fastest design velocity—153.0 km/h (95 mi/h)—was found to be significantly greater than the exposure time for both the 128.8-km/h (80-mi/h) and 104.7-km/h (65-mi/h) design velocities, which were 11.12 s and 8.61 s, respectively. The fact that there was no significant effect of driver's age, while design velocity affected the mean exposure time for the combined data and for the younger drivers alone, suggested that the pattern of means for the older drivers might resemble that for the younger drivers. And, as can be seen from figure 6, to a large extent the pattern of means obtained from the older drivers mirrors that of the younger drivers—with the exposure time increasing from 10.81 s for the 104.7-km/h (65-mi/h) design velocity, to 11.91 s for the 128.8-km/h (80-mi/h) velocity, and to 14.06 s for the 153.0-km/h (95-mi/h) velocity.

Combined Data—Main Effects on Exposure Time: (b) Intra-String Gap. Varying the size of the intra-string gap also had a significant effect on the exposure times for the combined data (with p = 0.0051). Post hoc testing showed that the mean exposure times obtained for both the smallest gap (0.0625 s) and the largest gap (1.00 s) were significantly longer than the mean obtained for the 0.25-s gap—they were 12.92 s and 12.31 s, respectively, vs. 9.86 s.

Combined Data—Main Effects on Exposure Time: (c) Unautomated Traffic Density. Table 7 shows that the combined mean exposure time was significantly affected (with p = 0.0001) by the change in the density of the unautomated traffic—as the density doubled from 6.21 v/km/ln (10 v/mi/ln) to 12.42 v/km/ln (20 v/mi/ln), the exposure time increased from 10.26 s to 13.19 s.

Combined Data—Interaction Effects: (a) Intra-String Gap and Unautomated Traffic Density. In addition to the three significant main effects for exposure time, as can be seen from table 7, there were also two significant interactions.

There was a two-way interaction between the size of the intra-string gap and the density of the unautomated traffic (p = 0.0205)—it is explored in figure 7, in which exposure time is plotted against the size of the intra-string gap for both the high- and the low-density traffic. First, considering density, the exposure time was greater for the 12.42-v/km/ln (20-v/mi/ln) density condition than for the 6.21-v/km/ln (10-v/mi/ln) density condition for all three gap sizes: however, the effect of unautomated traffic density was much larger when the intra-string gap was at its smallest—when the intra-string gap was 0.0625 s, the exposure time was 16.01 s with the high-density condition vs. 9.94 s with the low-density condition, instead of 10.56 s vs. 9.19 s for the 0.25-s gap, and 12.98 s vs. 11.72 s for the 1.00-s gap. Second, considering the size of the intra-string gap, the exposure time was longer for the 1.00-s gap than for the 0.25-s gap for both densities—12.98 s with the 1.00-s gap vs. 10.56 s with the 0.25-s gap for the 12.42-v/km/ln (20-v/mi/ln) density; and 11.72 s with the 1.00-s gap vs. 9.19 s with the 0.25-s gap for the 6.21-v/km/ln (10-v/mi/ln) density. However, when the 0.0625-s gap was compared with the 0.25-s gap, the exposure times were very similar for the low-density condition—they were 9.94 s with the 0.0625-s gap and 9.19 s with the 0.25-s gap—and very different for the high-density condition—16.01 s with the 0.0625-s gap and 10.56 s with the 0.25-s gap. Whichever way this interaction is considered, the mean exposure time was longest (16.01 s) when the drivers were faced with the combination of higher density and smallest intra-string gap.

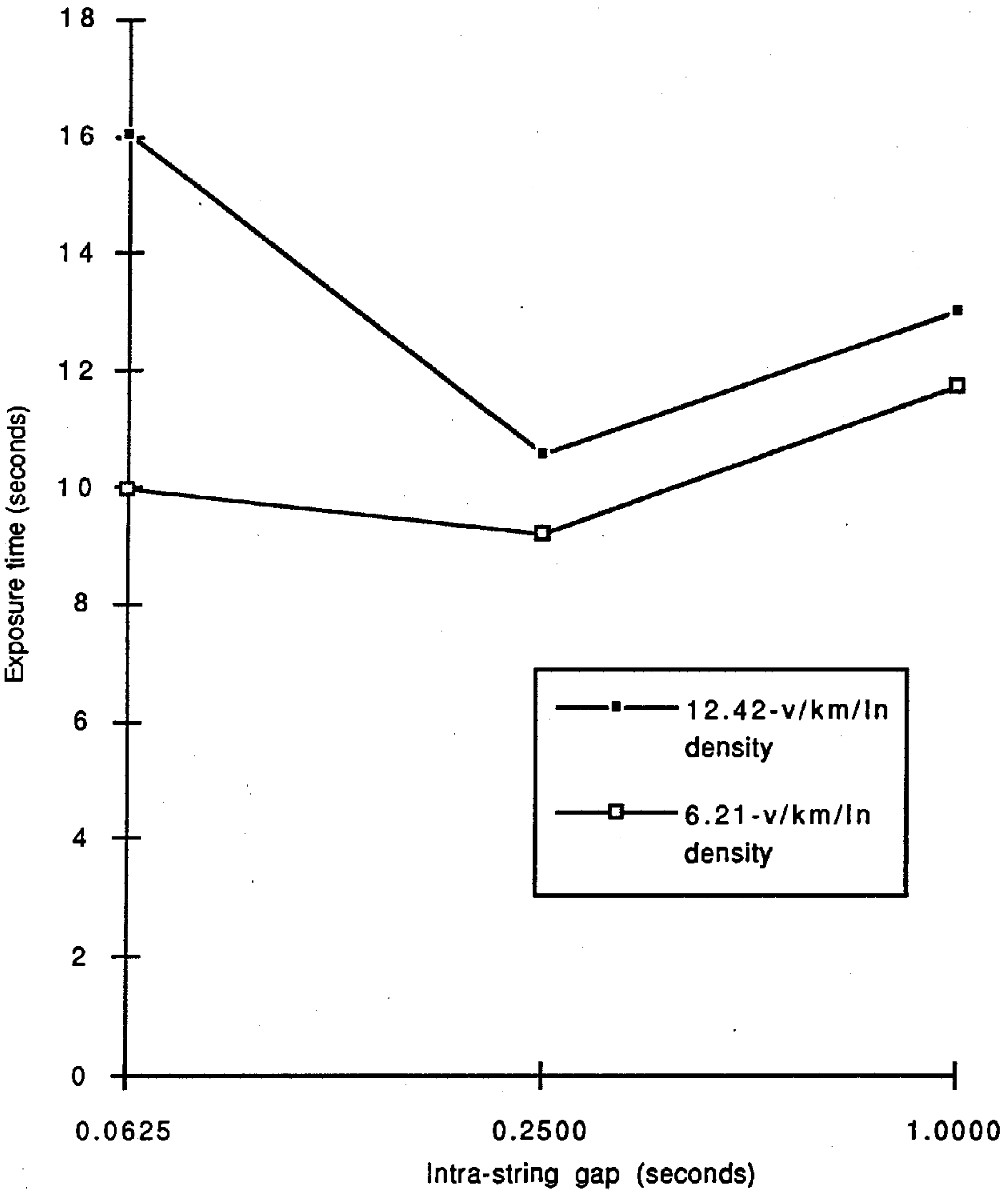


Figure 7. Exposure time as a function of intra-string gap for high- and low-traffic densities—combined data of younger and older drivers.

Combined Data—Interaction Effects: (b) Driver's Age, Design Velocity, and Unautomated Traffic Density. There was also a significant three-way interaction: the p-value was 0.0052 for the interaction involving the age of the driver, the design velocity, and the density of the traffic in the unautomated lane. This complex interaction is explored in figures 8 and 9. It will be necessary to make comparisons both within and between the figures to carry out this exploration. First, figure 8 shows the effect of design velocity on exposure time for both densities for the younger drivers. As the design velocity increases from 104.7 km/h (65 mi/h) to 153.0 km/h (95 mi/h), the mean exposure time increases, from 5.63 s to 14.19 s for the 6.21-v/km/ln (10-v/mi/ln) density, and from 8.94 s to 17.72 s for the 12.42-v/km/ln (20-v/mi/ln) density. The relationships appear to be roughly linear—however, it should be noted that if the relationship between exposure time and design velocity is in fact linear, the combination of the 128.8-km/h (80-mi/h) velocity and the 12.42-v/km/ln (20-v/mi/ln) density should have produced a mean exposure time close to 13.5 s, instead of the 11.31-s mean that was obtained.

Inspection of figure 9, which plots mean exposure time as a function of design velocity for the two densities for the older drivers, shows a somewhat different picture. In the high-density condition, the exposure time increased, as expected, from 10.65 s for the 104.7-km/h (65-mi/h) velocity to 16.10 s for the 128.8-km/h (80-mi/h) velocity; but then, instead of continuing to increase, as would be expected based on a linear relationship, it dropped to 14.93 s for the 153.0-km/h (95-mi/h) velocity—about 60 percent of what might have been expected. There was also an anomaly with the low-density condition: in this case, the exposure time increased from 8.10 s to 13.23 s as the design velocity increased from 128.8 km/h (80 mi/h) to 153.0 km/h (95 mi/h), as expected—but then the exposure time of 10.98 s obtained for the 104.7-km/h (65-mi/h) velocity was twice as long as expected.

The difference in the performance of the younger drivers shown in figure 8 and the performance of the older drivers shown in figure 9 produced the significant three-way interaction. It will be reconsidered when further experiments in the current series re-examine these variables.

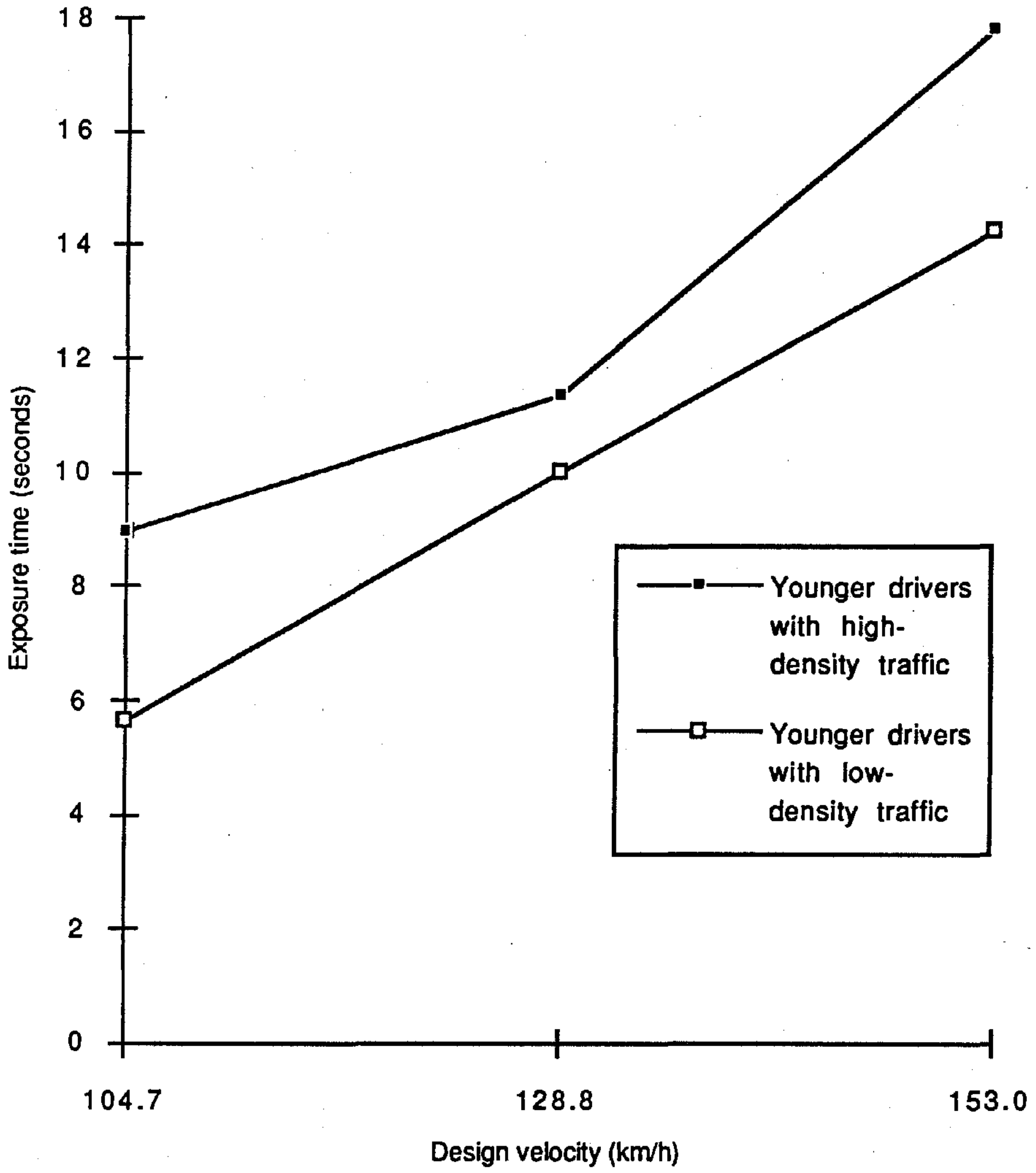


Figure 8. Exposure time as a function of design velocity for high- and low-traffic densities for younger drivers.

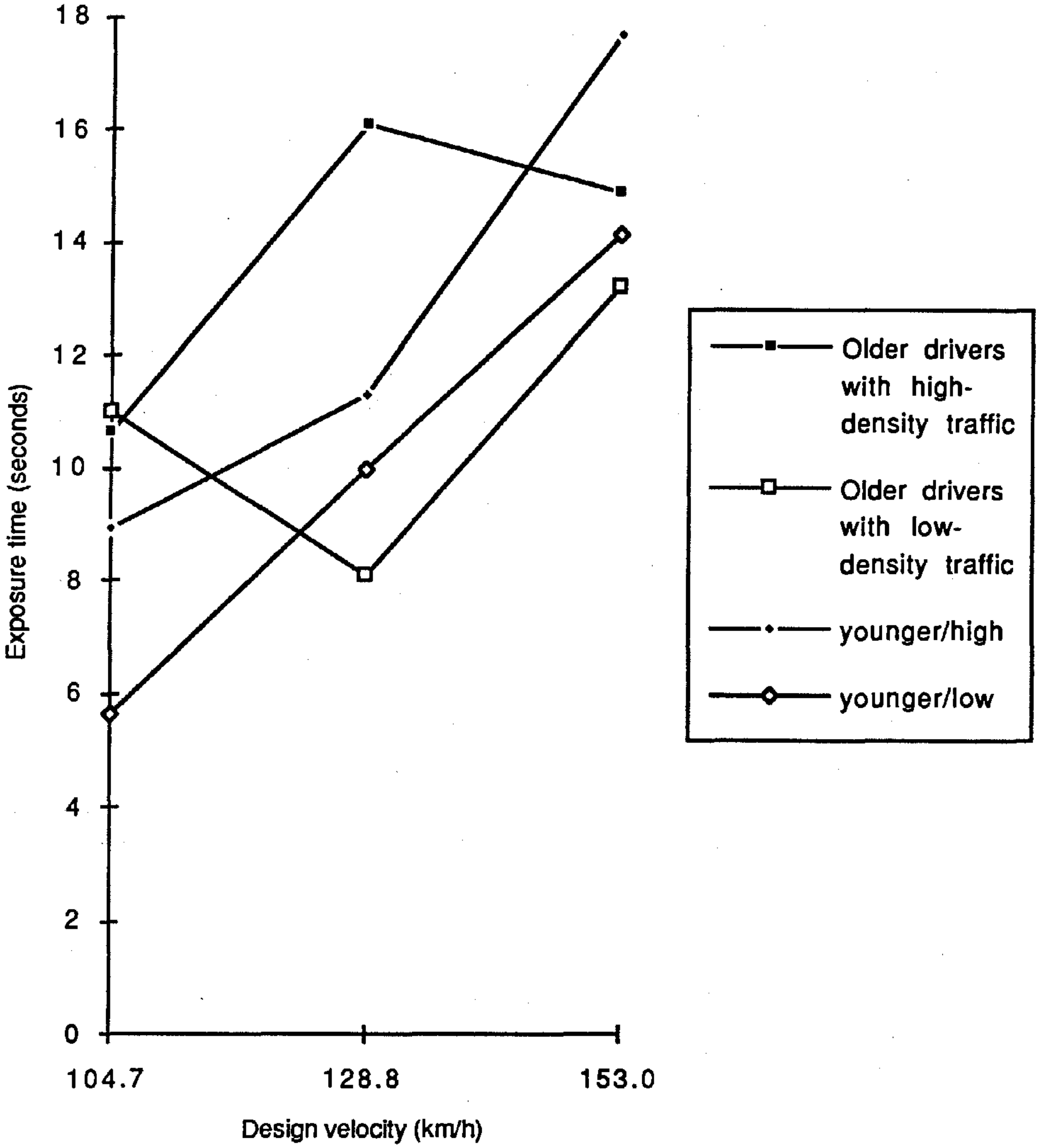


Figure 9. Exposure time as a function of design velocity for high- and low-traffic densities for older drivers.

Exit Velocity

In the last subsection, large differences were found between the mean exposure times obtained for the three design velocities. It seemed likely that this was because the drivers decided that the safest strategy to use in driving out of the automated lane was to decelerate in order to reduce the differential between the velocity of their vehicle and the velocity of the unautomated traffic into which they had to merge. This possibility was investigated by determining the velocity with which the driver's vehicle left the automated lane. Then, three ANOVAs were conducted on resultant exit velocities. Table 8 summarizes the findings of these ANOVAs.

Table 8. Summary of ANOVAs determining whether exit velocities were affected by variations in the design velocity, intra-string gap, traffic density, or the driver's age.

	Experiment #1 Younger Drivers	Experiment #2 Older Drivers	Combined Data Younger vs. Older
Age			—
Velocity	0.0020	0.0011	0.0001
Gap	—	—	—
Density	0.0292	0.0027	0.0001
Interactions	—	—	—

As table 8 shows, the pattern of significant effects was identical for the younger drivers, the older drivers, and for their combined data. In all three analyses, the mean exit velocity was affected by variations in both the design velocity (with p = 0.0020 for the younger drivers, p = 0.0011 for the older drivers, and p = 0.0001 for the combined data) and the density of the unautomated traffic density (with p = 0.0292 for the younger drivers, p = 0.0027 for the older drivers, and p = 0.0001 for the combined data). As table 8 also shows, when the combined data were analyzed, the age of the driver did not have a significant effect on the exit velocity, and there were no significant interactions in any of the three ANOVAs. Because of these ANOVA results and to avoid unnecessary repetition, in this subsection, only the combined data of the younger and older drivers will be presented.

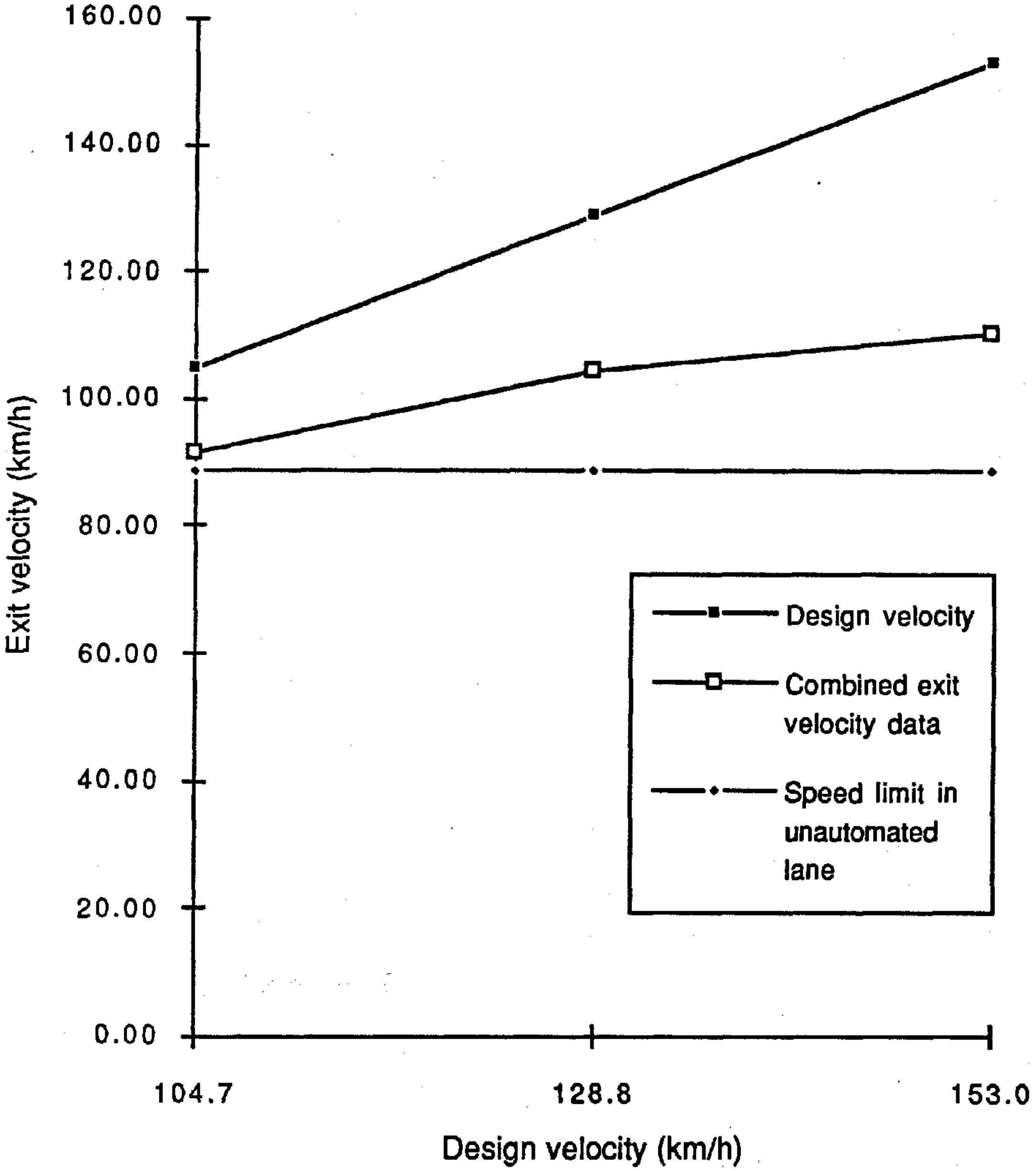


Figure 10. Exit velocity as a function of design velocity for the combined data of the younger and older drivers.

The Effect of Design Velocity on Exit Velocity. Figure 10 shows exit velocity—averaged over both the younger and older drivers—as a function of design velocity. The exit velocity can be seen between two other lines: the uppermost of these line indicates the design velocity at which the driver was traveling at the moment that control was transferred; and the lower line—which is parallel to the x-axis—shows the speed limit in the unautomated lane. As can be seen from figure 10, the drivers slowed down considerably in all three design velocity conditions—and, for the slowest design velocity condition, 104.7 km/h (65 mi/h), the mean exit velocity obtained was 91.51 km/h (56.84 mi/h), which was very close to the 88.55-km/h (55-mi/h) speed limit. Post hoc testing indicated that for the slowest design velocity condition, the exit velocity was significantly slower than the exit velocities obtained with the two faster design velocities. In these two conditions, although there were considerable reductions in velocity, the drivers did not slow down to the speed limit—for the 128.8-km/h (80-mi/h) design velocity condition, the exit velocity was 104.44 km/h (64.87 mi/h); and for the 153.0-km/h (95-mi/h) design velocity condition, the exit velocity was 109.84 km/h (68.94 mi/h).

The Effect of the Unautomated Traffic Density on Exit Velocity. The second significant independent variable was the unautomated traffic density. When the density increased from 6.21 v/km/ln (10 v/mi/ln) to 12.42 v/km/ln (20 v/mi/ln), the mean exit velocity dropped from 105.30 km/h (65.40 mi/h) to 99.54 km/h (61.83 mi/h).

Exit Velocity and Exposure Time. It was suggested at the beginning of this subsection, that the large differences found between the mean exposure times that were obtained for the three design velocities occurred because before driving out of the automated lane, the drivers decided to decelerate and reduce the differential between the velocity of their vehicle and the velocity of the unautomated traffic into which they had to merge. The exit velocity data presented in this subsection support this suggestion.

Lane-Change Time

The third experimental question was:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the **Lane-Change Time** (i.e., the length of time it takes to drive from the automated lane into the center lane)?*

The lane-change time started the moment that the first wheel of the driver's vehicle touched the line between the automated and center lanes on a successful lane change and ended the moment that the fourth wheel of the vehicle crossed that same line. Three separate ANOVAs were carried out on the lane-change time data from experiment #1, from experiment #2, and from both experiments combined. Table 9 summarizes their findings.

Table 9. Summary of ANOVAs determining whether mean lane-change times were affected by variations in the design velocity, intra-string gap, traffic density, or the driver's age.

	Experiment #1 Younger Drivers	Experiment #2 Older Drivers	Combined Data Younger vs. Older
Age			—
Velocity	0.0385	—	0.0229
Gap	—	—	—
Density	—	0.0432	—
Interactions			
A x G	—	—	0.0264

Lane-Change Time, Design Velocity, and the Younger Driver. Table 9 shows that there were significant differences (with p = 0.0385) in the mean lane-change times that were obtained with the three design velocity conditions for the younger drivers. Post hoc testing revealed that the mean lane-change time of 3.43 s that occurred with the 104.7-km/h (65-mi/h) design velocity was significantly longer than the 1.80-s mean that was obtained when the design velocity was 128.8 km/h (80 mi/h). While the mean lane-change time of 1.97 s obtained when the design velocity was 153.0 km/h (95 mi/h) is very close to the mean for the 128.8-km/h (80-mi/h) velocity, it was not significantly different from the 104.7-km/h (65-mi/h) design velocity lane-change time. Figure 11 shows the relationship between the mean lane-change time and the design velocity for the younger drivers.

Lane-Change Time, Unautomated Traffic Density, and the Older Driver. Table 9 indicates that variations in the density of the traffic in the unautomated lane had a significant effect (with p = 0.0432) on the mean lane-change times for the older drivers. Their mean lane-change time increased from 1.86 s for the 6.21-v/km/ln (10-v/mi/ln) density to 2.62 s for the 12.42-v/km/ln (20-v/mi/ln) density.

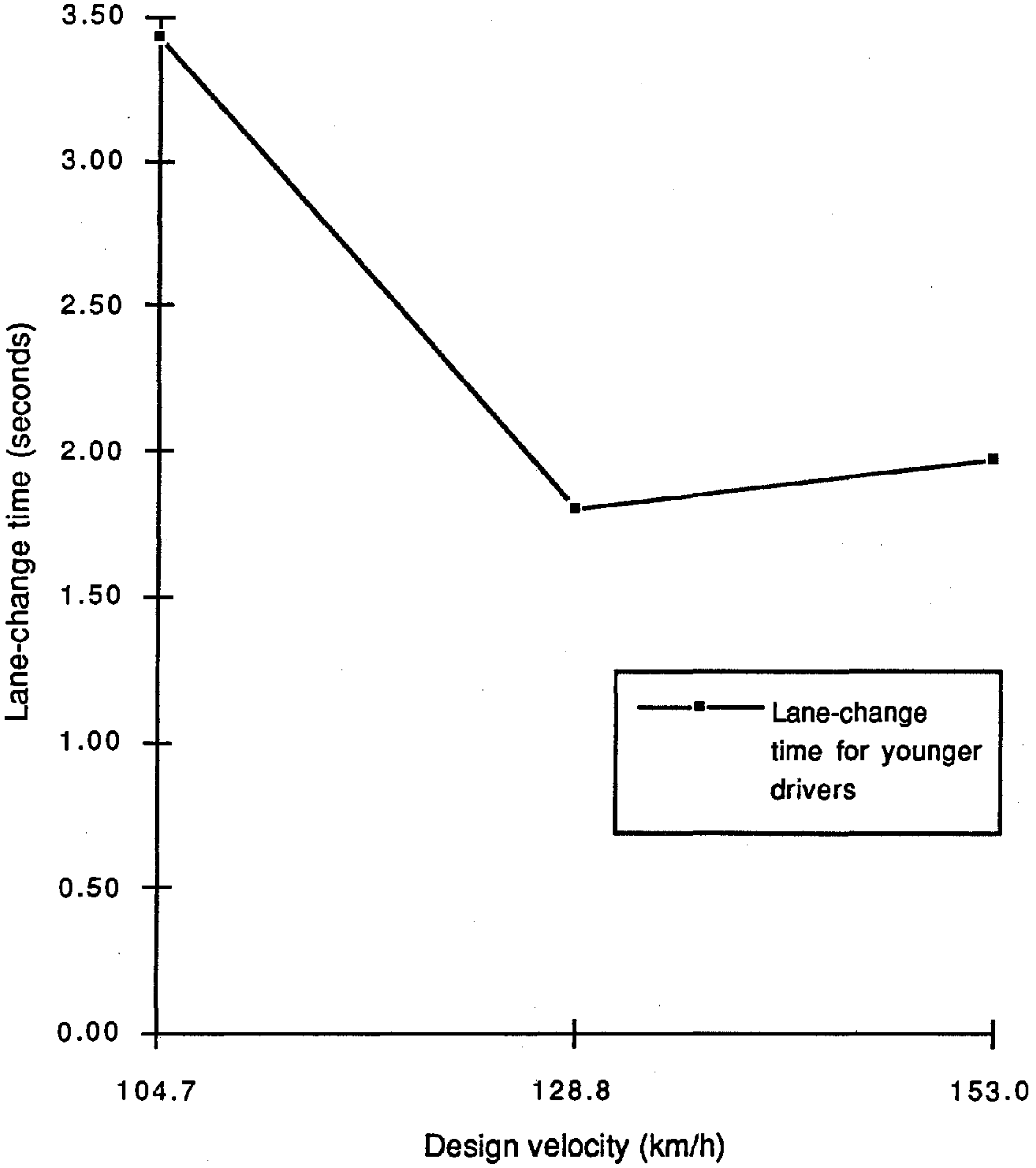


Figure 11. Lane-change time as a function of design velocity for the younger drivers.

Combined Data—Main Effects on Lane-Change Time: (a) Design Velocity. As can be seen from table 9, variations in the design velocity had a statistically significant effect on the mean lane-change time when the combined data of experiments #1 and #2 were analyzed. As already mentioned, it was also statistically significant for the younger drivers alone. Because the ANOVA carried out on the combined data failed to find a significant effect of the driver's age on the lane-change times, or a statistically significant interaction between the driver's age and design velocity, the combined data have been used in figure 12, which shows the overall relationship between the mean lane-change time and design velocity. Figure 12 shows that as the design velocity increases from 104.7 km/h (65 mi/h) to 153.0 km/h (95 mi/h), the lane-change time decreases from 3.20 s to 1.78 s. Post hoc testing showed that the difference between these two means was statistically significant—the mean lane-change time of 2.04 s obtained for the mid-range design velocity, 128.8 km/h (80 mi/h), was not different from either of these two means.

Combined Data—Main Effects on Lane-Change Time: (b) Unautomated Traffic Density. As already mentioned, variations in the density of the traffic in the unautomated lane had a significant effect on the mean lane-change times for the older drivers. They did not have a significant effect for the younger drivers: for them, the mean lane-change time for the two density conditions was virtually unchanged—it was 2.39 s when the density was 6.21 v/km/ln (10 v/mi/ln), and 2.38 s when the density was 12.42 v/km/ln (20 v/mi/ln). When the lane-change time data from the two experiments were combined, the effect found with the older drivers was submerged, and the interaction between driver's age and traffic density did not reach significance. However, given the significant effect for the older drivers and clear lack of effect for the younger drivers, it is possible that when driving from an automated lane to an unautomated lane, the behavior of older and younger drivers will, in fact, differ under some traffic density conditions.

Combined Data—The Interaction of Driver's Age and Intra-String Gap. Neither the driver's age nor the intra-string gap had a significant effect in any of the three ANOVAs carried out on the lane-change time data. However, in the analysis of the combined data, the interaction of these two variables was statistically significant (with $p = 0.0264$) and, as figure 13 indicates, the behavior of the drivers in the two age groups did differ. For the younger drivers, lane-change time increased from 1.87 s to 3.05 s as the gap increased from 0.0625 s to 1.0 s, while just the opposite happened with the older drivers—for them, lane-change time decreased from 2.69 s to 1.84 s as the gap increased.

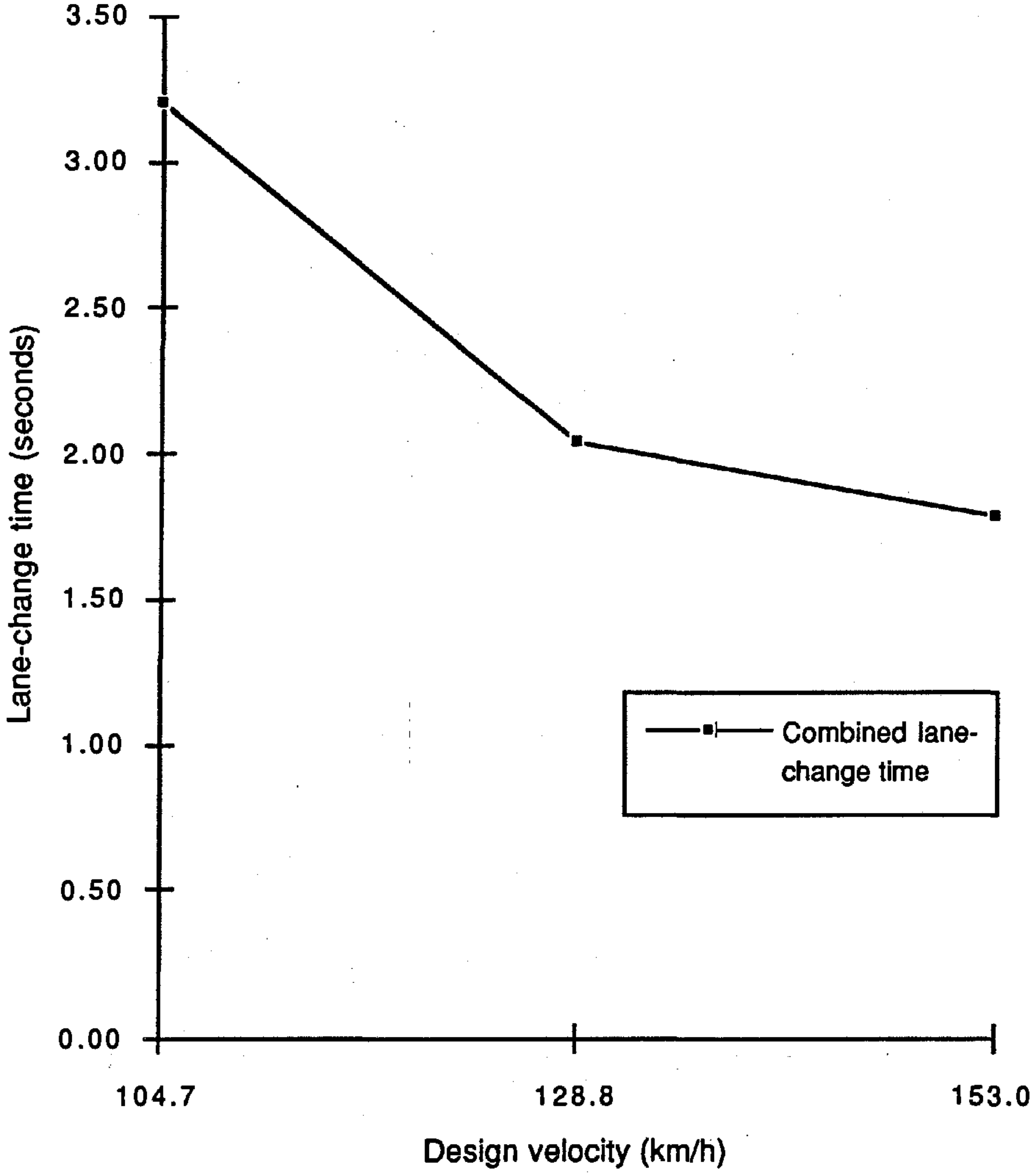


Figure 12. Lane-change time as a function of design velocity for the combined data of the younger and older drivers.

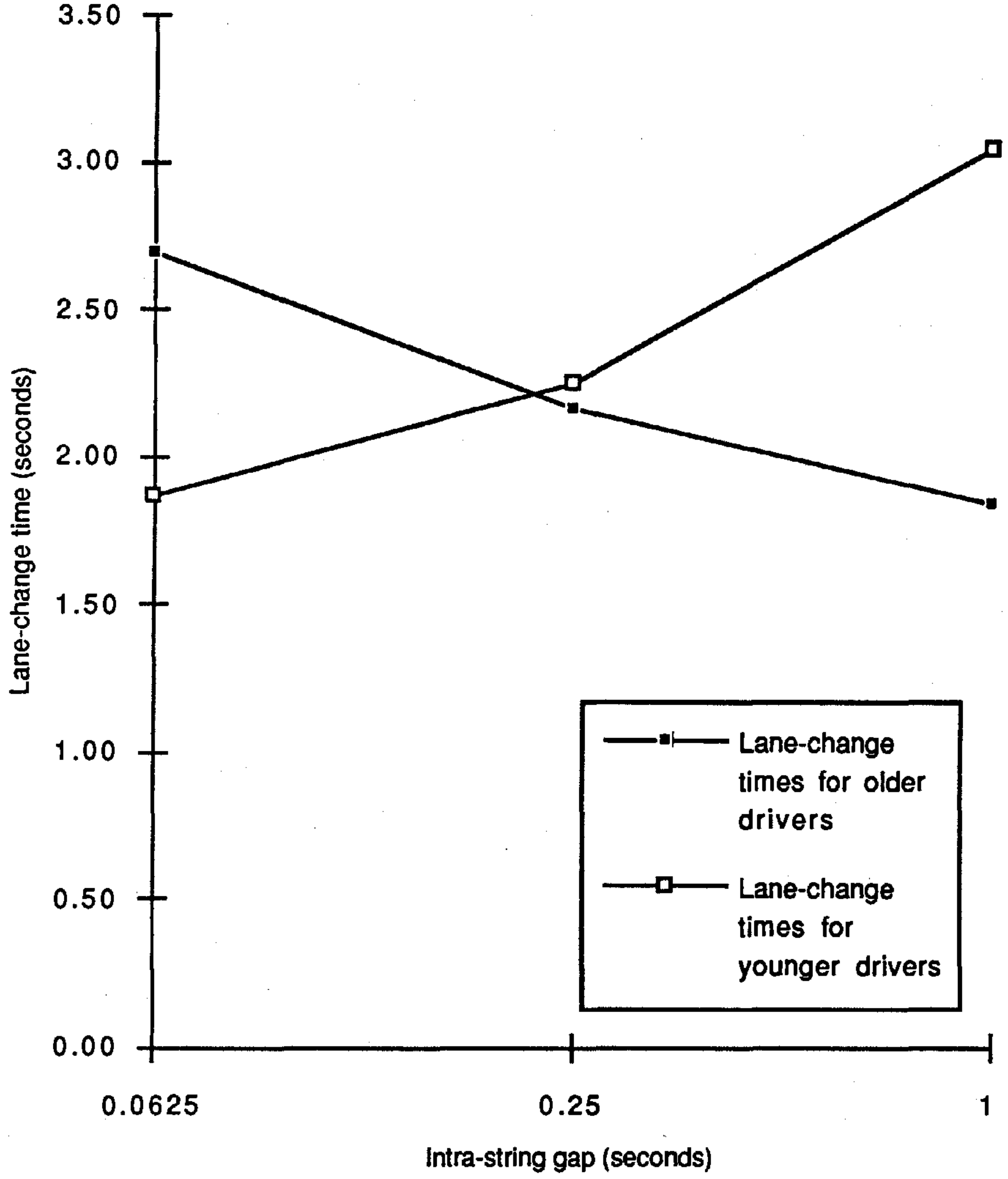


Figure 13. Lane-change time as a function of intra-string gap for younger and older drivers.

Center Lane Time

Our fourth experimental question was:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Center Lane Time*** *(i.e., the time the driver spent in the center lane after leaving the automated lane)?*

Three separate ANOVAs were carried out on the center lane time data from experiment #1, from experiment #2, and from both experiments combined. Table 10 summarizes the findings of these three ANOVAs.

Table 10. Summary of ANOVAs determining whether mean center lane times were affected by variations in the design velocity, intra-string gap, traffic density, or the driver's age.

	Experiment #1 Younger Drivers	Experiment #2 Older Drivers	Combined Data Younger vs. Older
Age			0.0002
Velocity	—	—	—
Gap	—	—	—
Density	—	—	—
Interactions	—	—	—

As table 10 indicates, there were no significant differences in the time spent in the center lane caused by variations in the design velocity, the intra-string gap, or the density of the traffic in the unautomated lane in any of these three ANOVAs.

Center Lane Time and the Age of the Driver. Table 10 indicates that the variation in the age of the drivers did have a significant effect (with $p = 0.0002$) on the time spent in the center lane. This effect is illustrated in figure 14—it shows a plot of the mean center lane time as a function of design velocity for both the younger and the older drivers. The point of interest in this figure is the clear difference between the plot for the younger drivers and the plot for the older drivers. When the data were collapsed over the three design velocities, the mean center lane time for the older drivers was 6.72 s, while for the younger drivers it was 11.52 s—they stayed in the center lane more than 70 percent longer than the older drivers.

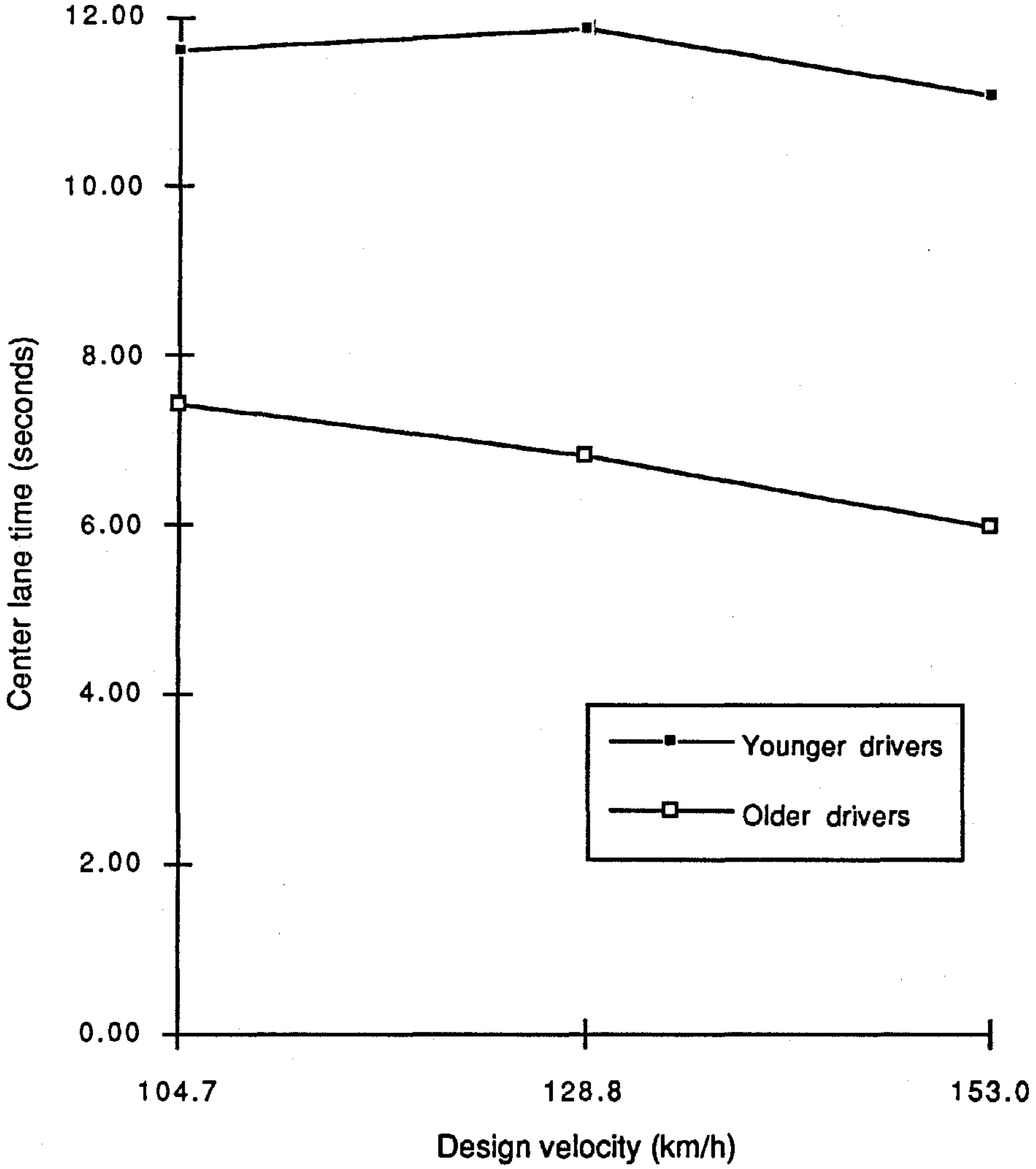


Figure 14. Center lane time as a function of design velocity for the younger and older drivers.

Delay Time

Our fifth experimental question was:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the* ***Delay Time*** *experienced by the vehicle immediately behind the driver's vehicle in the automated lane?*

After the driver took control of the vehicle and while the driver's vehicle was still in the automated lane, the automated vehicle traveling immediately behind the driver's vehicle was not simply under the control of the AHS, but had to respond to the deceleration behavior of the driver's vehicle. As a result, this vehicle was delayed. As mentioned above, the length of time it was delayed is given by the following equation:

$$T_d \quad = \quad (d_1 - d_2)/V$$

where:

T_d — was the delay time (which was the measured delay time in the first part of the analysis, and was the total delay time in the second part).

d_1 — was the distance traveled by the string of vehicles following the driver's vehicle in T_d.

d_2 — was the distance that would have been traveled by the string of vehicles following the driver's vehicle, in T_d, if the driver had not, in fact, taken control of the vehicle.

V — was the design velocity.

Using the data from experiment #1 and experiment #2, the above equation was used to calculate the measured and the total delay time in each trial. Then, three ANOVAs were carried out on the measured delay time—the first using the data from experiment #1, the second using the data from experiment #2, and the third comparing the data from both experiments. An additional three ANOVAs were carried out on the total delay time—the first on the data from experiment #1, the second on the data from experiment #2, and the third comparing the data from both experiments. Table 11 summarizes the six ANOVAs.

As can be seen from table 11, the differences in delay time associated with the size of the intra-string gap and the age of the driver did not reach significance; in addition, none of the interaction terms—including those involving the age of the driver—were significant. However, the other two independent variables—design velocity and the density of the traffic in the unautomated lanes—both did affect delay time. The remainder of this subsection is organized in terms of these two variables. The effect on delay time of design velocity is discussed—first, for the younger drivers; second, for the older drivers; and third, for the combined data. Then, the effect of the density of the traffic in the unautomated lanes will be discussed in the same way.

Table 11. Summary of six ANOVAs determining the effect for younger and older drivers and for their combined data on the measured and total delay time of variations in the design velocity of the automated lane, the size of the intra-string gap, the traffic density in the unautomated lanes, and the age of the driver.

	Younger		Older		Combined	
	Measured	Total	Measured	Total	Measured	Total
Age	—	—	—	—	—	—
Velocity	0.0006	0.0001	—	0.0028	0.0002	0.0001
Gap	—	—	—	—	—	—
Density	—	—	0.0059	0.0082	0.0083	0.0052
Interactions	—	—	—	—	—	—

<u>Delay Time and Design Velocity: (a) The Younger Driver.</u> As shown in table 11 for the younger drivers, design velocity had a significant effect on both delay times—for the measured delay time, the p-value was 0.0006; for the total delay time, it was 0.0001. The measured and total delay times both increased as the design velocity increased. Post hoc testing indicated that the mean measured delay time of 3.92 s, obtained when the design velocity was 153 km/h (95 mi/h), was significantly longer than both the 0.83 s obtained with the 104.7-km/h (65-mi/h) design velocity, and the 1.67 s obtained when it was 128.8 km/h (80 mi/h). Similarly, the mean total delay time of 7.03 s that was obtained when the design velocity was 153 km/h (95 mi/h) was significantly longer than both the 1.03 s obtained with the 104.7-km/h (65-mi/h) design velocity, and the 2.52 s obtained when it was 128.8 km/h (80 mi/h).

<u>Delay Time and Design Velocity: (b) The Older Driver.</u> For the older drivers, design velocity had a significant effect only on the total delay time (with p = 0.0028). The mean total delay time increased as the design velocity increased. As with the younger drivers, the post hoc tests indicated that for the older drivers, total delay time of 6.21 s obtained when the design velocity was 153 km/h (95 mi/h) was significantly longer than both the 1.88 s obtained with the 104.7-km/h (65-mi/h) design velocity, and the 2.71 s obtained when it was 128.8 km/h (80 mi/h).

<u>Delay Time and Design Velocity: (c) Combined Data.</u> Table 11 shows that for the combined data, both delay times were affected by variations in the design velocity—the p-values were

0.0002 for the measured delay time and 0.0001 for the total delay time. The measured and total delay times increased together as the design velocity increased. Post hoc testing showed that both the measured and total delay times for the 153-km/h (95-mi/h) design velocity were significantly longer than the delay times obtained with the 104.7-km/h (65-mi/h) and 128.8-km/h (80-mi/h) design velocities. The effect on the measured and total delay times of varying the design velocity of the automated lane is shown for the combined data in figure 15. However, the relationship between delay time and design velocity is not linear—as can be seen in figure 15, it is an accelerating function, with the rate of increase in the delay time also increasing with the design velocity. The mean measured delay time was 1.14 s when the design velocity was 104.7 km/h (65 mi/h), 1.73 s when it was 128.8 km/h (80 mi/h), and 3.63 s when it was 153 km/h (90 mi/h); the mean total delay time was 1.36 s when the design velocity was 104.7 km/h (65 mi/h), 2.59 s when it was 128.8 km/h (80 mi/h), and 6.70 s when it was 153 km/h (90 mi/h).

Density of the Unautomated Traffic: (a) Younger Drivers. Variations in the traffic density in the unautomated lanes did not significantly affect the measured and total delay times for the younger drivers.

Density of the Unautomated Traffic: (b) Older Drivers. However, as table 11 shows, for the older drivers both delay times were affected by variations in the design velocity—the p-values were 0.0059 for the measured delay time and 0.0082 for the total delay time. The mean measured delay time was 1.76 s when the traffic density was 12.42 v/km/ln (20 v/mi/ln), and 2.78 s when it was 6.21 v/km/ln (10 v/mi/ln); and the total delay time was 4.44 s in the high-density condition, and 3.03 s in the low-density condition.

Density of the Unautomated Traffic: (c) Combined Data. For the combined data, both delay times were affected by variations in the design velocity—the p-values were 0.0083 for the measured delay time and 0.0052 for the total delay time. Since, as already mentioned, the driver's age did not have a significant effect on the delay time and the interaction between driver's age and traffic density was not significant, the effect of density on delay time can be characterized using the combined data—the effect is shown in figure 16. The mean delay times were approximately 30 percent longer when the traffic density was 12.42 v/km/ln (20 v/mi/ln) than when it was 6.21 v/km/ln (10 v/mi/ln)—2.53 s vs. 1.91 s for the measured delay time, and 4.12 s vs. 3.21 s for the total delay time.

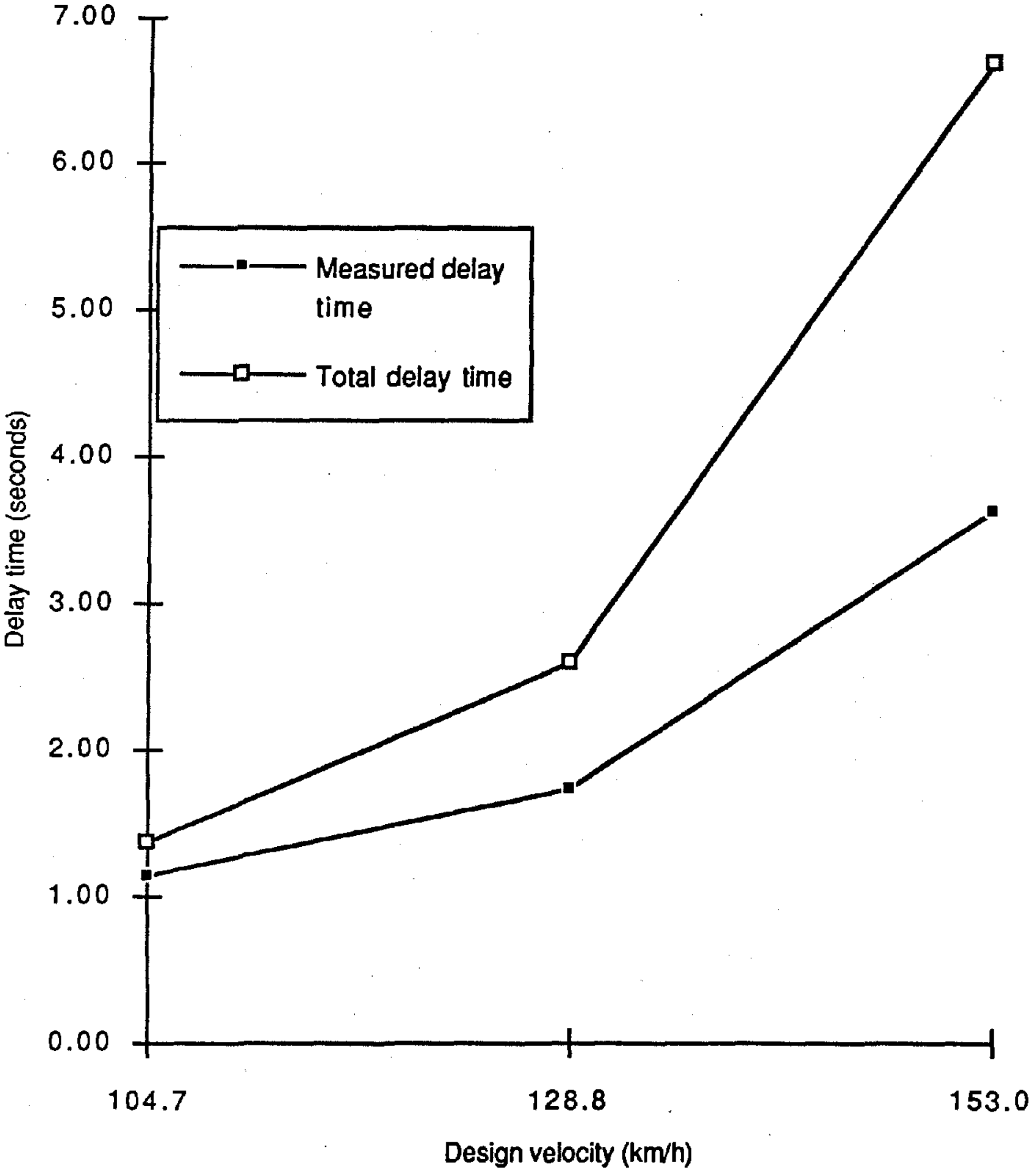


Figure 15. Delay time as a function of design velocity—combined data of younger and older drivers.

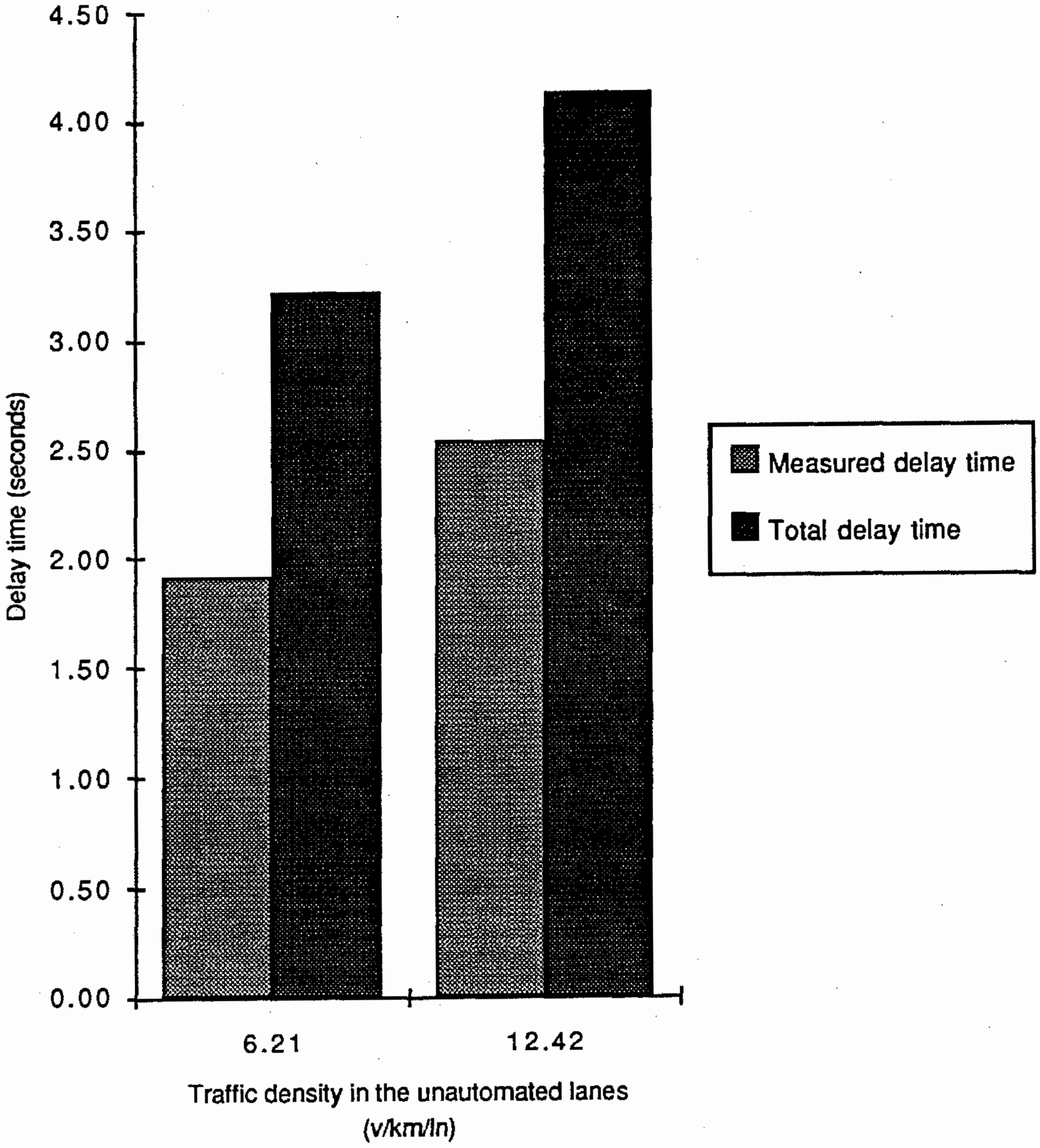


Figure 16. Delay time as a function of the traffic density in the unautomated lanes—combined data of younger and older drivers.

Collisions and Lane Incursions

The final experimental question was:

- *What effects do variations in the design velocity of the automated lane, the intra-string gap between automated vehicles, the density of the unautomated vehicles, and the age of the driver have on the driver's ability to avoid* ***collisions*** *with other vehicles or* ***lane incursions*** *(i.e., incomplete lane changes)?*

During and just after the transfer of control from the AHS to the driver, the avoidance of collisions is a paramount aspect of safety for the driver. Six collisions occurred in the two experiments. However, three of these collisions—two in experiment #1 and one in experiment #2—appear to have been experimental artifacts. In experiment #1, one collision occurred because of jittering in the simulator imagery caused when there was a rare, momentary overload in the imagery demand on the CT-6 image generator. With a second collision in experiment #1, the driver failed to respond to the *Exit* advisory and, when informed of this by the experimenter, immediately took control of the vehicle, changed lanes while still traveling at the design velocity, and then collided with the vehicle ahead in the center lane. And, in experiment #2, one collision occurred when the simulator vehicle, in changing lanes, sideswiped a center-lane vehicle that was in the driver's blind spot—probably because the simulator vehicle lacks a right-side mirror.

The remaining three collisions can be attributed to the exit maneuver that was used after the driver took control of the simulator vehicle while it was in the automated lane. These three collisions occurred when the driver moved the simulator vehicle into the center lane at what proved to be too high a velocity for the gap that was available—in two cases, the simulator vehicle collided with the vehicle ahead in the center lane; in the third case, to avoid colliding with the vehicle ahead, the driver moved the vehicle back to the automated lane and collided with an automated string of vehicles. It is important to note that there were no collisions during either experiment when the driver changed from the center to the right lane: thus, the three collisions attributed to the exit maneuver are not likely to be due to the lack of a right-side mirror on the simulator vehicle.

While far less serious than collisions, the driver will also wish to avoid lane incursions, where the driver begins to change lanes and then aborts the maneuver. For these experiments, an incursion was defined as an occasion on which at least one wheel of the driver's vehicle touched or crossed the line between lanes without a lane change being completed. In experiment #1, in addition to the single collision related to the exit maneuver used when the driver took control of the simulator vehicle, there were 6 incursions in 216 trials with the 36 younger drivers. In experiment #2, in addition to the 2 collisions related to the exit maneuver, there were 8 incursions in the 144 trials with the 24 drivers.

There were too few collisions and incursions to allow a meaningful statistical analysis to be performed. Table 12 reports the number of collisions related to the exit maneuver and the number of lane incursions that occurred, with each combination of design velocity, intra-string gap size, traffic density, and driver's age. Considering both experiments together, the 14 incursions were spread across the design-velocity conditions, but occurred more often with the high-density traffic and with the 0.0625-s intra-string gap, while all 3 collisions occurred in the 120 trials in which the design velocity was 153.0 km/h (95 mi/h). The absence of a statistical analysis notwithstanding, these were relatively high collision and incursion rates.

Table 12. The number of collisions related to the exit maneuver and of lane incursions occurring in each combination of design velocity, intra-string gap, traffic density, and driver's age.

[Notes: (1) collisions are indicated in boldface; (2) where "1-Y" and "1-O" are listed in the row for collisions or incursions, they should be read as "one occurrence involving a younger driver" and "one occurrence involving an older driver," respectively; (3) "2s" is used to indicate a trial in which there were two separate incursions.]

	Intra-string gap (s)					
	1 second		0.25 second		0.0625 second	
Density (v/km/ln)	6.21	12.42	6.21	12.42	6.21	12.42
Design velocity						
104.7 km/h (65 mi/h)						
Incursions	0	0	0	1-Y, 1-O	2-Y	3-O (2s)
Collisions	0	0	0	0	0	0
128.8 km/h (80 mi/h)						
Incursions	0	0	1-O	0	0	1-Y, 1-O
Collisions	0	0	0	0	0	0
153.0 km/h (95 mi/h)						
Incursions	1-Y	0	0	1-Y, 1-O	0	1-O
Collisions	0	0	0	**2-Y, 1-O**	**1-O**	0

Questionnaire Data

A copy of the questionnaire that was given to each driver in both experiments #1 and #2 is presented in appendix 4. After questions 1 to 19 and 23, a 104-mm 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 response. Each response was measured, in mm, 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 53 and 104 reflects a response that favors the extreme to the right—the closer the score is to 104, the more it favors the extreme position. The neutral point was 52.

A series of ANOVAs was conducted to examine whether the responses to questions 1 to 19 and 23 were affected by the age of the driver, the gender of the driver, or the design velocity that the driver had experienced while traveling in the automated lane. The results of these analyses are presented in the subsections that follow.

Simulator Realism. The first six questions of the questionnaire were designed to elicit the opinions of the drivers on the realism of the Iowa Driving Simulator. The ANOVAs carried out on these questions failed to show any statistically significant differences in the responses to any of the first six questions. As a result, the average response data presented in table 13 are collapsed over age, gender, and design velocity.

Inspection of table 13 shows that the average response to question 2 was 60.9, suggesting that the simulator experience was slightly more similar than dissimilar to normal driving. The average responses to the other five questions in this set ranged between 70.3 (for question 5) to 88.4 (for question 1), suggesting that the simulator experience appeared to be realistic, and had not produced any feeling of queasiness for the younger and older drivers, whether they were male or female, and irrespective of whether the design velocity was 104.7 km/h (65 mi/h), 128.8 km/h (80 mi/h), or 153.0 km/h (95 mi/h).

Design Speed and Intra-String Gap. The next two questions dealt with the speed of travel and the intra-string gap between the vehicles in the automated lane. The ANOVA for question 7 indicated that the design velocity affected the responses (p = 0.0263). However, no significant effects emerged from the ANOVA for question 8. Table 14 shows the responses to these two questions.

Table 13. Simulator realism.

Question	Overall Mean
1. How much did you enjoy driving the simulator? 0. Not at all 104. A great deal	88.4
2. How did driving in the simulator compare to driving in your car? 0. Very different 104. Very similar	60.9
3. How realistic was the view out of the windshield in the simulator? 0. Very artificial 104. Very realistic	71.9
4. How realistic were the sounds in the simulator? 0. Very artificial 104. Very realistic	72.1
5. How realistic was the vehicle motion in the simulator? 0. Very artificial 104. Very realistic	70.3
6. While driving the simulator, did you feel queasy or unwell? 0. Felt unwell 104. Felt fine	75.7

For question 7, the average response of the drivers who experienced the 104.7-km/h (65-mi/h) design velocity in the automated lane was 67.6, between the neutral and much faster anchor points; while the response of those who experienced the 128.8-km/h (80-mi/h) design velocity was 51.6, an essentially neutral response; and the response of those who experienced the 153.0-km/h (95-mi/h) design velocity was 56.0, which is close to neutral, though slightly favoring the faster anchor point.

For question 8, the overall mean response of 31.4 clearly indicated that the drivers tended to prefer the longer intra-vehicle distance that they experienced while in the automated lane.

Table 14. Design speed and intra-string gap.

Question	104.5 km/h (65 mi/h)	128.8 km/h (80 mi/h)	153.0 km/h (95 mi/h)
7. In this study, when your car was under automatic control, were you comfortable with the speed, or would you have preferred to have traveled faster or slower? 0. Would prefer much slower 104. Would prefer much faster	67.6	51.6	56.0

	Overall Mean
8. In this study, when your car was under automatic control, the distance between you and the cars in front and behind was varied from trial to trial—which separation distance did you prefer? 0. Preferred longer distance 104. Preferred shorter distance	31.4

<u>AHS Message.</u> Questions 9 and 10 dealt with the *Exit* advisory. No statistically significant differences emerged when ANOVAs were conducted on the responses to these questions. As a result, the average response data presented in table 15 are collapsed over age, gender, and design velocity. The average response of 91.5 to question 9 indicates that the drivers were easily able to understand the *Exit* advisory. Similarly, the response of 88.4 to question 10 suggests that the advisory was given with sufficient time for them to respond.

Table 15. AHS message.

Question	Overall Mean
9. Was the message saying that you should take control of the car easy for you to understand? 0. Hard to understand 104. Easy to understand	91.5
10. Was the message saying that you should take control of the car presented early enough to give you time to react and prepare for exiting? 0. Insufficient time 104. Sufficient time	88.4

Safety and Control. The next five questions dealt with safety and control. The ANOVAs conducted on these questions indicated that there were several significant effects: velocity was significant for question 11; gender was significant for question 12; velocity and gender were significant for question 13; velocity and age were significant for question 14; though there were no significant effects for question 15. Table 16 shows the average responses for the various significant variables for each of these questions. [Note that where there were two significant variables, the responses related to both variables are given in the table.]

For question 11, asking how safe the speed at which the driver left the automated lane felt, the average of drivers who experienced the 104.7-km/h (65-mi/h) design velocity was 76.2, midway between the neutral and very safe anchor points; while the drivers who experienced the two higher velocities gave neutral average responses—54.3 for those in the 128.8-km/h (80-mi/h) velocity condition, and 51.2 for those in the 153.0-km/h (95-mi/h) velocity condition.

For question 12, on describing the manner in which the driver controlled the vehicle when first taking control, the male drivers gave an average response of 59.6, which was close to neutral, but slightly favored the well-controlled side; while the female drivers gave an average response of 47.2, which was also close to neutral, but slightly favored the poorly controlled side.

For question 13, asking the extent to which the driver felt in control of the situation immediately after leaving the automated lane, both gender and velocity produced significant differences. The male drivers gave a response of 69.2, which was in the controlled region of the continuum; while the average response of the female drivers was 53.0, an essentially neutral response. As to velocity, the drivers who experienced the 104.7-km/h (65-mi/h) design velocity gave an average response in the controlled region of the continuum (it was 70.3); while those experiencing the 128.8-km/h (80-mi/h) velocity only slightly favored the controlled side (with a response of 60.6); and those who were in the 153.0-km/h (95-mi/h) velocity condition were essentially neutral (their response averaged 52.4).

Question 14 asked whether the drivers preferred being in the automated or unautomated lanes. Both velocity and age produced significant effects. The drivers in the 153.0-km/h (95-mi/h) velocity condition had a stronger preference (with an average of 83.3) for the automated lane than the drivers in the two slower velocity conditions, who had averages of 69.9 and 65.3 for the 128.8-km/h (80-mi/h) and 104.7-km/h (65-mi/h) velocity condition, respectively. Also, the younger drivers expressed a stronger preference than the older drivers for the automated lane (81.2 vs. 67.2).

Table 16. Safety and control.

<table>
<tr><th>Question</th><th colspan="2">104.7 km/h (80 mi/h)</th><th colspan="2">128.8 km/h (80 mi/h)</th><th colspan="2">153.0 km/h (95 mi/h)</th></tr>
<tr><td>11. How safe did the speed at which you left the automated lane feel?
0. Very unsafe
104. Very safe</td><td colspan="2">76.2</td><td colspan="2">54.3</td><td colspan="2">51.2</td></tr>
<tr><td></td><td colspan="3">Male</td><td colspan="3">Female</td></tr>
<tr><td>12. How would you describe the manner in which you controlled your car immediately after leaving the automated lane, when you first drove in the manual lane?
0. Poorly controlled
104. Well controlled</td><td colspan="3">59.6</td><td colspan="3">47.2</td></tr>
<tr><td></td><td colspan="2">104.7 km/h (65 mi/h)</td><td colspan="2">128.8 km/h (80 mi/h)</td><td colspan="2">153.0 km/h (95 mi/h)</td></tr>
<tr><td>13. To what extent did you feel in control of the situation immediately after leaving the automated lane, when you first drove in the manual lane?
0. Not at all
104. To a great extent</td><td colspan="2">70.3</td><td colspan="2">60.6</td><td colspan="2">52.4</td></tr>
<tr><td></td><td colspan="3">Male</td><td colspan="3">Female</td></tr>
<tr><td>0. Not at all
104. To a great extent</td><td colspan="3">69.2</td><td colspan="3">53.0</td></tr>
<tr><td></td><td colspan="2">104.7 km/h (65 mi/h)</td><td colspan="2">128.8 km/h (80 mi/h)</td><td colspan="2">153.0 km/h (95 mi/h)</td></tr>
<tr><td>14. In this study, you spent some time in the automated lane and some time in the manual lanes: which lane did you prefer?
0. Strongly preferred manual lane
104. Strongly preferred automatic lane</td><td colspan="2">65.3</td><td colspan="2">69.9</td><td colspan="2">83.3</td></tr>
<tr><td></td><td colspan="3">Younger</td><td colspan="3">Older</td></tr>
<tr><td>0. Strongly preferred manual lane
104. Strongly preferred automatic lane</td><td colspan="3">81.2</td><td colspan="3">67.2</td></tr>
</table>

Table 16. Safety and control (continued).

	Overall Mean
15. Was it more challenging to be in the automated lane or the manual lanes? 0. More challenging in manual lanes 104. More challenging in the automated lane	18.8

Table 17. Attitude toward the AHS.

Question	Overall Mean
16. How would you feel if an Automated Highway System was installed on I-380 between Iowa City and Waterloo? 0. Very unenthusiastic 104. Very enthusiastic	78.7
17. If an Automated Highway System was installed on I-380, would you prefer driving in the automated lanes or the manual lanes? 0. Strongly prefer manual lanes 104. Strongly prefer automated lanes	75.1
18. If an Automated Highway System was installed, would you feel safer driving on I-380 than you do now without the System? 0. Much safer with current freeways 104. Much safer with Automated Highway System	63.6
19. How will the installation of an Automated Highway System affect the stress of driving? 0. Will greatly decrease stress 104. Will greatly increase stress	29.6

With question 15, there were no significant effects. All the drivers, no matter which velocity condition they had experienced, indicated (with an average response of 18.8) that it was more challenging to be in the unautomated lanes than it was to be in the automated lane.

Attitude Toward the AHS. The next four questions dealt with the attitude of the drivers toward the AHS. The ANOVAs conducted for these questions found no significant effect for any of the questions. The responses to these questions are presented in table 17.

The response to question 16 suggested that the drivers would feel enthusiastic if an AHS were to be installed on I-380, a local freeway (the average response was 78.7). Further, they indicated by their response to question 18 that if it were installed, they would prefer driving in the automated lane (the average response was 75.1).

The response to question 18 suggested that the drivers felt that driving in the automated lane would be somewhat safer than driving in the unautomated lanes (the average response was 63.6). And, all drivers seemed to believe that the installation of an AHS will reduce stress (the average response to question 19 was 29.6).

Cruise Control. The responses to question 22 indicated that 22 of the 36 younger drivers, and 23 of the 24 older drivers had cruise control. Question 23 asked how often these 45 drivers used their cruise control. No significant differences were found when an ANOVA was conducted on the responses to this question. As table 18 indicates, the average response of 74.1 suggested that these drivers used the cruise control often.

Table 18. Cruise control.

Question	**Overall Mean**
23. How do you use the cruise control on your vehicle? 0. Hardly ever 104. Very often	74.1

SECTION 4: DISCUSSION

EXPLANATIONS

The objective of experiments #1 and #2 was to determine the conditions under which control can be transferred from the AHS to the driver, when the latter leaves the automated lane, with due regard to safety and with the minimum of interference to the flow of traffic in the automated lane.

In both experiments, at the start of each experimental trial, the simulator vehicle was in the middle of a string of automated vehicles that was traveling in an automated lane under the control of the AHS. The driver's task was to take control of the vehicle while it was in the automated lane, then drive it into the unautomated center lane and the right lane, before leaving the freeway at a designated exit. The velocity of the vehicles in the automated lane (the design velocity), the gap between the vehicles within the string (the intra-string gap), and the density of the traffic in the unautomated lane (the traffic density) were varied from trial to trial. A group of 36 younger drivers (aged between 25 and 34) took part in experiment #1; and 24 older drivers (aged 65 or older) participated in experiment #2. The data obtained in both experiments were analyzed separately to determine whether the design velocity, the intra-string gap, or the traffic density had affected driving performance. In addition, the combined data from both experiments were analyzed to determine whether the age of the driver affected performance. The particular driving performance measures that were examined in these three analyses were: the response time, exposure time, exit velocity, lane-change time, center lane time, and the delay time.

Response Time

The response time was the time between the moment that the *Exit* advisory was issued by the AHS and the moment that the driver took control of the vehicle. The advisory was issued 60 s before the driver's vehicle would have arrived at the designated exit, if it continued to travel at the design velocity. The driver had plenty of time in which to respond—in such a situation, the driver has a great deal of discretion, and a wide range of response times might be obtained without suggesting poor driving performance.

The analysis of the data obtained from the younger drivers in experiment #1 indicated there were no significant effects of the design velocity, the intra-string gap, and the traffic density on the

Preceding page blank

response time. However, a similar analysis of the data obtained from the older drivers in experiment #2 showed that one of the variables—the design velocity—did have a statistically significant effect on the response time and, when the data from the two experiments were analyzed together, design velocity was found to affect the response time. Averaging over all 60 drivers who took part in both experiments, the response time was found to be shorter when the design velocity was 128.8 km/h (80 mi/h) than when it was 104.7 km/h (65 mi/h)—it was 10.16 s vs. 13.41 s.

In looking for an explanation as to why this difference might have occurred, it is useful to consider how similar the experience of driving in the experiment might have been to driving in real life.

When under automated control in the left lane with the 104.7-km/h (65-mi/h) design velocity, the experience may have seemed to the driver to be similar to the current driving experience of being under cruise control in the fast lane of a freeway. With the faster 128-km/h (80-mi/h) design velocity, the situation may have seemed less similar—with the result that the driver felt the need to leave the left lane sooner to ensure that there would be sufficient time to leave the freeway at the designated exit. If this explanation is correct, one would expect the mean response time to be shorter still when the design velocity was 153.0 km/h (95 mi/h): in fact, it was 10.94 s—not as short as expected, but also not inconsistent with this explanation.

Exposure Time

The exposure time was the time between the moment that the driver took control of the vehicle and the moment that the first wheel of the vehicle touched the white line between the automated and center lanes as the driver drove out of the automated lane.

The analysis of the data obtained from the younger drivers in experiment #1 indicated that the design velocity, the intra-string gap, and the traffic density all had significant effects on the exposure time. The analysis of the data obtained from the older drivers in experiment #2 showed that only one of these variables—the traffic density—had a statistically significant effect on the exposure time. When the data from the two experiments were analyzed together, all three main variables were found to affect the exposure time. However, the effects of the four variables must be discussed together since they were involved in significant interactions.

First, the interaction between intra-string gap and traffic density will be considered. Figure 7 (on page 34) shows that the interaction between these two variables was mainly the result of the exposure time for the combination of the smallest intra-string gap and higher traffic density being relatively long (16.01 s) when compared to the other five combinations of gap and density, which had exposure times that ranged from 9.19 s to 12.98 s. The most likely explanation for these results is as follows: the driver had to stay in the automated lane longer when faced with the combination of the smallest intra-string gap and the highest density because the small gap would tend to restrict forward visibility and the high density would tend to reduce the number of gaps in the unautomated lane that would be large enough to move into.

There was also a three-way interaction between the age of the driver, the design velocity, and the traffic density—the interaction can be seen by comparing figure 8 (on page 36) with figure 9 (on page 37). Figure 8 shows that for the younger drivers, the exposure time increased as the design velocity increased, and that longer exposure times occurred when the traffic density was high. The picture is not as clear for the older drivers, as figure 9 shows: on this figure, there appear to be two anomalous data points—one occurring for the combination of low density and slowest design velocity, where the mean exposure time was double what might have been expected from the overall pattern of the data; the other occurring for the combination of high density and fastest design velocity, where the mean exposure time was about 60 percent of what might have been expected. The interaction effect observed here will be reconsidered when further experiments in the current series re-examine these variables.

If the two data points are, in fact, anomalous, the traffic density and design velocity effects can be described and explained simply, as follows. [And it should be noted that both of these explanations are supported by the analysis of the exit velocity data that is discussed in the next subsection.]

Averaging over the 60 drivers who took part in both experiments, the exposure time was found to be longer for the higher density condition than for the lower—13.19 s vs. 10.26 s. The obvious explanation of this is that the higher the traffic density in the center lane, the more the driver decelerated—so that it would be possible to change lanes into a smaller gap.

The overall exposure time was also found to be longer with the design velocity of 153.0 km/h (95 mi/h) than when the design velocity was either 128.8 km/h (80 mi/h) or 104.7 km/h (65 mi/h)—the exposure time dropped from 15.23 s to 11.12 s to 8.62 s as the design velocity decreased. The most probable explanation of this effect is that the driver remained in the automated lane in order to decelerate until the vehicle's velocity was slow enough to allow a safe transition into the slower traffic in the unautomated lanes, and that it inevitably took longer to decelerate when the design velocity was higher.

Exit Velocity

The exit velocity was the velocity of the driver's vehicle as its fourth wheel crossed the white line between the automated and center lanes as the driver drove out of the automated lane.

All three analyses of the data obtained from the younger drivers in experiment #1, the data obtained from the older drivers in experiment #2, and the combined data obtained from both experiments indicated that both the design velocity and the traffic density had significant effects on the exit velocity. Neither the intra-string gap nor the age of the driver had a significant effect on exit velocity. In addition, none of the interactions reached significance.

In the previous subsection, it was suggested that the reason why longer exposure times were found for the high-density condition than for the low-density condition was that the higher the traffic density in the center lane, the more the driver decelerated so that it would be possible to change lanes into a smaller gap. This explanation is supported by the fact that the exit velocity was 99.54 km/h (61.83 mi/h) for the high-density condition—5.76 km/h (3.57 mi/h) slower than the 105.30 km/h (65.40 mi/h) obtained, on average, for the low-density condition.

It was also suggested in the previous subsection that the reason why exposure time increased as the design velocity increased was that the driver remained in the automated lane in order to decelerate until the vehicle's velocity was slow enough to allow a safe transition into the slower traffic in the unautomated lanes—and that it was bound to take longer to reach this safe velocity when the design velocity was higher. To examine this possibility, it is necessary to examine both the exit velocity and the extent to which the driver reduced velocity while controlling the vehicle in the automated lane—this reduction can be obtained by calculating the difference between the design velocity and the exit velocity. First, exit velocity was considered directly: the exit velocities obtained with the 104.7-km/h (65-mi/h), the 128.8-km/h (80-mi/h), and the 153.0-km/h (95-mi/h) design velocities were 91.51 km/h (56.84 mi/h), 104.44 km/h (64.87 mi/h), and 110.30 km/h (68.51 mi/h), respectively. Second, the reduction in velocity was determined, then plotted in figure 17 as a function of the design velocity. The figure shows that as design velocity increased from 104.7 km/h (65 mi/h), to 128.8 km/h (80 mi/h), to 153.0 km/h (95 mi/h), the reduction in velocity increased from 13.18 km/h (8.16 mi/h), to 24.36 km/h (15.13 mi/h), to

42.7 km/h (26.49 mi/h). Clearly, the reason why the exposure time increased with design velocity was because it took longer for the driver to decelerate to an exit velocity that was acceptable for the lane-change maneuver.

Lane-Change Time

The lane-change time was the time between the moment that the first wheel of the driver's vehicle touched the line between the automated and center lanes and the moment that the fourth wheel crossed that same line. The lane-change times were affected by the design velocity, the traffic density, and the interaction between the driver's age and the intra-string gap.

Figure 12, on page 44, shows that as the design velocity increased from 104.7 km/h (65 mi/h) to 153.0 km/h (95 mi/h), the lane-change time decreased from 3.20 s to 1.78 s. This is to be expected in light of the exit velocity data—since the exit velocity increased as the design velocity increased, the velocity at which the driver's vehicle was traveling during the lane changes also had to have increased as the design velocity increased and, as a result, the time taken for the lane change had to have decreased.

As mentioned on page 41, the lane-change time of the older drivers increased from 1.86 s to 2.62 s as the traffic density increased from 6.21 v/km/ln (10 v/mi/ln) to 12.42 v/km/ln (20 v/mi/ln). A likely explanation for this is that the older drivers became more cautious when the traffic density was higher, and so were slower in making the lane change. In contrast, as mentioned on page 43, the lane-change time for the younger drivers was unaffected by the increase in the traffic density—it was 2.39 s for the low-traffic density and 2.38 s for the high-traffic density. Future experiments in this series may provide more information about this possible difference between younger and older drivers.

Figure 13, on page 45, shows the interaction between the driver's age and the intra-string gap. For the younger drivers, the lane-change time increased as the intra-string gap increased; for the older drivers, the lane-change time decreased as the intra-string gap increased. A possible explanation for this is that the two groups of drivers may have reacted differently to the presence of the vehicle immediately behind the driver's vehicle in the automated lane. As the driver decelerated during the exposure time, the distance between the driver's vehicle and the vehicle ahead increased—however, during this same time, the vehicle immediately behind maintained the intra-string gap. The younger drivers may have reacted to this vehicle by driving out of the automated lane faster when the gap was smallest—i.e., by getting out of its way quickly when it was close.

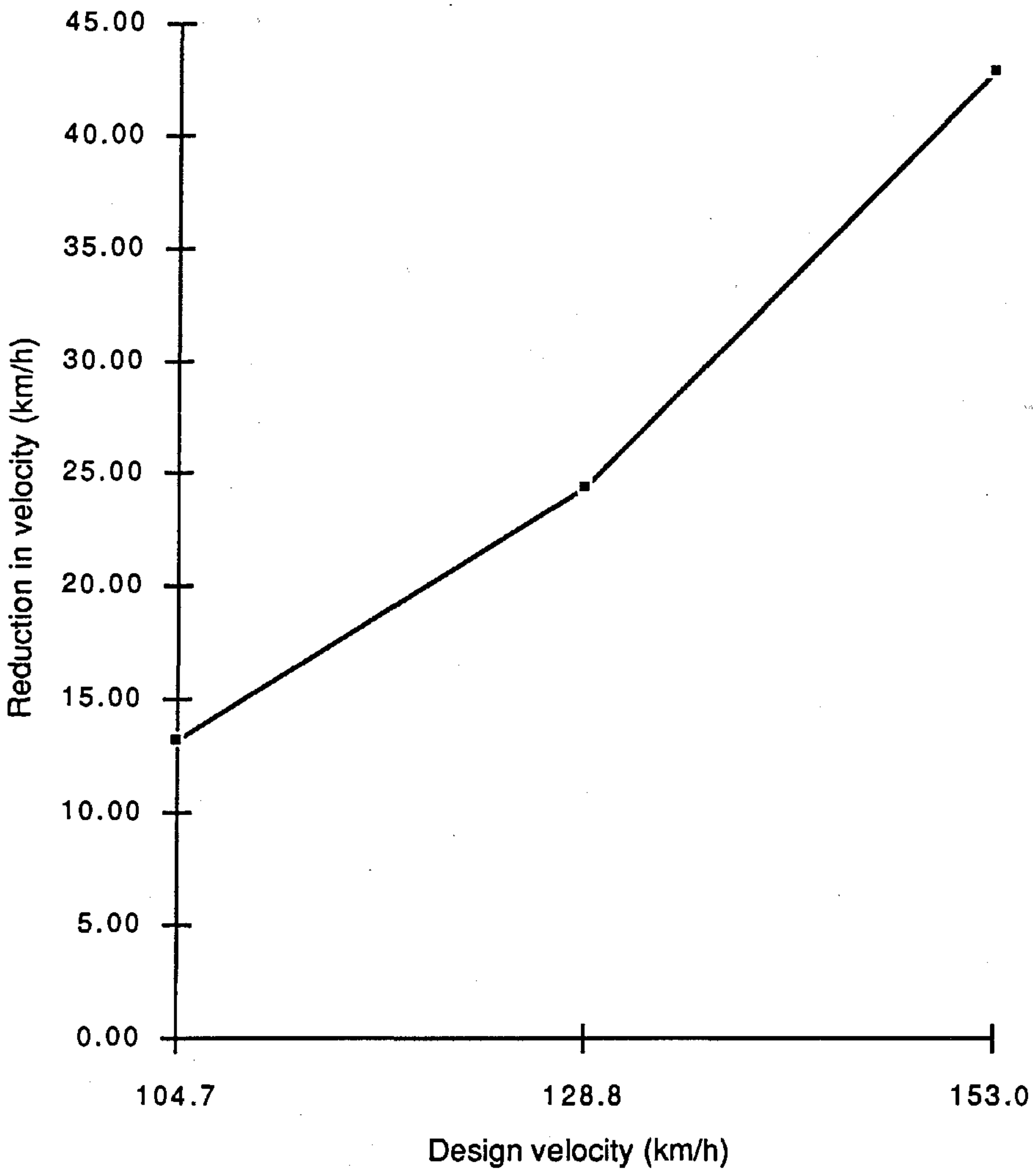


Figure 17. Reduction in velocity (from design velocity to exit velocity) as a function of design velocity.

In contrast, the older drivers may have reacted with more caution because of the proximity of this vehicle.

Center Lane Time

The center lane time is the time between the moment that the fourth wheel of the driver's vehicle had crossed the line between the automated lane and the center lane, and the moment that the first wheel of the driver's vehicle touched the line between the center lane and the right lane on a completed lane change.

The only variable to affect the center lane time was the age of the driver—the mean center lane time of the younger drivers was 11.52 s, more than 70 percent longer than the mean of 6.72 s obtained with the older drivers. This was the clearest difference in the driving performance of the younger and older drivers found in this experiment. It is unlikely that it has anything to do with the AHS: instead the explanation is to be found in a difference in driving behavior that can be observed between the two groups when they drive under normal conditions—the more cautious older driver is likely to leave the center lane and move to the right lane earlier than the younger driver, who elects to stay in the center lane longer, probably driving faster.

Delay Time

After the driver took control of the vehicle and while the driver's vehicle was still in the automated lane, the automated vehicle traveling immediately behind the driver's vehicle was not simply under the control of the AHS, but had to respond to the deceleration behavior of the driver's vehicle. As a result, this vehicle was delayed.

There were two components to the amount of time this vehicle was delayed. First, the measured delay time, which occurred during the period that the driver's vehicle was decelerating while it was in the path of the automated vehicle that was following it, and which was dependent on the way in which the driver carried out the task of regaining control of the vehicle while it was still in the automated lane. Second, an inferred delay time that occurred during the period that the vehicle immediately following the driver's vehicle was accelerating back to the design velocity after the driver's vehicle had moved out of its path, and that was dependent on the driver's behavior and on the simulator vehicle's acceleration characteristics. The data on delay time given earlier in this report (pages 48 to 52) were presented in terms of the measured delay time and the total delay time—this is the sum of the measured and inferred delay times. Essentially, these data can be summarized as follows.

As can be seen in figure 15 (on page 51), delay time was an accelerating function of design velocity—the total delay time increased from 1.36 s when the design velocity was 104.7 km/h (65 mi/h), to 2.59 s when it was 128.8 km/h (80 mi/h), and to 6.70 s when it was 153 km/h (95 mi/h). This increase in the total delay time occurred as a direct result of: (1) the increase in the exposure time, and (2) the decrease in velocity (from the design velocity to the exit velocity) during the exposure time, that both occurred as the design velocity increased.

Figure 16 (on page 52) shows that the total delay time increased from 3.21 s to 4.12 s as a function of the traffic density. This increase is a direct result of: (1) the increase in the exposure time, and (2) the decrease in velocity (from the design velocity to the exit velocity) during the exposure time, that both occurred as the density of the traffic in the unautomated lane increased.

SAFETY IMPLICATIONS

Possible AHS Carry-Over Effects

It is possible that traveling at relatively high velocities under the control of the AHS may affect driving performance when the driver resumes control. The exit velocity data reported here are pertinent in this regard. Two of the design velocities experienced by the drivers in this experiment were considerably faster than the average velocity of the vehicles traveling in the unautomated lane—the 128.8-km/h (80-mi/h) and 153.0-km/h (95-mi/h) design velocities were 30.25 km/h (25 mi/h) and 64.45 km/h (40 mi/h), respectively, faster than the unautomated vehicle average. After the drivers took control, they slowed down while still in the automated lane. However, even though they slowed down after traveling at 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h), when they chose to move into the unautomated lane they were driving at velocities that were, on average, 15.89 km/h (9.87 mi/h) or 21.75 km/h (13.51 mi/h), respectively, faster than the average velocity of the other vehicles in the unautomated lane. The drivers may have done this because of a carry-over effect—and, it should be noted, a carry-over effect that may have occurred after what was only a relatively brief exposure to automated travel.

Many different AHS scenarios are currently under consideration: in most of them, the driver would not be allowed to regain control until the velocity of the vehicle had been reduced under automated control to the speed limit of the unautomated traffic. The current experiment does not address these circumstances. Further experimentation will be required to determine whether on regaining control in such circumstances, the driver would drive faster than normal because of a carry-over effect from traveling at a relatively higher velocity under automated control.

Collision and Lane Incursion Data

There was a total of 360 trials in experiments #1 and #2. Three collisions and fourteen incursions occurred in these 360 trials. Considering that the portion of the trials in which the drivers had control of the vehicle was between 1.0 and 2.0 min, these are relatively high rates that would clearly not be acceptable. [It should also be noted that the collision and incursion rates were higher for the older drivers than for the younger drivers.]

Questionnaire Data

Additional information on safety was obtained from the responses of the drivers to the questionnaire. Three of the questions in the questionnaire explored the drivers' impressions and perceptions of safety and control while leaving the automated lane.

First, in response to the question, "How safe did the speed at which you left the automated lane feel?" (question #11), there was a considerable difference between those drivers for whom the design velocity had been 104.7 km/h (65 mi/h)—their average response was halfway between neutral and very safe—and those drivers for whom the design velocity had been 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h)—their average responses were essentially neutral. Second, in replying to the question, "How would you describe the manner in which you controlled your car immediately after leaving the automated lane, when you first drove in the manual lane?" (question #12), the average response of male drivers was close to neutral, but on the safe side of the neutral point, while the average response of female drivers was also close to neutral, but on the unsafe side of the neutral point. Third, when asked, "To what extent did you feel in control of the situation immediately after leaving the automated lane, when you first drove in the manual lane?" (question #13), there were both speed and gender effects. The average response of drivers for whom the design speed had been 104.7 km/h (65 mi/h) was halfway between neutral and very safe; while for drivers for whom the design speed had been 128.8 km/h (80 mi/h), it was nearer neutral and on the safe side of the continuum; and for those for whom the design speed was 153.0 km/h (95 mi/h), it was neutral. And the average response of the male drivers was halfway between neutral and very safe, while the average response of the female drivers was neutral.

The responses of the drivers in the 104.7-km/h (65-mi/h) condition to these questions might have been expected, given that their mean exit velocity was 91.51 km/h (56.84 mi/h). However, the responses of the drivers in the two other design-velocity conditions were less predictable. When asked about the safety of the velocity at which they left the automated lane and when asked about the amount of control they had on entering the unautomated lane, they gave neutral responses—since their mean exit velocities were 104.44 km/h (64.87 mi/h) and 109.84 km/h (68.94 mi/h) for the 128.8-km/h (80-mi/h) and 153.0-km/h (95-mi/h) design velocity conditions, respectively; the question is why didn't they slow down more? There are two possibilities. The drivers may have weighed safety and a desire to leave the freeway at the designated exit, then decided to leave the automated lane early enough to ensure that the designated exit would not be missed, but having done so at the cost of leaving at an exit velocity higher than the speed limit, when feeling neutral about safety. It should be noted that this explanation is challenged by the fact that in the response to question 10, the drivers indicated that they had sufficient time to respond to the *Exit* advisory. An alternative and perhaps more satisfactory explanation is that the driver may have adapted to traveling in the automated lane at a higher-than-normal velocity, may have left the automated lane at a velocity faster than realized, and then, as far as safety is concerned, may have felt neutral rather than very safe. This issue will be explored further in a later experiment.

Summary

The exit velocity data suggest that after regaining control, the driver may drive faster than normal because of a carry-over effect from traveling at a relatively higher velocity under automated control—this possibility warrants further investigation. The relatively high collision and incursion rates obtained with the AHS configuration explored in these two experiments suggest that if the configuration were to be implemented unmodified, its value would be questionable. However, the responses to the questionnaire, particularly to question 7 (dealing with safety and design velocity), suggest that the drivers who experienced the slower design velocity [104.7 km/h (65 mi/h)] thought it would be safe, while the drivers who experienced the faster design velocities [128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h)] did not think they would be unsafe. Also, the responses dealing with the drivers' attitudes toward the AHS (questions 16 through 19) showed that they were receptive to the concept of an AHS.

IMPLICATIONS FOR AHS EFFICIENCY

When a vehicle leaves the automated lane and enters the unautomated lane, the timing of the maneuver will be of critical importance. If it leaves rapidly, the vehicle will have a minimal effect on the string of vehicles immediately behind it—the delay time introduced by the vehicle leaving the automated lane will be small, and the impact on the efficiency of the system will be minimized. On the other hand, if the vehicle is significantly delayed as it leaves the automated lane, it could cause a considerable slowdown for the string of vehicles following it, and as a result, could have a significant impact on the efficiency of the AHS.

The driving situation investigated in the experiments reported here involved a driver who was in the second position in a string of vehicles leaving the automated lane under manual control. As mentioned above, the delay time produced in this situation was influenced by the design velocity—the mean total delay time increased from 1.36 s when the velocity was 104.7 km/h (65 mi/h), to 2.59 s when it was 128.8 km/h (80 mi/h), and to 6.70 s when it was 153.0 km/h (95 mi/h).

In an AHS in which the driver took control of the vehicle before leaving the automated lane, if the driver was free to leave the lane at any time, in order to avoid causing delays for the automated vehicles following the driver's vehicle, the minimum operating intra-string gap would have to be large enough to allow the driver to decelerate—it would have to be at least as large as the delay times obtained in this experiment. The potential effect on traffic flow of using a minimum intra-string gap of this size was calculated—the steps in the calculation are shown in table 19. In making these calculations, several assumptions were made: first, it was assumed that after the driver had slowed down and was about to leave the automated lane, his/her vehicle would need to be at least 0.0625 s in front of the next vehicle; second, the average length of a vehicle was assumed to be 4.42 m (14.5 ft); and third, it was assumed that the inter-string separation would be 2.0 s.

Similar delays to those shown in table 19 might be expected if any central member of a string of vehicles were to attempt to leave the string under manual control—the delays might not be as large for either the lead vehicle or the last vehicle in the string.

Table 19. Maximum traffic flow possible when the intra-string gap is large enough to allow a vehicle to leave the automated lane without disrupting the traffic flow in the automated lane.

1.	Design velocity.	104.7 km/h (65 mi/h)	128.8 km/h (80 mi/h)	153.0 km/h (95 mi/h)
2.	Experimentally determined average total delay time.	1.36 s	2.59 s	6.70 s
3.	Required intra-string gap time [minimum gap of 0.0625 s plus the average total delay time from line 2].	1.43 s	2.65 s	6.77 s
4.	Required intra-string gap distance [derived from line 3].	41.58 m (136.33 ft)	94.83 m (310.93 ft)	287.70 m (943.29 ft)
5.	Number of four-vehicle strings per 1.61 km (1 mi), [with a 2.0-s inter-string gap and the required intra-string gap derived in line 4].	8.03	4.31	1.67
6.	Hourly traffic capacity (i.e., number of vehicles per hour), [with the number of four-vehicle strings per 1.61 km (1 mi) that were derived in line 5].	2087.8	1379.2	634.6

For comparison purposes, it should be noted that theoretically, without an AHS, an hourly throughput of 1,672 v/h would be possible—assuming that the unautomated vehicles traveled with a 2.0-s inter-vehicle spacing at 104.7 km/h (65 mi/h) and that the average vehicle length was 4.42 m (14.5 ft). As table 19 shows, if the design velocity selected for the AHS was 153.0 km/h (95 mi/h) or 128.8 km (80 mi/h), the resultant traffic capacities would be 634.6 v/h and 1379.2 v/h, respectively—i.e., only 38 percent and 82.5 percent, respectively, of the capacity expected without an AHS. On the other hand, if a design velocity of 104.7 km/h (65 mi/h) was selected, an hourly capacity of 2087.8 v/h could be achieved—24.9 percent more than the capacity without an AHS.

The hourly capacities shown in table 19 are very modest—even for the 104.7-km/h (65-mi/h) design velocity. Much higher capacities are to be expected if the driver does not take control until the vehicle has left the automated lane and if the driver does not control the time that the lane departure occurs—since then much smaller intra-string gaps could be used.

However, while higher capacities than those shown in table 19 are to be expected with other AHS scenarios, it should be emphasized that if those other scenarios were implemented, much larger traffic capacities would still be expected when the velocity differential between the automated and unautomated traffic is relatively low—like the 16.1-km/h (10-mi/h) differential that was the smallest used in the current experiment—than when it is relatively high—like the 64.5-km/h (40-mi/h) differential that was the largest investigated here.

APPENDIX 1: PRELIMINARY TAXONOMY OF INTERACTIONS BETWEEN THE DRIVER AND THE AHS

In considering the transfer of control from the AHS to the driver, many different variables must be considered, either as variables to manipulate, variables to control, or variables to measure. To deal with these variables in a systematic way, a preliminary taxonomy was developed—it was used as a guide in selecting the representative driving situation simulated in experiment #1. This preliminary taxonomy focuses on issues related to the transfer of control from system to driver or driver to system. However, eventually it is expected that it will evolve into a comprehensive taxonomy of the interactions between the driver and the AHS.

Preliminary Taxonomy of Interactions between the Driver and the Automated Highway System (AHS): Transfer of Control Between the System and the Driver.[1]

A. <u>Environmental Conditions</u>

1. Weather [Dry][1]
2. Time of day —
    - Night, dusk, daylight (sun angle & direction) [Midday]

B. <u>The Road</u>

1. Number of lanes of each type
    - (a) Automated lanes (1, 2, or 3) [1]
    - (b) Transition lanes (0 or 1) [0]
    - (c) Unautomated lanes (1 or 2) [2]
2. Relationship of automated and other lanes
    - (a) Automated and other lanes completely segregated from each other (with barriers) [Not used]
    - (b) Transition lane between automated lane and unautomated lane: barriers, with entry and exit gaps, between transition and automated lane [Not used]
    - (c) Automated and unautomated lanes adjacent to each other, with no transition lane or barriers used [Used]
3. Construction of barriers [Not applicable]
4. Width of automated and transition lanes [3.67 m (12 ft)]
5. Road geometry [Orchids freeway]
6. Road surface [Standard freeway]

C. <u>State of the Automated Lane(s)</u>

1. Control relationship between vehicles and AHS
    - (a) All automated vehicles directly controlled by AHS [Used]
    - (b) Some automated vehicles directly controlled by AHS, with those vehicles controlling the other vehicles [Not used]

---

[1] Note the values given in brackets were selected for experiments #1 and #2.

Preceding page blank

2. Vehicles	
(a) Vehicles operating as individual free agents	[Not used]
(b) Vehicles operating in groups	
(i) Number of vehicles in group	[Set]
(ii) Position of own vehicle in group	[Set]
3. Separation between vehicles	
(Where vehicles are in groups —	
(i) Separation between groups	[Not applicable]
(ii) Separation between vehicles within groups)	[Experimental variable]
4. Velocity of automated vehicles	[Experimental variable]
5. Variability around selected velocity	[Set within predetermined limits]

D. State of Controls While Vehicle Is Automated

1. Steering wheel	
(a) Locked firm	
(b) Moving to reflect vehicle behavior	
(c) Disconnected	[Locked]
2. Accelerator pedal	
(a) Locked firm	
(b) Moving to reflect vehicle behavior	
(c) Disconnected	[Disconnected]
3. Brake pedal	
(a) Locked firm	
(b) Moving to reflect vehicle behavior	
(c) Disconnected	[Disconnected]

E. Driver Profile

1. Age	[Recorded]
2. Gender	[Recorded]
3. Reaction time	[Measured]
4. Vision	[Measured]
5. Health	[Recorded]
6. Driving history	[Recorded]

F. Driver in the Automated Lane

1. Driver attention inside/outside of vehicle	[Driving-related task directing attention outside vehicle used]
2. Length of time traveled in automated lane	[Varied]
3. Distance traveled in automated lane	[Varied]

G. State of the Unautomated Lane(s)

1. Velocity of unautomated vehicles	[88.6 km/h (55 mi/h)]
2. Variability around velocity	[Set within predetermined limits]
3. Density of unautomated vehicles	[Experimental variable]

H. Transfer Variables

1. Type of warning signal	
(a) Exit information	[Used]
(b) System failure information	[Not used]
2. Mode of warning signal	[Auditory]
3. Level of detail of warnings	[Set]
4. Duration of warning signals	[Set]
5. Amount of time between warning and transfer point	[120 s]
6. Pattern of warning signals	[Tone, followed by verbal confirmation]
7. Location of transfer —	
(a) Automated lane	[Used]
(b) Transition lane	[Not applicable]
(c) Unautomated lane	[Not used]
(d) Off freeway	[Not used]
8. Velocity of transferring vehicle at time of transfer	[Same as velocity of automated vehicles]
9. Relative position of nearest unautomated vehicle at time of transfer	[Recorded]
10. Relative velocity of transferring vehicle and nearest unautomated vehicle at time of transfer	[Calculated]
11. How transfer of control is implemented —	
(a) Hands first	[Not used]
(b) Feet first	[Not used]
(c) Hands & feet together	[Used]
(d) Error basket	[Not used]

APPENDIX 2: DETERMINATION OF THE FLOW OF THE UNAUTOMATED TRAFFIC IN EXPERIMENTS #1 AND #2

This appendix describes the steps involved in producing the specifications for a realistic, valid flow of traffic in the unautomated lanes in the Iowa simulator for experiments #1 and #2.

The mean velocity of the unautomated traffic and two traffic-density levels for these vehicles were selected when the experiment was designed Then, using these selected values, the particular velocity and the specific time at which each vehicle would appear in the simulation were determined. The same procedure was used for both unautomated lanes. The steps in producing the specifications were as follows:

(A) Velocity

The mean velocity of the vehicles in the unautomated lanes selected for experiments #1 and #2 was 88.6 km/h (55 mi/h). The way in which an appropriate distribution of velocities based on this mean value was selected and the method used to specify the parameters of the distribution is described below.

(1) Distribution of unautomated traffic velocities

The Department of Transportation report on the introduction of the 88.6-km/h (55-mi/h) speed limit suggests that since the limit was introduced, the distribution of velocities of individual vehicles on freeways has been approximately normal.(8) The report used data gathered by the Department of Transportation in *Highway Statistics, Annual Issues 1972 - 1983.*(9) Figure 18 reproduces figure 6 of the Department of Transportation report.(8) It shows that the distribution of velocities of individual vehicles on freeways for 1974 more closely approximates the normal distribution than the 1973 distribution. The mean velocity in 1974 was 92.7 km/h (57.6 mi/h). The Department of Transportation report also states that while motorists began to drive faster after 1974—the mean velocity had increased to 95.2 km/h (59.1 mi/h) in 1983—the sharp reduction in the variability of the velocity was sustained.

Preceding page blank

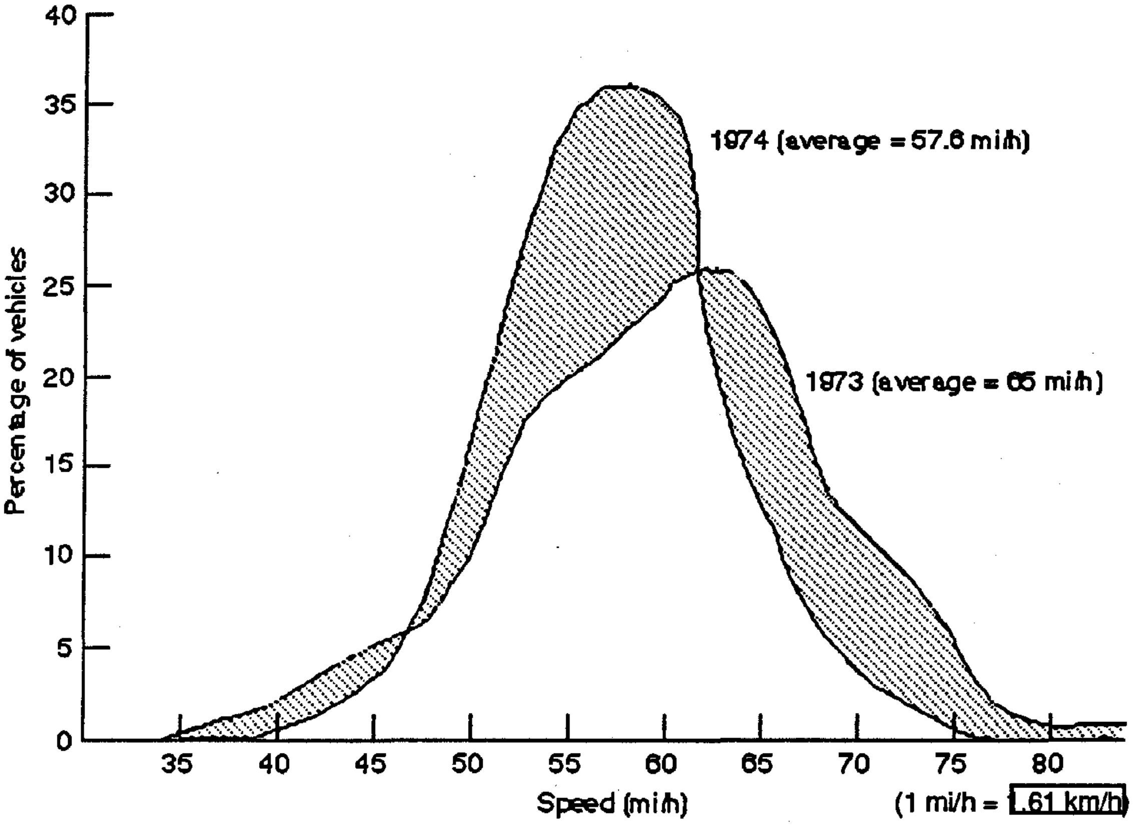


Figure 18. Distributions of velocities on Interstate highways in 1973 and 1974.[8]

(2) Standard deviation of the unautomated traffic velocities

Figure 18 shows that the distribution of velocities reported for 1974 was approximately normal. Therefore, it is reasonable to use the Empirical Rule to estimate the standard deviation (the Empirical Rule states that for a normal distribution, approximately 95 percent of the distribution lies within two standard deviations of the mean). Figure 18 shows that most of the 1974 distribution lies between 72.5 km/h and 112.7 km/h (45 mi/h and 70 mi/h)—i.e., approximately 95 percent of the distribution lies within 20.1 km/h (12.5 mi/h) of the mean speed of 92.7 km/h (57.6 mi/h).

Therefore:

$$2s = 12.5$$

(where s is the standard deviation of the speed variability)

and $$s = 6.25$$

(3) Velocity values for experiment #1

Given these findings and calculations in steps 1 and 2, it was clear that the velocities of the vehicles in the unautomated lanes in the simulation for experiment #1 should be distributed normally, with a mean velocity of 88.6 km/h (55 mi/h) and a standard deviation of 10.1 km/h (6.25 mi/h)—so that 95 percent of the velocities would be between 68.4 and 108.7 km/h (42.5 and 67.5 mi/h).

(B) Time Headways

Two traffic densities were selected for the unautomated lanes. The first was the 6.21-v/km/ln (10-v/mi/ln) density, a relatively low-traffic density level that should produce free flow. The second was the 12.42-v/km/ln (20-v/mi/ln) density, which is in the range of stable flow, although the presence of other users is noticeable. These traffic densities were used to determine time headways and then, as with velocity, an appropriate distribution of these time headways had to be determined, and its parameters had to be specified.

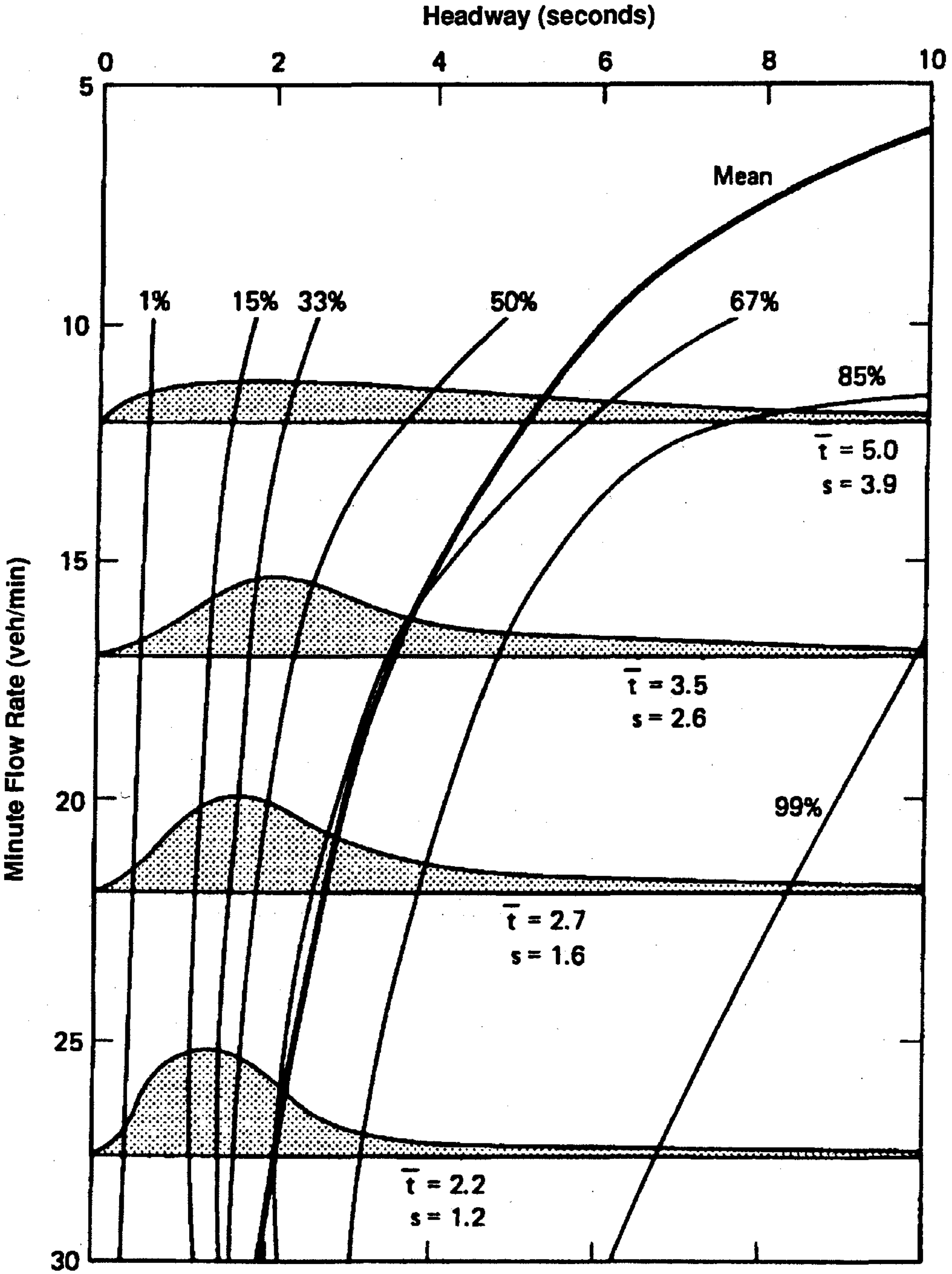


Figure 19. Distributions of measured time headways.(5)

(1) Distribution of the time headway

May compared empirically obtained time headway distributions with various distribution models.(4) The empirical data, which is time distribution headway data for four traffic flow levels—10-14, 15-19, 20-24, and 25-29 vehicles/min—came from an observational study that May conducted earlier, and is shown here in figure 19.(5) The distribution models to which May compared these distributions were:

- The negative exponential distribution—this is the mathematical distribution that characterizes the distribution of random intervals, which might be obtained if the vehicles on a roadway do not interact with each other.

- The normal distribution—this would be the appropriate distribution for a situation in which all the drivers on a roadway were to attempt to drive at a constant time headway, and driver errors caused the time headways to vary.

- A composite distribution model, which uses the combination of a shifted negative exponential distribution to deal with vehicles that do not interact with other vehicles, and a normal distribution to deal with vehicles that are in a vehicle-following mode.

- The Pearson Type III family of distributions, which are likely to be appropriate in situations where drivers do not select time headways entirely at random, and do not attempt to maintain exactly the same time headways as each other.

May produced the set of graphs shown in figures 20, 21, 22, and 23 in comparing the extent to which each of these theoretical distributions provided a fit to his empirical distributions. Observation of figures 20 and 21 shows that neither the negative exponential nor the normal distribution provides a good fit to May's 1965 data. As figures 22 and 23 show, the composite and Pearson Type III distributions were both better—the fit obtained with the Pearson Type III distribution (in figure 23) appeared best and, consequently, was used as the model for generating the time headways in the scenario for experiments #1 and #2.

The general equation for the Pearson Type III family of distribution models is as follows:

$$f(t) = \frac{\lambda}{\tau(K)}[\lambda(t-\alpha)]^{K-1}e^{-\lambda(t-\alpha)}$$

where,

$f(t)$ is the probability density function;

λ is a function of the mean time headway, $\bar{t}$ and K and α;

K is a user-selected parameter, between zero and infinity, that affects the shape of the distribution;

α is a user-selected parameter (in seconds)—representing the minimum expected time headway—that is greater than or equal to zero, and that affects the shift of the distribution;

t is the time constant (in seconds) that is being investigated; and $\tau(K)$ is the gamma function, equivalent to $(K-1)!$

(2) Parameters of the Pearson Type III distribution

May describes a multi-step process to apply the Pearson Type III distribution to time headway distributions.(4)

(2.1) Mean time headway—The first step is to calculate the mean time headway, $\bar{t}$. For experiments #1 and #2, a mean velocity for the unautomated traffic of 88.6 km/h (55 mi/h), with traffic densities of either 6.21 or 12.42 v/km/ln (10 or 20 v/mi/ln), were selected. In order to determine the mean time headways that are equivalent to these traffic densities, the equivalent hourly traffic flow rates have to be determined first.

The hourly traffic flow rate, V, is a function of the mean velocity of the vehicles (in mi/h) and the density of the unautomated vehicles; it can be calculated from the selected mean velocity and density levels. For the 10-v/mi/ln density traffic, the hourly traffic flow rate, V_{10}, is given by:

$$\begin{aligned} V_{10} &= (55)(10) \\ &= 550 \end{aligned}$$

And, for the 20-v/mi/ln density level, the hourly traffic flow rate, V_{20}, is given by:

$$\begin{aligned} V_{20} &= (55)(20) \\ &= 1100 \end{aligned}$$

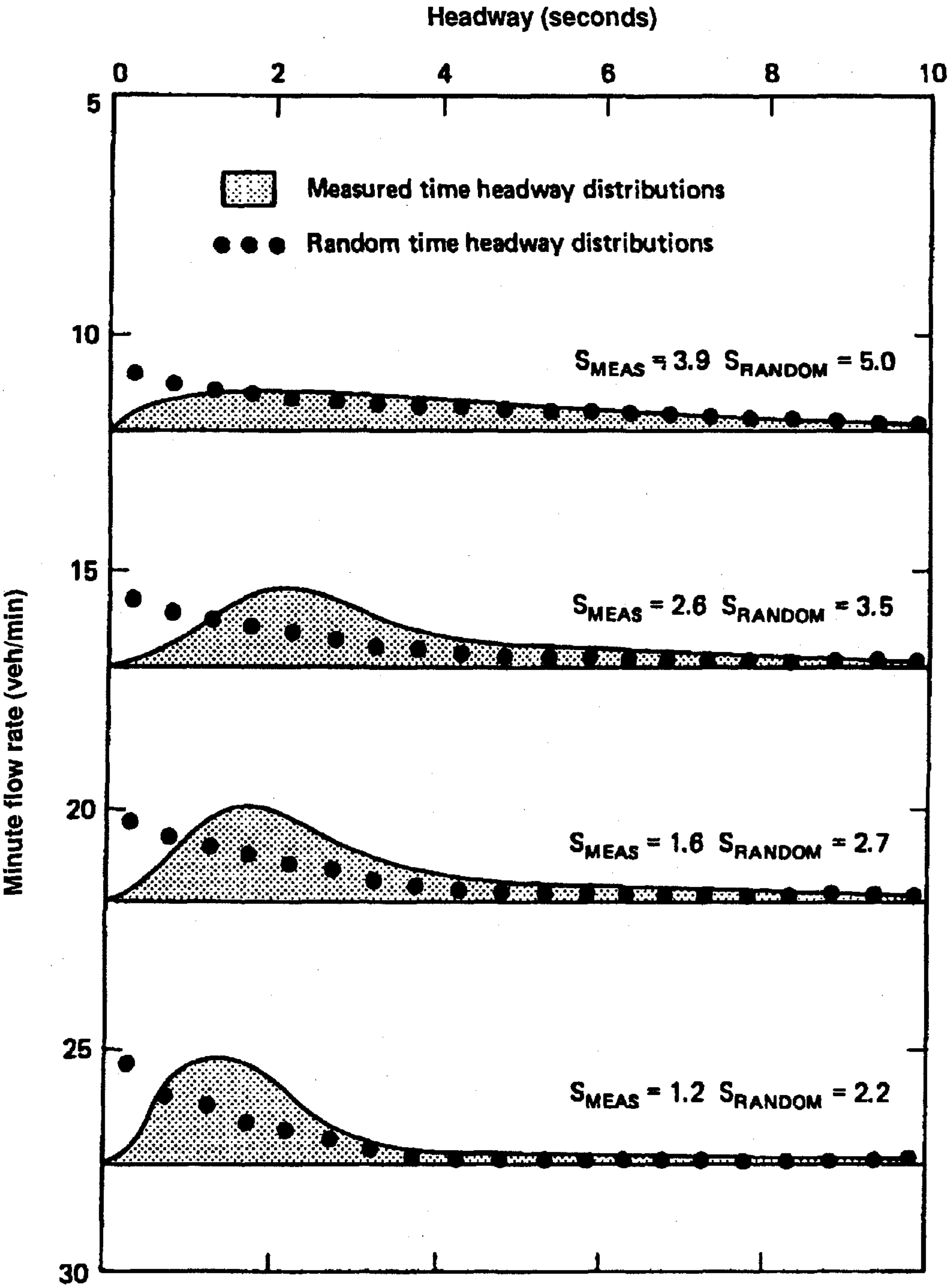


Figure 20. Theoretical negative exponential distributions fitted to measured time headway distributions from figure 19.(4)

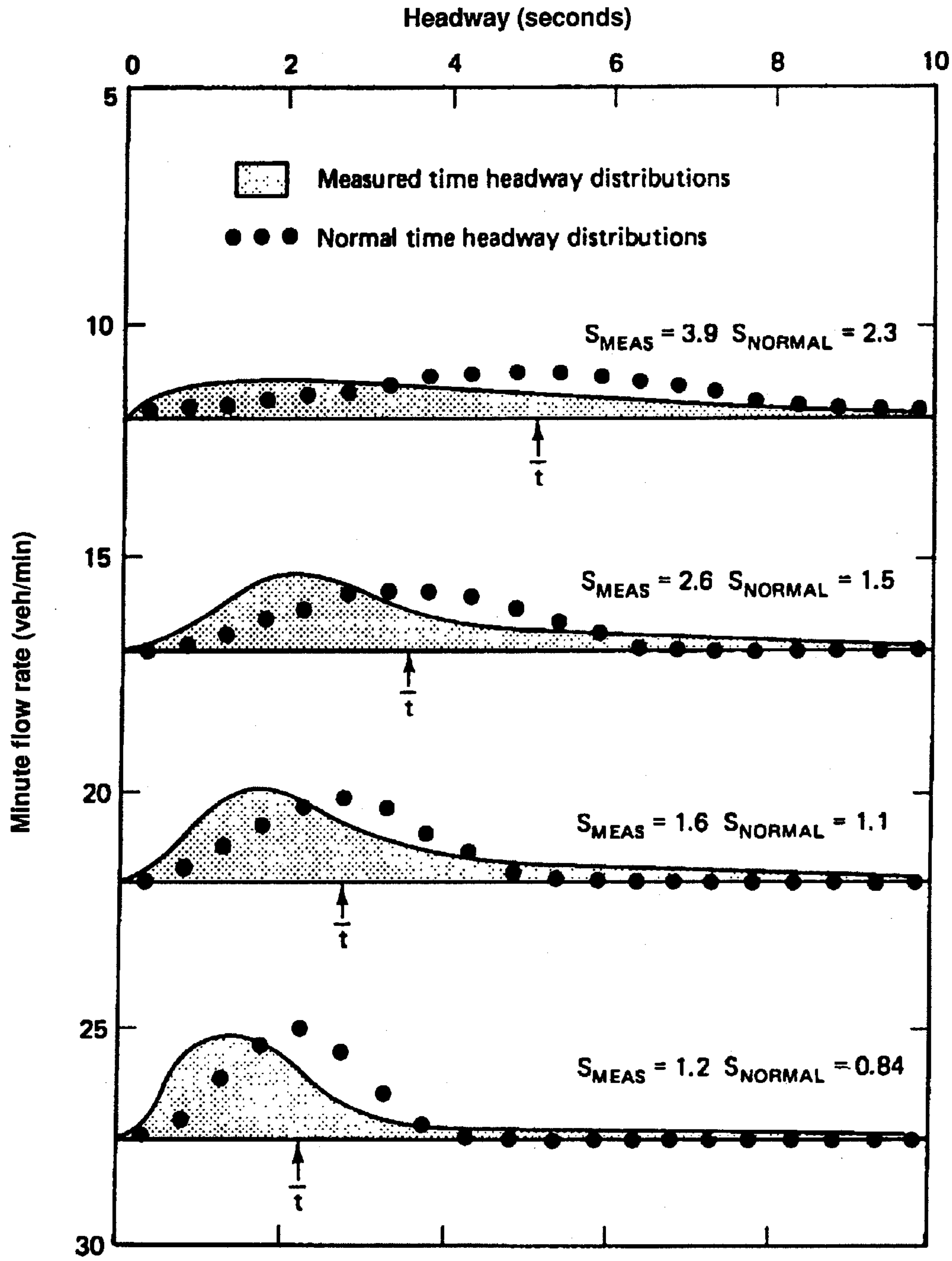


Figure 21. Theoretical normal distributions fitted to measured time headway distributions from figure 19.(4)

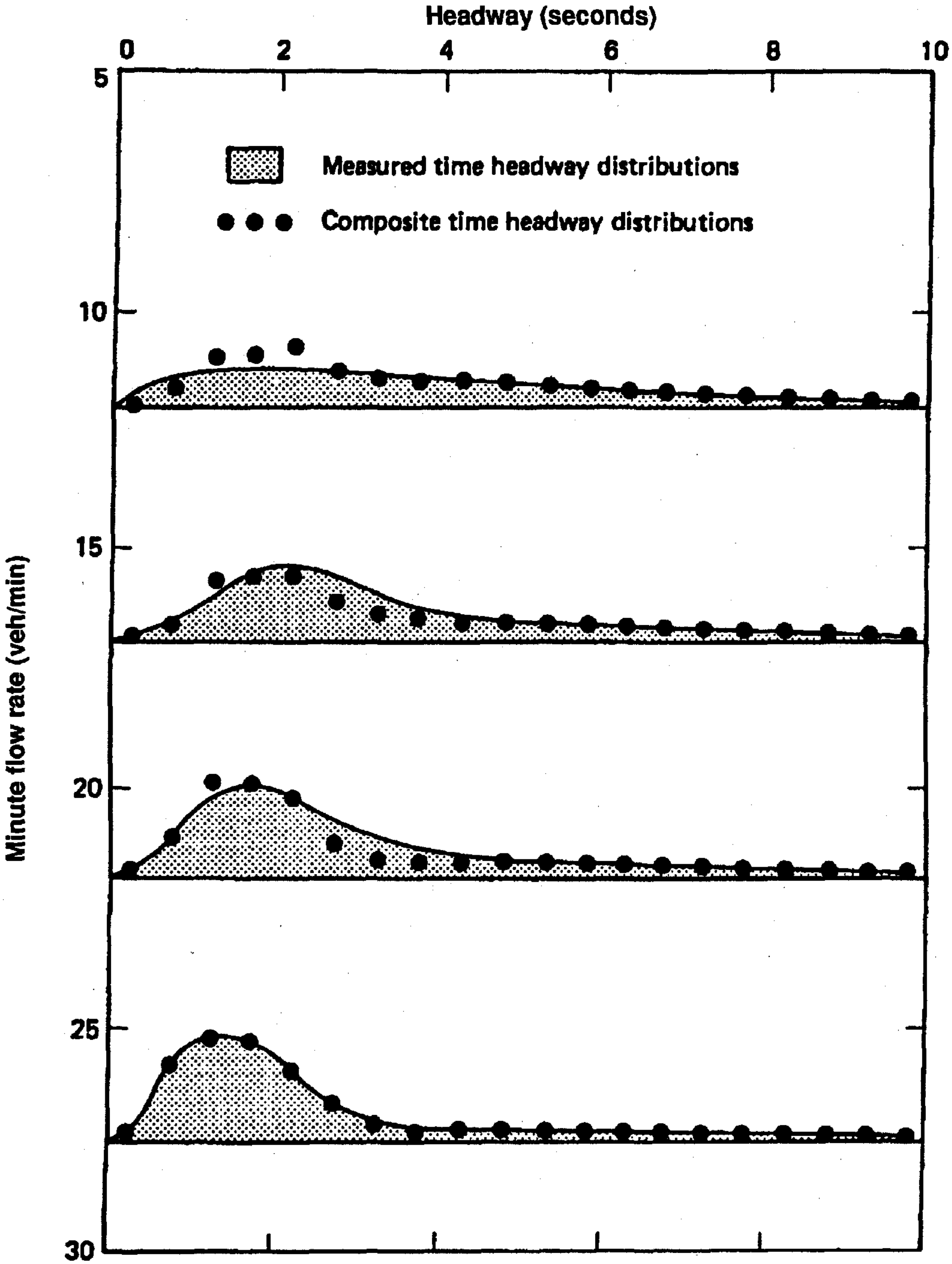


Figure 22. Theoretical composite distributions fitted to measured time headway distributions from figure 19. (4)

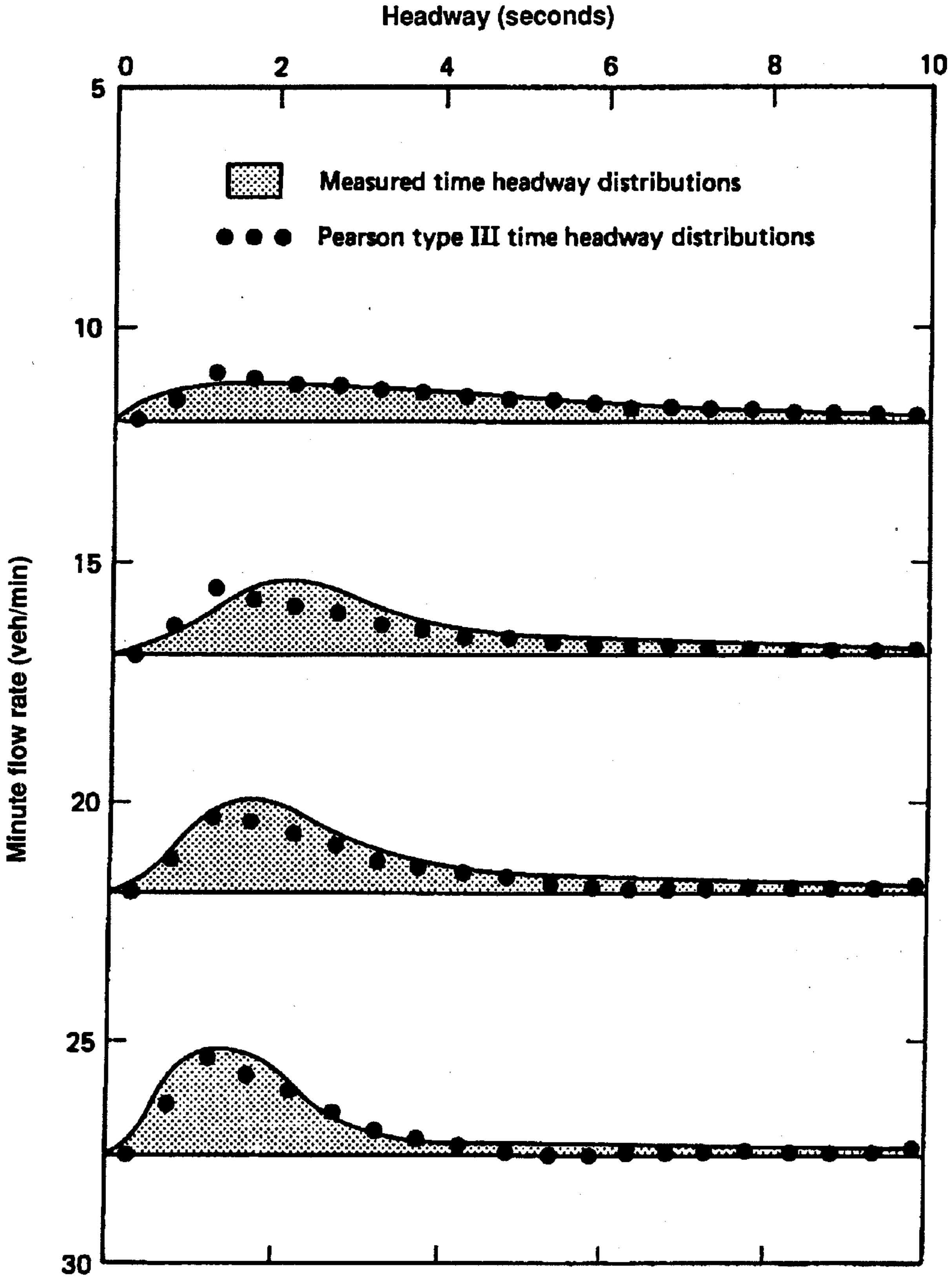


Figure 23. Theoretical Pearson Type III distributions fitted to measured time headway distributions from figure 19.(4)

Now, the mean time headway, $\bar{t}$, can be calculated. As May states, it is given by the following equation:(4)

$$\bar{t} = \frac{3600}{V}$$

Therefore, the mean time headway for the 10-v/mi/ln density level, $\bar{t}_{10}$, is:

$$\begin{aligned}\bar{t}_{10} &= \frac{3600}{V_{10}} \\ &= \frac{3600}{550} \\ &= 6.545\end{aligned}$$

And the mean time headway for the 20-v/mi/ln density level, $\bar{t}_{20}$, is:

$$\begin{aligned}\bar{t}_{20} &= \frac{3600}{V_{20}} \\ &= \frac{3600}{1100} \\ &= 3.273\end{aligned}$$

(2.2) The minute traffic flow rate—The next step is to determine the minute traffic flow rates for our two density conditions. These rates were needed so that comparisons could be made with May's data, so that estimates of the standard deviations of the time headways could be made by extrapolating from it.(4)

The minute traffic flow rate, M, is the hourly rate divided by 60. Therefore, the minute flow rate for the 10-v/mi/ln density level, M_{10}, is given by:

$$\begin{aligned}M_{10} &= \frac{V_{10}}{60} \\ &= \frac{550}{60} \\ &= 9.167\end{aligned}$$

And the minute flow rate, for the 20-v/mi/ln density level, M_{20}, is given by:

$$\begin{aligned} M_{20} &= \frac{V_{20}}{60} \\ &= \frac{1100}{60} \\ &= 18.333 \end{aligned}$$

(2.3) The standard deviation of the headway time distribution—An estimate of the standard deviations, s, around the mean time headway, can be obtained by comparing the minute traffic flow for our two density conditions to the minute traffic flow rates obtained in May's observational study and extrapolating.(4)

Table 13 is based on May's data; it shows the minute traffic flow, the mean time headway, $\bar{t}$, the standard deviation, s, and the ratio of standard deviation to mean time headway for four time headway distributions.

It also includes, in boldface, entries for the two density conditions to be used in experiment #1, with the minute flow rates and $\bar{t}$ values calculated in the two previous steps. Then, by plotting s against the minute traffic flow for May's data, we can interpolate and extrapolate to obtain the values of s shown in both boldface and italics in table 20—this procedure gives us estimates of 5.3 and 0.8 for s for the 10- and 20-v/mi/ln density conditions.

Table 20. The minute traffic flow, mean time headway, standard deviation, and ratio of standard deviation to mean time headway for May's 1965 data.

Minute flow rate	$\bar{t}$	s	Ratio of $s/\bar{t}$
(mean = 9.167)	**6.545**	**5.3**	**0.8097**
10-14 (mean = 12)	5.0	3.9	0.7800
15-19 (mean = 17)	3.5	2.6	0.7428
(mean = 18.333)	**3.273**	**2.27**	**0.6936**
20-24 (mean = 22)	2.7	1.6	0.5926
25-29 (mean = 27)	2.2	1.2	0.5455

(2.4) Minimum expected time headway—May suggests that, in practice, the minimum expected time headway, α, is rarely less than 0.5 s.(4) For a vehicle traveling at 88.5 km/h (55 mi/h), if $\alpha = 0.5$ s, there would be a headway separation distance of 12.4 m (40.8 ft)—which would pro-

4.0-m (13-ft) car length is subtracted. For the current calculations, it was assumed that $\alpha = 0.5$ s.

(2.5) Determining K—May suggests that an approximate value of K can be obtained from the following equation:

$$K = \frac{\bar{t} - \alpha}{s}$$

This equation was used to determine values of K_{10} and K_{20}, using:
$\bar{t}_{10} = 6.545$ and $\bar{t}_{20} = 3.273$ —the values obtained in step 2.1, with $\alpha = 0.5$ s—as in step 2.4, and with $s_{10} = 5.3$ and $s_{20} = 2.27$—the values estimated in step 2.3.

Substituting these values in the equation:

$$K_{10} = \frac{6.545 - 0.5}{5.3}$$
$$= 1.14$$

And,

$$K_{20} = \frac{3.273 - 0.5}{2.27}$$
$$= 1.22$$

(2.6) Determining λ—λ is a function of the mean time headway, K and $\bar{t}$ and α; it is given by the equation:

$$\lambda = \frac{K}{\bar{t} - \alpha}$$

Therefore,

$$\lambda_{10} = \frac{1.14}{6.545 - 0.5}$$
$$= 0.189$$

And,

$$\lambda_{20} = \frac{1.22}{3.273 - 0.5}$$
$$= 0.44$$

(2.7) Calculating the gamma function, (K–1)!—If K is an integer, the gamma function is easy to calculate. However, when it is a decimal, as it is for both K_{10} and K_{20}, it is necessary to use a gamma function table like that provided by May, p. 437.(4)

(2.8) Solving the Pearson Type III equation—At this point, the Pearson Type III equation can be solved for desired values of t using the values obtained in steps 2.1 through 2.7.

$$f(t) = \frac{\lambda}{\tau(K)}[\lambda(t-\alpha)]^{K-1}e^{-\lambda(t-\alpha)}$$

For the 10-v/mi/ln density, this equation becomes:

$$f(t) = \frac{0.189}{\tau(1.14)}[0.189(t-0.5)]^{0.14}e^{-0.189(t-0.5)}$$

And for the 20-v/mi/ln density, it becomes:

$$f(t) = \frac{0.44}{\tau(1.22)}[0.44(t-0.5)]^{0.22}e^{-0.44(t-0.5)}$$

After these equations have been solved for the desired values of t —usually these values are multiples of 0.5 s—time headway group probabilities are calculated using the following equation:

$$P(t \leq h < t+\Delta t) = [\frac{f(t)+f(t+\Delta t)}{2}]\Delta t$$

where h is an individual time headway.

Then, the time headway group frequencies are calculated using the following equation:

$$F(t \leq h < t+\Delta t) = N[P(t \leq h \leq t+\Delta t)]$$

where N is the total number of observed headways required.

APPENDIX 3: PROTOCOL FOR EXPERIMENTS #1 AND #2

[Introduction]

[After the usual introductions and thanking the driver-subject for agreeing to participate in the experiment...]

Experimenter to Driver-Subject: Please listen to this tape. It will give you some introductory information about the experiment.

[*E* turns on tape containing Background Information]

[*E* should be prepared to show the schematic drawing of the six-lane freeway with the position of the automated and unautomated lanes at the appropriate point during the playing of the tape]

Narrator (on tape): You will be here for about 2 hours. First, I will give you some introductory information about the experiment. Then, your eyesight will be tested. After that, the experimenter will take you to the simulator. There, the main part of the experiment will take place. The experiment will consist of several trials. In each trial, you will drive on a section of roadway. When you finish driving in these trials, the experimenter will bring you back to this room and ask you to fill out a questionnaire.

N: The experiment that you are about to take part in is part of an on-going study of Automated Highway Systems. We are conducting the study for the FHWA (the Federal Highway Administration). The FHWA is responsible for safety and travel effectiveness on our highways. In this study, 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 experiments 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 of how the Automated Highway System should be designed and operated. Remember, 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.

N: The Automated Highway System could be designed in a number of ways. [*E* shows *D-S* the schematic drawing of the six-lane freeway at this point during the playing of the tape] The version that you will drive in the simulator uses a six-lane expressway with three lanes in each direction. All cars and trucks enter the freeway just as they enter it today. But only specially equipped vehicles are allowed into the left-most lane, which is the automated lane. These specially equipped vehicles will be controlled by the Automated Highway System. As the driver of one of these vehicles, you would enter the freeway as you do now, move to the center lane, and then request entry to the automated lane. When the Automated Highway System has determined that your vehicle is properly equipped, and that there is a space for you in the automated lane, you would be instructed to drive into that lane, and transfer control of your vehicle to the system. Then, the Automated Highway System would move you rapidly along in the automated lane, steering your car and controlling its speed automatically.

N: At the start of each experimental trial, your car will be under automatic control in the automated lane. You will be driven down the highway for a few minutes. Then, you will be warned that you are approaching your exit. You should take control of the car and leave the freeway at this exit.
[tape ends]

E: Do you have any questions?

[Signing of the Consent Forms]

E: Please read this consent form carefully and let me know if you have any questions.

[*E* answers any questions that the *D-S* might have]

E: Please sign in the place marked.

[Vision Testing]

E: Please come over to the Vision Tester

[*E* takes *D-S* over to the Vision Tester]

E: Do you wear glasses or contact lenses for seeing things at a distance?

[If *D-S* answers "Yes"]
—*E:* Please, would you put them on? Do you have bifocal lenses?

[If *D-S* answers "Yes," *E* notes whether they are progressive or split lenses]

E: I am going to show some images that are focused at a far distance.

[If *D-S* has bifocal lenses,
—*E adds:* Please look at them through the top part of the lenses of your glasses.]

1. [*E* switches on the Titmus Vision Tester and makes sure that the lenses are clean. *E* positions the "Far/Near" knob at the Far Setting, and positions the circular knob with Setting #1 below the green light. With this arrangement, the vision tester gives visual acuity for far vision.]

E: Please look in here. You will see a series of diamonds with three broken circles and one complete circle in each of them. Diamond #1 has the largest circles, diamond #2 the next largest. Please look at each diamond, starting with #1—and then tell me its number and whether the complete circle is at the top, bottom, left, or right of the diamond.

2. [When this procedure is complete, *E* positions the circular knob at Setting #4—with this arrangement the vision tester assesses the *D-S's* stereo depth perception.]

E: Now, you will see another set of diamonds with circles in them. Look at diamond #1. You should see one of the circles pop out, as if it is nearer to you than the other circles in the diamond. Please look at each diamond, starting with #1, and tell me whether the circle that seems to pop out is at the top, bottom, left, or right of the diamond.

3. [When this procedure is complete, *E* positions the circular knob at Setting #5—with this arrangement the vision tester assesses whether the *D-S* has any color deficiencies.]

E: Now, you should see six circles, each containing a number. The numbers are formed by dots of different colors. Starting with circle A, please tell me what number you can see in each of the circles.

[If the *D-S* does not see a number in circle F]
—*E:* Do not worry about not seeing a number in circle F, there isn't one there.

[If the *D-S* does report seeing a number in circle F, *E* should make no comment, but note that this *D-S* may have a red-green deficiency]

4. [When this procedure is complete, *E* positions the circular knob at Setting #6—with this arrangement the vision tester assesses whether there is any lateral misalignment of the *D-S's* eyes.]

E: You should be able to see several figures that look like musical notes and a long horizontal red-dotted line. Each of the musical notes has a small horizontal line in it. The long red-dotted line should go through one of the small lines on the notes. Please tell me the number of that note.

5. [When this procedure is complete, *E* positions the circular knob at Setting #7—with this arrangement the vision tester assesses whether there is any vertical misalignment of the *D-S's* eyes.]

E: You should see another series of musical notes. This time there is a thick arrow above them. Please tell me the number of the musical note that the arrow is pointing at.

6. [When this procedure is complete, *E* positions the "Far/Near" knob at the Far Setting, and positions the circular knob at Setting #8. With this arrangement, the vision tester gives visual acuity for near vision.]

E: Now, I am going to show some images that are focused at a near distance.

[Note, if the *D-S* is using bifocal lenses]
—*E adds:* Please look at them through the lower part of the lenses of your glasses.

E: This is like the first test, except that it tests near visual acuity. You will see another series of diamonds with three broken circles and one complete circle in each of them. Diamond #1 has the largest circles, diamond #2 the next largest. Please look at each diamond, starting with #1, then tell me its number and whether the complete circle is at the top, bottom, left, or right of the diamond.

[Vision Testing—Spatial Localization Perimeter]

E: Now, we will move to the other side of the room for the perimetry eye test.

E: Please, make yourself comfortable while I turn off the lights.

[The interaction between the *E* and the perimeter monitor is as follows]
At C:/ prompt, type: TEST
Type 1 <enter>
Type NEW in gray box.
Number = subject number (e.g., 3)
Name = subject number with gender [e.g., 3f (female) or 3m (male)]
Fill in all the rest with the subject's given information.
When you get to the bottom and the screen asks: "Any Changes?" Type N.
Type 3 <enter>
Default until you get to the page with the circle targets (Images Presented During Test).

E: This screen shows you the messages that you may receive during the vision test and shows the various sizes of the targets, or objects, that you will be looking for. One of these targets will be displayed randomly, starting with the target fifth from the left. As the test goes on, the targets will get smaller until we discover the size of the smallest target you can see. I'll demonstrate how the test is performed.

[*E* shuts blind.
Type C to continue. Demonstrate about 10 times. X stops example.
Hit any key to continue. Then type C]

E: When you see the target, you need to make a two-step response. First, as soon as you see the target, tap the bottom-middle portion of the screen with the light pen. Second, touch the position of the monitor where the target was displayed as accurately as you can. The purpose of the first touch is to measure your reaction time to the target. The purpose of the second touch is to accurately touch the target center. Hitting the target center can be difficult, so don't worry if you're not exactly on. Now you try it. Remember this is only practice. When you do hit the target center you will be rewarded with fireworks. It is important that you keep the light pen perpendicular to the screen throughout the test. You can rest your hand on the bottom of the monitor with the light pen about 1/8 inch from the screen while you wait. Move your hand and your eyes for the accuracy touch. Then return your focus to the X.

[Allow the subject to practice until he/she is proficient—i.e., so that the subject is able to perform the task when the target is well above threshold, before the next target appears]

E: Are you able to see the granularity of the screen? [If they are unable to see the granularity of the screen, we will arrange for the subject to be examined by Dr. Mike Wall in the Ophthalmology Department]

[Type X to exit. Type 3. Then default to introduction page. To pause, press the space bar or S. Then touch the screen with the light pen when ready to start again. REVIEW]

E: OK, now we are ready to begin the real test. It will take about 10 minutes. We need to get you in a comfortable position with your eyes 22 cm directly in front of the X. Let me know if you need to take a break.

[*E* checks the subject's position, whether the subject is holding the light pen perpendicular to screen, and whether his/her eyes are fixed on the X. Check regularly. Encourage subject]

E: OK, let's begin.

[There is a break after 100 trials. *E* continues when subject is ready to do so]
E: There are just a few more minutes left. Keep up the good work.

[When the first circle test is complete, the end-of-test screen will appear.
Press any key to return to the main menu.
At the main menu, type 4 (circles print and save results).
Press F10 to get back to the main menu]

E: How are you doing? Now we will continue with the motion test.

[Type 5 (motion test). <enter> through all defaults]

E: OK, now we are ready to begin the motion test. It will take about 10 minutes. Let me check your position.

[*E* checks the subject's position, whether the subject is holding the light pen perpendicular to screen, and whether his/her eyes are fixed on the X. Check regularly. Encourage subject]
E: OK, let's begin.

[There is a break after 100 trials. *E* continues when subject is ready to do so]
E: There are just a few more minutes left. Keep up the good work.

[When the first circle test is complete, the end-of-test screen will appear.
Press any key to return to the main menu.
At the main menu, type 6 (motion print and save).
Press F10 to get back to main menu.
Turn off monitor]

[Entering the Simulator]

[*E* takes the *D-S* to the simulator bay, and *D-S* sits in simulator vehicle]

E: Please put on your seat belt. If you need to, please adjust the seat and the mirrors.

E: If you want to stop the simulator at any point during the experiment, please tell me. In the event of an emergency, press this button.
[*E* points to the emergency button]

E: When the experiment is complete, the simulator will take about 45 seconds to come to a stop. The steps up to the simulator are moved away during the experiment, and we will have to wait for the operator outside to replace them. Please stay in the car and wait for me to escort you. Do not open the simulator door unless accompanied by me, or by one of the simulator personnel.

[Familiarization Trials]

E: At first, when you drive, we will not use the Automated Highway System. In the first trial, you will drive in a rural setting on a regular two-lane road; in the second trial, you will drive on a segment of freeway. These two trials will allow you to become familiar with simulator driving.

E: Do you have any questions?

E to Simulator Operator: Please start the first practice trial.

[*D-S* drives simulator on rural roads in Familiarization Trial #1]

[Towards the end of the trial...]
—*E:* As we approach the barn, the simulator operator will stop the trial—you should not slow down.

[Then, when the vehicle has stopped...]
—*E:* The simulator operator will end all the trials in this way, with your vehicle in motion.

E: How are you doing?

E: In that trial, there were no other vehicles on the rural road. In the next trial, you will drive on a segment of freeway where there is a 55 mile an hour speed limit, and where there will be other vehicles. When the trial starts, you will be close to a bridge over the freeway. You should start driving and go on to the entry way to the freeway. Do you have any questions?

E to Simulator Operator: Please start the second practice trial.

[*D-S* drives simulator on freeway in Familiarization Trial #2]
[During the trial...]
—*E:* Please, would you move into the center lane when it is safe to do so?

[Also, during the trial...]
—*E:* Please, would you move back into the right lane when it is safe to do so?

E: How are you doing? Do you have any comments or questions?

[Presentation of Instructions]

E: Please listen carefully to the instructions on this tape.
[*E* turns on tape containing Experimental Instructions]

N: In the trials that follow, we will use the Automated Highway System. At the beginning of each trial, you will be traveling along in a three-lane freeway. You will be in the left lane—the automated lane. You will be in the middle of a string of three vehicles, all of which are under automatic control.

N: In each trial, while you are under automated control, the distance between your car and the cars in front of you and behind you will be constant. If the vehicle in front of you were to slow down—either because the system reduced its speed automatically, or because its driver took control and reduced speed manually—your vehicle would slow down automatically so that you stay a constant distance behind. In the same way, if your vehicle slows down for any reason while you are in the automated lane, the vehicle behind you will slow down automatically, and remain at a constant distance behind you.

N: So, the distance between your car and the cars in front and behind will be constant in each trial. However, from trial to trial this distance will vary; in some trials you will be very close to the cars in front and behind, in other trials you will be further away.

N: The center and right lanes will contain vehicles that are not under automated control—these vehicles will behave in the way that traffic usually behaves on a freeway. The speed limit in these two lanes will be 55 miles an hour.

N: Each trial will begin with your vehicle already under automatic control; and you will remain under automatic control for a few minutes. During this time, you will be driven along in the automated lane, overtaking the slower traffic in the other two lanes. Then, when you are 60 seconds away from your exit, you will hear a tone. The tone will be followed by a voice informing you that your exit is approaching and that you should take control of the car. This is what you will hear:
[Tone and voice inserted here]

N: As the tone comes 60 seconds before the exit, you do not have to take control immediately. You will have enough time to drive out of the automated lane and leave the freeway at your exit.

N: You will not be able to take control until you have heard this tone. After the tone, you should take control of your vehicle. This is how you do it: first, you must hold the steering wheel; then, you must press either the accelerator or the brake pedal. When you have control of your vehicle, you will hear a second tone. This will also be followed by an auditory message—this time informing you that control has been transferred to you. This is what you will hear:
[Tone and voice inserted here]

N: As soon as it is safe to do so, you should drive your car into the center lane. Then, drive into the right lane so that you can leave the freeway at your exit. While you are under automated control, you will be traveling faster than the traffic in the other two lanes. You will need to slow down when you leave the automated lane so that you can drive in the normal way when you are in the center and right lanes—remember, there is a 55 miles an hour speed limit for these two lanes.

N: I will repeat how you take control of the vehicle. After hearing the tone indicating that you are approaching your exit, you must first hold the steering wheel, then press the accelerator or brake pedal. You will hear a second tone confirming that you have control of your car. When you have control, you will drive your car first into the center lane, then into the right lane, and then leave the freeway at your exit.
[Tape ends]

E: Do you have any questions about the experiment or about what you have to do? [Be prepared to say: "After you hear the tone telling you that you are approaching your exit, hold the steering wheel, then press the accelerator or the brake pedal to take control of your car. Only after you have pressed the accelerator or brake pedal will you be able to steer the car."]

[When the *D-S's* questions have been answered]

E to Simulator Operator: Please start the first trial.

[*D-S* drives simulator in Experimental Trial #1]
E: How are you doing? Do you have any comments or questions?

E to Simulator Operator: Please start the second trial.

[*D-S* drives simulator in Experimental Trial #2]
E: How are you doing? Do you have any comments or questions?

E to Simulator Operator: Please start the third trial.

[*D-S* drives simulator in Experimental Trial #3]
E: How are you doing? Do you have any comments or questions?

E to Simulator Operator: Please start the fourth trial.

[*D-S* drives simulator in Experimental Trial #4]
E: How are you doing? Do you have any comments or questions?

E to Simulator Operator: Please start the fifth trial.

[*D-S* drives simulator in Experimental Trial #5]
E: How are you doing? Do you have any comments or questions?

E to Simulator Operator: Please start the sixth trial.

[*D-S* drives simulator in Experimental Trial #6]
E: How are you doing? Do you have any comments or questions?

[Debriefing]

[*E* leads the *D-S* to the subject preparation room for debriefing]

E: Would you like a beverage?

E: Please fill out this questionnaire.

[*E* will hand the *D-S* the questionnaire and remain in the room while it is being completed. When it is complete, look at the response to question #9—if the response is less than three-quarters of the way towards the "easy to understand" marker, ask the *D-S* , "Did you have problems with the content or the clarity of the message?"]

E: How well did the instructions prepare you for carrying out the experiment?
[Record answer]

E: Do you have any other comments on the experiment?

E: Would you be interested in participating in another experiment investigating Automated Highway Systems?
[Record answer]

[Payment]

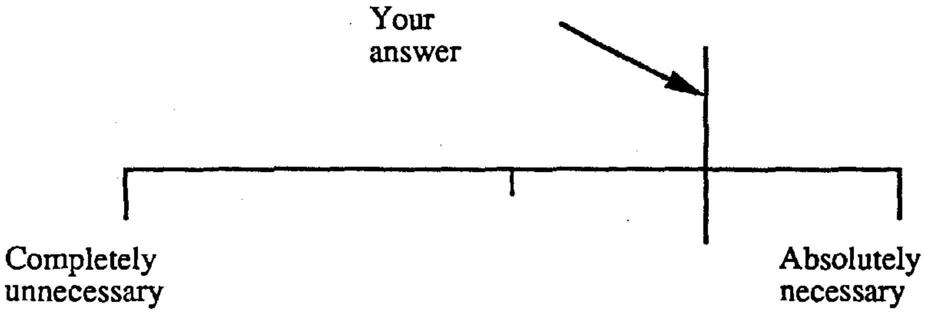
[*E* pays the *D-S* with a check, thanks him/her for participating in the experiment, and then escorts him/her out of the building.]

APPENDIX 4: QUESTIONNAIRE FOR EXPERIMENTS #1 AND #2

INTRODUCTION

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

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



---

1. How much did you enjoy driving the simulator?

Not at all — A great deal

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

Very different — Very similar

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

Very artificial — Very realistic

4. How realistic were the sounds in the simulator?

Very artificial

Very realistic

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

Very artificial

Very realistic

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

Felt unwell

Felt fine

7. In this study, when your car was under automatic control, were you comfortable with the speed, or would you have preferred to have traveled faster or slower?

Would prefer
much slower

Would prefer
much faster

8. In this study, when your car was under automatic control, the distance between you and the cars in front and behind was varied from trial to trial—which separation distances did you prefer?

Strongly preferred
longest distance

Strongly preferred
smallest distance

9. Was the message saying that you should take control of the car easy for you to understand?

Hard to understand — Easy to understand

10. Was the message saying that you should take control of the car presented early enough to give you time to react and prepare for exiting?

Insufficient time — Sufficient time

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

Very unsafe — Very safe

12. How would you describe the manner in which you controlled your car immediately after leaving the automated lane, when you first drove in the manual lane?

Very uncontrolled — Very controlled

13. To what extent did you feel in control of the situation immediately after leaving the automated lane, when you first drove in the manual lane?

Not at all — To a great extent

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

Strongly preferred manual lane	Strongly preferred automatic lane

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

More challenging in manual lanes	More challenging in automated lane

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

Very unenthusiastic	Very enthusiastic

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

Strongly prefer manual lanes	Strongly prefer automated lanes

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

Much safer with current freeways	Much safer with Automated Highway System

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

Will greatly decrease stress		Will greatly increase stress

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

21. What type of vehicle do you usually drive?

Type	Make	Year
Car		
Van		
Truck		
Motorcycle		
Other		

22. Does your vehicle have cruise control?

(a) Yes______________(If you tick yes, please answer Question #23)

(b) No_______________(If you tick no, you have completed the questionnaire)

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

Hardly ever Very often

APPENDIX 5: ANOVA SUMMARY TABLES

Appendix 5 contains the full summary tables for the ANOVAs conducted on the data from experiments #1 and #2. They are presented in the same order in which they are discussed in section 3 of the main report.

RESPONSE TIMES:

Data of Younger Drivers (Experiment #1)

Table 21. ANOVA summary determining whether the response times of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	p-value
Velocity (V)	2	245.26	122.63	0.87	0.4271
Subjects (within V) [S (w/V)]	33	4635.02	140.46		
Gap (G)	2	235.06	117.53	2.23	0.1158
V x G	4	140.06	35.01	0.66	0.6194
G x S (w/V)	66	3481.58	52.75		
Density (D)	1	13.09	13.09	0.43	0.5167
V x D	2	140.35	70.17	2.30	0.1157
D x S (w/V)	33	1005.25	30.46		
G x D	2	60.51	30.25	0.64	0.5316
V x G x D	4	47.72	11.93	0.25	0.9075
G x D x S (w/V)	61	2890.71	47.39		

RESPONSE TIMES:

Data of Older Drivers (Experiment #2)

Table 22. ANOVA summary determining whether the response times of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	711.74	355.87	4.73	0.0201
S(w/V)	21	1578.58	75.17		
(G)	2	90.47	45.23	0.62	0.5454
V x G	4	186.32	46.58	0.63	0.6413
G x S (w/V)	40	2939.52	73.48		
D	1	13.22	13.22	0.34	0.5681
V x D	2	206.22	103.11	2.62	0.0962
D x S (w/V)	21	825.44	39.44		
G x D	2	122.08	61.04	0.98	0.3869
V x G x D	4	68.11	17.03	0.27	0.8922
G x D x S (w/V)	28	1739.55	62.13		

RESPONSE TIMES:

Comparison of Data from Younger and Older Drivers (Experiments #1 and #2)

Table 23. ANOVA summary determining whether the response times of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
Age (A)	1	1.65	1.65	0.01	0.9052
Velocity (V)	2	938.44	469.22	4.08	0.0224
A x V	2	139.36	69.68	0.61	0.5494
Subjects (within A & V) S (W/A & V)	54	6213.60	115.06		
Gap (G)	2	28.39	14.20	0.23	0.7915
A x G	2	261.14	130.57	2.16	0.1209
V x G	4	161.01	40.25	0.66	0.6180
A x V x G	4	182.54	45.64	0.75	0.5580
G x S (w/A & V)	106	6421.10	60.58		
Density (D)	1	0.53	0.53	0.02	0.9010
A x D	1	24.97	24.97	0.74	0.3945
V x D	2	203.93	101.96	3.01	0.0578
A x V x D	2	157.17	78.59	2.32	0.1082
D x S (w/A & V)	54	1830.69	33.90		
G x D	2	159.73	79.87	1.54	0.2211
A x G x D	2	47.27	23.63	0.45	0.6364
V x G x D	4	36.18	9.05	0.17	0.9513
A x V x G x D	4	90.97	22.74	0.44	0.7814
G x D x S (w/A & V)	89	4630.27	52.03		

EXPOSURE TIMES:

Data of Younger Drivers (Experiment #1)

Table 24. ANOVA summary determining whether the exposure times of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	2744.61	1372.31	6.43	0.0044
S (w/V)	33	7047.87	213.57		
G	2	382.52	191.26	4.69	0.0124
V x G	4	98.86	24.72	0.61	0.6594
G x S (w/V)	66	2689.92	40.76		
D	1	329.57	329.57	11.16	0.0021
V x D	2	50.15	25.07	0.85	0.4370
D x S (w/V)	33	974.59	29.53		
G x D	2	236.29	118.14	2.32	0.1072
V x G x D	4	173.22	43.31	0.85	0.4997
G x D x S (w/V)	61	2890.72	47.39		

EXPOSURE TIMES:

Data of Older Drivers (Experiment #2)

Table 25. ANOVA summary determining whether the exposure times of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
Velocity	2	187.46	93.73	0.93	0.4119
S (w/V)	21	2126.90	101.28		
Gap (G)	2	183.82	91.91	2.97	0.0630
V x G	4	231.41	57.85	1.87	0.1352
G x S (w/V)	40	1239.61	30.99		
D	1	319.67	319.67	10.64	0.0037
V x D	2	323.65	161.82	5.38	0.0130
D x S (w/V)	21	631.23	30.06		
G x D	2	355.20	177.60	1.95	0.1608
V x G x D	4	113.73	28.43	0.31	0.8672
G x D x S (w/V)	28	2547.51	90.98		

EXPOSURE TIMES:

Comparison of Data from Younger and Older Drivers (Experiments #1 and #2)

Table 26. ANOVA summary determining whether the exposure times of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
A	1	51.20	51.20	0.30	0.5853
V	2	1871.12	935.56	5.51	0.0067
A x V	2	466.29	233.14	1.37	0.2622
S (w/A & V)	54	9174.77	169.90		
G	2	412.10	206.05	5.56	0.0051
A x G	2	87.41	43.71	1.18	0.3116
V x G	4	298.30	74.58	2.01	0.0981
A x V x G	4	74.26	18.56	0.50	0.7352
G x S (w/A & V)	106	3929.53	37.07		
D	1	633.05	633.05	21.29	0.0001
A x D	1	13.45	13.45	0.45	0.5040
V x D	2	103.77	51.89	1.74	0.1844
A x V x D	2	345.27	172.64	5.81	0.0052
D x S (w/A & V)	54	1605.81	29.74		
G x D	2	516.30	258.15	4.06	0.0205
A x G x D	2	134.32	67.16	1.06	0.3520
V x G x D	4	22.68	5.67	0.09	0.9856
A x V x G x D	4	254.33	63.58	1.00	0.4119
G x D x S (w/A & V)	89	5658.45	63.58		

EXIT VELOCITIES:

Data of Younger Drivers (Experiment #1)

Table 27. ANOVA summary determining whether the exit velocities of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	638.48	319.24	7.57	0.0020
S (w/V)	33	1391.41	42.16		
G	2	49.99	25.00	2.39	0.1000
V x G	4	3.38	0.84	0.08	0.9880
G x S (w/V)	64	669.94	10.46		
D	1	49.49	49.49	5.20	0.0292
V x D	2	7.07	3.54	0.37	0.6926
D x S (w/V)	33	314.14	9.52		
G x D	2	42.41	21.21	1.82	0.1715
V x G x D	4	34.52	8.63	0.74	0.5679
G x D x S (w/V)	54	628.54	11.63		

EXIT VELOCITIES:

Data of Older Drivers (Experiment #2)

Table 28. ANOVA summary determining whether the exit velocities of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	969.10	484.55	9.64	0.0011
S (w/V)	21	1055.43	50.26		
G	2	14.87	7.44	0.62	0.5415
V x G	4	13.38	3.34	0.28	0.8891
G x S (w/V)	40	477.46	11.94		
D	1	110.53	110.53	11.55	0.0027
V x D	2	28.39	14.19	1.48	0.2496
D x S (w/V)	21	200.94	9.57		
G x D	2	2.29	1.15	0.09	0.9154
V x G x D	4	18.43	4.61	0.36	0.8376
G x D x S (w/V)	30	387.99	12.93		

EXIT VELOCITIES:

Comparison of Data from Younger and Older Drivers (Experiments #1 and #2)

Table 29. ANOVA summary determining whether the exit velocities of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
A	1	11.33	11.33	0.25	0.6191
V	2	1598.27	799.14	17.64	0.0001
A x V	2	81.87	40.94	0.90	0.4112
S (w/A & V)	54	2446.83	45.31		
G	2	42.22	21.11	1.91	0.1528
A x G	2	15.24	7.62	0.69	0.5034
V x G	4	3.75	0.94	0.08	0.9869
A x V x G	4	14.81	3.70	0.34	0.8535
G x S (w/A & V)	104	1147.40	11.03		
D	1	159.03	159.03	16.67	0.0001
A x D	1	15.57	15.57	1.63	0.2068
V x D	2	22.84	11.42	1.20	0.3099
A x V x D	2	17.83	8.92	0.94	0.3988
D x S (w/A & V)	54	515.08	9.54		
G x D	2	19.44	9.72	0.80	0.4513
A x G x D	2	16.31	8.16	0.67	0.5124
V x G x D	4	2.64	0.66	0.05	0.9944
A x V x G x D	4	45.02	11.25	0.93	0.4506
G x D x S (w/A & V)	84	1016.53	12.10		

LANE-CHANGE TIMES:

Data of Younger Drivers (Experiment #1)

Table 30. ANOVA summary determining whether the lane-change times of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	136.76	68.38	3.60	0.0385
S (w/V)	33	626.41	18.98		
G	2	45.47	22.73	2.46	0.0931
V x G	4	55.58	13.90	1.51	0.2110
G x S (w/V)	65	600.02	9.23		
D	1	1.65	1.65	0.10	0.7576
V x D	2	5.17	2.58	0.15	0.8601
D x S (w/V)	33	563.42	17.07		
G x D	2	4.70	2.35	0.28	0.7538
V x G x D	4	26.13	6.53	0.79	0.5362
G x D x S (w/V)	60	496.11	8.27		

LANE-CHANGE TIMES:

Data of Older Drivers (Experiment #2)

Table 31. ANOVA summary determining whether the lane-change times of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	37.58	18.79	2.38	0.1170
S (w/V)	21	165.79	7.89		
G	2	20.18	10.09	2.09	0.1365
V x G	4	10.86	2.72	0.56	0.6903
G x S (w/V)	40	192.73	4.82		
D	1	18.81	18.81	4.63	0.0432
V x D	2	21.85	10.93	2.69	0.0911
D x S (w/V)	21	85.26	4.05		
G x D	2	7.34	3.67	0.49	0.6195
V x G x D	4	20.56	5.14	0.68	0.6102
G x D x S (w/V)	28	210.97	7.53		

LANE-CHANGE TIMES:

Comparison of Data from Younger and Older Drivers (Experiments #1 and #2)

Table 32. ANOVA summary determining whether the lane-change times of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
A	1	3.15	3.15	0.21	0.6451
V	2	119.00	59.50	4.06	0.0229
A x V	2	31.48	15.74	1.07	0.3492
S (w/A & V)	54	792.20	14.67		
G	2	3.77	1.89	0.25	0.7794
A x G	2	56.83	28.41	3.76	0.0264
V x G	4	36.31	9.08	1.20	0.3143
A x V x G	4	21.48	5.37	0.71	0.5860
G x S (w/A & V)	105	792.75	7.55		
D	1	7.23	7.23	0.60	0.4413
A x D	1	17.82	17.82	1.48	0.2286
V x D	2	23.45	11.73	0.98	0.3833
A x V x D	2	8.63	4.31	0.36	0.7000
D x S (w/A & V)	54	648.68	12.01		
G x D	2	7.60	3.80	0.47	0.6247
A x G x D	2	4.80	2.40	0.30	0.7427
V x G x D	4	21.24	5.31	0.66	0.6208
A x V x G x D	4	22.98	5.74	0.71	0.5839
G x D x S (w/A & V)	88	707.08	8.04		

CENTER LANE TIMES:

Data of Younger Drivers (Experiment #1)

Table 33. ANOVA summary determining whether the center lane times of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	31.16	15.58	0.13	0.8770
S (w/V)	33	3900.83	118.21		
G	2	49.33	24.66	0.37	0.6880
V x G	4	466.80	116.70	1.77	0.1450
G x S (w/V)	64	4209.79	65.78		
D	1	13.42	13.42	0.19	0.6625
V x D	2	451.12	225.56	3.26	0.0510
D x S (w/V)	33	2282.88	69.18		
G x D	2	84.41	42.21	0.52	0.5984
V x G x D	4	227.16	56.79	0.70	0.5969
G x D x S (w/V)	48	3903.30	81.32		

CENTER LANE TIMES:

Data of Older Drivers (Experiment #2)

Table 34. ANOVA summary determining whether the center lane times of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	26.69	13.34	0.20	0.8215
S (w/V)	21	1469.66	69.98		
G	2	199.60	99.80	2.44	0.1000
V x G	4	364.95	91.24	2.23	0.0829
G x S (w/V)	40	1549.53	38.74		
D	1	69.36	69.36	1.22	0.3038
V x D	2	61.01	30.50	0.49	0.6203
D x S (w/V)	21	1311.02	62.43		
G x D	2	172.98	86.49	2.71	0.0884
V x G x D	4	9.67	2.42	0.08	0.9888
G x D x S (w/V)	22	701.18	31.87		

CENTER LANE TIMES:

Comparison of Data from Younger and Older Drivers (Experiments #1 and #2)

Table 35. ANOVA summary determining whether the center lane times of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
A	1	1600.55	1600.55	16.27	0.0002
V	2	55.21	27.60	0.28	0.7564
A x V	2	2.68	1.34	0.01	0.9865
S (w/A & V)	54	5312.46	98.38		
G	2	188.46	94.23	1.68	0.1921
A x G	2	96.06	48.03	0.85	0.4285
V x G	4	291.43	72.86	1.30	0.2764
A x V x G	4	526.49	131.62	2.34	0.0598
G x S (w/A & V)	104	5845.96	56.21		
D	1	76.87	76.87	1.15	0.2873
A x D	1	19.42	19.42	0.29	0.5912
V x D	2	183.19	91.60	1.38	0.2612
A x V x D	2	218.91	109.46	1.64	0.2026
D x S (w/A & V)	54	3593.90	66.55		
G x D	2	38.26	19.13	0.29	0.7485
A x G x D	2	236.53	118.27	1.80	0.1732
V x G x D	4	77.88	19.47	0.30	0.8796
A x V x G x D	4	95.12	23.78	0.36	0.8352
G x D x S (w/A & V)	70	4604.48	65.78		

DELAY TIMES:

Data of Younger Drivers (Experiment #1)

Measured Delay Time

Table 36. ANOVA summary determining whether the measured delay times of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	334.69	167.34	9.34	0.0006
S (w/V)	33	591.01	17.91		
G	2	18.72	9.36	2.66	0.0779
V x G	4	21.66	5.42	1.54	0.2021
G x S (w/V)	64	225.48	3.52		
D	1	5.21	5.21	1.20	0.2812
V x D	2	5.02	2.51	0.58	0.5665
D x S (w/V)	33	143.11	4.34		
G x D	2	4.96	2.48	0.57	0.5667
V x G x D	4	4.35	1.87	0.25	0.9073
G x D x S (w/V)	54	233.23	4.32		

DELAY TIMES:

Data of Younger Drivers (Experiment #1)

Total Delay Time

Table 37. ANOVA summary determining whether the total delay times of younger drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	1291.50	645.75	17.42	0.0001
S (w/V)	33	1223.57	37.08		
G	2	31.11	15.56	2.56	0.0856
V x G	4	26.92	6.73	1.11	0.3617
G x S (w/V)	64	389.61	6.09		
D	1	14.47	14.47	1.88	0.1791
V x D	2	11.44	5.72	0.75	0.4824
D x S (w/V)	33	253.36	7.68		
G x D	2	14.12	7.06	0.83	0.4418
V x G x D	4	7.88	1.97	0.23	0.9195
G x D x S (w/V)	54	459.78	8.51		

DELAY TIMES:

Data of Older Drivers (Experiment #2)

Measured Delay Time

Table 38. ANOVA summary determining whether the measured delay times of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	63.25	31.62	2.35	0.1197
S (w/V)	21	282.26	13.44		
G	2	6.68	3.34	1.10	0.3439
V x G	4	7.01	1.75	0.58	0.6822
G x S (w/V)	40	121.83	3.05		
D	1	23.74	23.74	9.41	0.0059
V x D	2	7.28	3.64	1.44	0.2589
D x S (w/V)	21	53.01	2.52		
G x D	2	26.81	13.41	1.28	0.2930
V x G x D	4	4.47	1.12	0.11	0.9792
G x D x S (w/V)	30	314.42	10.48		

DELAY TIMES:

Data of Older Drivers (Experiment #2)

Total Delay Time

Table 39. ANOVA summary determining whether the total delay times of older drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), or the density (D) of the traffic in the unautomated lanes.

Source	df	SS	MS	F	p
V	2	456.31	228.16	7.89	0.0028
S (w/V)	21	606.97	28.90		
G	2	4.76	2.38	0.48	0.6217
V x G	4	8.40	2.10	0.42	0.7901
G x S (w/V)	40	197.94	4.95		
D	1	43.86	43.86	8.52	0.0082
V x D	2	11.66	5.83	1.13	0.3413
D x S (w/V)	21	108.14	5.15		
G x D	2	31.58	15.79	0.88	0.4240
V x G x D	4	7.25	1.84	0.10	0.9811
G x D x S (w/V)	30	536.55	17.89		

DELAY TIMES:

Comparison of Measured Delay Time Data from Younger and Older Drivers (Experiments #1 and #2)

Table 40. ANOVA summary determining whether the measured delay times of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
A	1	0.35	0.35	0.02	0.8829
V	2	317.16	158.58	9.81	0.0002
A x V	2	28.25	14.12	0.87	0.4234
S (w/A & V)	54	873.27	16.17		
G	2	20.31	10.15	3.04	0.0521
A x G	2	2.30	1.15	0.34	0.7100
V x G	4	16.90	4.22	1.27	0.2885
A x V x G	4	8.39	2.10	0.63	0.6437
G x (w/A & V)	104	347.31	3.34		
D	1	27.32	27.32	7.52	0.0083
A x D	1	5.88	5.88	1.62	0.2088
V x D	2	4.88	2.44	0.67	0.5149
A x V x D	2	8.06	4.03	1.11	0.3373
D x S (w/A & V)	54	196.12	3.63		
G x D	2	21.91	10.96	1.68	0.1925
A x G x D	2	16.14	8.07	1.24	0.2952
V x G x D	4	1.78	0.44	0.07	0.9914
A x V x G x D	4	7.11	1.77	0.27	0.8949
G x D x S (w/A & V)	84	547.65	6.52		

DELAY TIMES:

Comparison of Total Delay Time Data from Younger and Older Drivers (Experiments #1 and #2)

Table 41. ANOVA summary determining whether the total delay times of drivers were affected by variations in the design velocity (V), the size of the intra-string gap (G), the density (D) of the traffic in the unautomated lanes, or the age (A) of the driver.

Source	df	SS	MS	F	p
A	1	0.49	0.49	0.01	0.9046
V	2	1552.98	776.49	22.91	0.0001
A x V	2	35.10	17.55	0.52	0.5988
S (w/A & V)	54	1830.54	33.90		
G	2	26.23	13.12	2.32	0.1032
A x G	2	3.57	1.78	0.32	0.7299
V x G	4	18.62	4.66	0.82	0.5127
A x V x G	4	12.15	3.04	0.54	0.7083
G x S (w/A & V)	104	587.55	5.65		
D	1	56.84	56.84	8.49	0.0052
A x D	1	8.17	8.16	1.22	0.2742
V x D	2	11.31	5.65	0.84	0.4353
A x V x D	2	12.14	6.07	0.91	0.4097
D x S (w/A & V)	54	361.50	6.69		
G x D	2	32.81	16.41	1.38	0.2564
A x G x D	2	18.42	9.21	0.78	0.4632
V x G x D	4	3.42	0.85	0.07	0.9904
A x V x G x D	4	11.59	2.89	0.24	0.9124
G x D x S (w/A & V)	84	996.33	11.86		

REFERENCES

1. Zhang, W.-B., Shladover, S., Hall, R., Levitan, L., Plocher, T., and Bloomfield, J.R. (1993). *Definition of Functions for an Ideal Automated Highway System*. Technical Report, Federal Highway Administration.
2. 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* (to appear Summer 1995).
3. 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. pp. 117-126.
4. May, A.D. (1990) *Traffic Flow Fundamentals*. Prentice-Hall: Englewood Cliffs, New Jersey.
5. May, A.D. (1965) *Gap Availability Studies*. Highway Research Board Record 72, HRB, Washington, DC, pp. 105-136.
6. Transportation Research Board. (1985) *Highway Capacity Manual: Special Report 209*. National Research Council: Washington, DC.
7. Wall, M. (1994) "Motion Perimetry in Optic Neuropathies." Presented at XIIth International Perimetric Society Meeting, Washington, DC, July 1994. Also: (in press) In: Mills, R.P. and Wall, M. (editors) *Perimetry Update 1994/95*. Kugler Publications, Amsterdam/New York.
8. Transportation Research Board. (1984) *55: A Decade of Experience*. U.S. Department of Transportation Research Board Special Report 204, Washington, DC.
9. Transportation Research Board. *Highway Statistics, Annual Issues 1972-1983*, Tables VS-1 and VS-2. U.S. Department of Transportation Research Board, Washington, DC (cited in Transportation Research Board, 1984).

Preceding page blank