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

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FOREWORD

This report presents the results of the third in a series of 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

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16. Abstract
The third in a series of experiments exploring human factors issues related to the Automated Highway System (AHS) investigated the transfer of control from the driver of a vehicle entering an automated lane to the AHS. Twenty-four drivers aged between 25 and 34 years drove in the Iowa Driving Simulator—a moving base hexapod platform containing a mid-sized sedan with a 3.35-rad (180°) projection screen to the front and a 1.13-rad (60°) screen to the rear. The experiment focused on a generic AHS configuration in which the left lane was reserved for automated vehicles, the center and right lanes were reserved for unautomated vehicles, and in which there was no transition lane and no barrier. The driver took the simulator vehicle onto a freeway, moved to the center lane, and then, after receiving an *Enter* command, drove into an automated lane and transferred control to the AHS. Then, the AHS moved the vehicle into the lead position of the string of vehicles approaching it from behind.

Results: The entering response time, lane-change time, entering exposure time, and string-joining time, data were used to determine the minimum inter-string gap required to enable the driver's vehicle to enter the automated lane without causing a delay to the string it joins. The required minimum inter-string gap varied with the design velocity and the method of transferring control. With the partially automated transfer method, the required minimum inter-string gap time increased from 1.14 s for the 104.7-km/h (65-mi/h) design velocity, through 3.38 s for the 128.8-km/h (80-mi/h) design velocity, to 7.33 s for the 153.0-km/h (95-mi/h) design velocity. The hourly capacity when the design velocity is 104.7 km/h (65 mi/h) is likely to be four times greater than when the design velocity is 153.0 km/h (95 mi/h) (the hourly capacity for the latter would be only slightly more than the traffic flow that could be achieved without an AHS). It is not the design velocity of 104.7 km/h (65 mi/h) per se that produces the higher capacity—it is the relatively low velocity differential between the design velocity and the speed limit in the unautomated lanes. If the transfer of control from the driver to the AHS were to occur before the driver moved into the automated lane, the required minimum inter-string gap times should be reduced—a possibility that is being investigated in the next in the experimental series. No collisions occurred, suggesting that the drivers were able to join the automated lane safely—a suggestion reinforced by the responses to a questionnaire indicating that the drivers felt safe and believed they controlled the vehicle well during the entry maneuver.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

(Revised September 1993)

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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 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. This report describes the third experiment in the series.

The series of experiments investigates human factors aspects of a generic AHS configuration that requires little 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. There is no transition lane and there are no barriers between the automated and unautomated lanes.

In the first two experiments of the series, Bloomfield, Buck, Carroll, Booth, Romano, McGehee, and North investigated the transfer of control from the AHS to the driver of the simulator vehicle.(2) At the beginning of the experimental trials in these two experiments, the driver's vehicle was under automated control, in the middle of a string of three vehicles, in an automated lane—the driver's task was to take control of the vehicle, drive it out of the automated lane into an unautomated lane, and then leave the freeway at a designated exit.

In the current experiment, this situation was reversed. In this study, each experimental trial started with the driver's vehicle on a freeway entry ramp, and the driver's task was to drive into the right lane of the freeway, move to the center lane, and then, after receiving an *Enter* command, drive into the automated lane and transfer control of the vehicle to the AHS. At this point, the AHS would move the simulator vehicle into the lead position of the string of vehicles that was approaching it from behind.

As mentioned above, the AHS configuration used in this experiment was a three-lane freeway, with the left lane reserved for the vehicles under automated control, the center and right lanes reserved for unautomated traffic, with no transition lane, and with no barriers between the automated and unautomated lanes. The vehicles in the automated lane traveled in short strings—with up to four vehicles per string and with a 0.0625-s distance between the vehicles in the strings. The experiment was designed so that it explored whether the behavior of a driver who entered the automated lane and transferred control of the vehicle to the AHS was affected by variations in the:

- Method by which control was transferred from the driver to the AHS.
- Distance between the strings of vehicles in the automated lane (inter-string gap).
- Velocity of the vehicles in the automated lane (design velocity).

OBJECTIVE

The objective of this experiment was to determine the conditions under which a driver in the unautomated lane could safely enter the automated lane and transfer control of the vehicle to the automated system with the minimum of interference to the flow of traffic in the automated lane. To achieve this objective, the experiment focused on the following questions:

- *Does the **Entering Response Time** (i.e., the length of time between the moment that the AHS issued the* Enter *command and the moment that the driver started to move the vehicle into the automated lane) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

- *Does the **Lane-Changing Time** (i.e., the length of time from the moment that the driver began to drive the vehicle into the automated lane to the moment that the lane-change maneuver was completed) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

- *Does the **Entering Exposure Time** (i.e., the length of time between the moment that the driver completed the lane change maneuver and the moment that control was transferred to the system) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

- *Does the **String-Joining Time** (i.e., the length of time from the moment that control was transferred to the system until the moment that the vehicle became the lead vehicle of the string of vehicles immediately behind it) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

- *Does the **Possible Time Delay** incurred during the entry maneuver vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

- *Does the driver's ability to avoid* ***Collisions*** *with other vehicles vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

- *Does the entry maneuver cause the string of vehicles immediately behind the driver's vehicle to slow down, and, if so, what is the potential effect on* ***AHS efficiency?***

SECTION 2: METHOD

SUBJECTS

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

- The drivers had no licensing restrictions, other than wearing eyeglasses for vision correction during driving.
- The drivers did not require special driving devices—the simulator is not equipped for such devices.
- There were 24 drivers—half were male and half were female—between the ages of 25 and 34.

The 24 drivers who took part in this experiment were volunteers who had replied to advertisements in the Iowa City and University of Iowa daily newspapers and who met the above selection criteria.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator, located in the Center for Computer-Aided Design at the University of Iowa, Iowa City, is shown in figure 1.(3) The simulator has a moving base hexapod platform that is covered with a projection dome. In the current experiment, a mid-size Ford sedan was placed on this platform, and the simulator was controlled by a computer complex that included a Harris Nighthawk 4400, an Alliant FX/2800, and an Evans and Sutherland CT-6 Image Generator. The Nighthawk and Alliant systems were controlled simultaneously by the same operating system.(4) The Nighthawk was the system master—arbitrating subsystem scheduling and performing motion control and data collection operations—while the Alliant, a 26-processor shared-memory parallel computer, performed the multibody vehicle dynamics and complex scenario control simulation.

The inner walls of the dome act as a screen. For the current experiment, the CT6 visual projection system projected correlated imagery onto two sections of these walls—one, a 3.35-rad (192°) section in front of the simulator vehicle, the other, a 1.13-rad (65°) section to its rear. The driver of the simulator vehicle viewed the imagery shown on the forward section through the windshield and side windows, and the imagery projected to the rear, either by turning around or through an interior driving mirror and a left-hand side driving mirror mounted outside the vehicle.

DESIGN CONSIDERATIONS

The AHS configuration used in this experiment involved three freeway lanes, one of which was automated. It is one of several possible AHS configurations that would allow vehicles to enter the automated lane at a velocity slower than the preferred design velocity. A two-lane AHS configuration with one automated and one unautomated lane would pose more problems than this configuration. On the other hand, AHS configurations that utilized multiple lanes with two or more automated lanes would pose fewer problems—for example, if the design velocity increased in stepwise fashion from one lane to the next, starting with the automated lane closest to the unautomated lane having a design velocity close to the unautomated lane speed limit, and ending with the automated lane furthest from the unautomated lane having the fastest design velocity—e.g., 153.0 km/h (95 mi/h)—it would be relatively easy for a vehicle to enter the AHS.

However many lanes are available, to minimize the complexity of the system and to maintain the flow of traffic in both the automated and unautomated lanes, it would be desirable to have a vehicle enter the automated lane while the automated vehicles continue to move at the design velocity, with only minor adjustments. To do this, between the strings of vehicles in the automated lane, there must be a gap that is big enough to allow a vehicle to enter at a velocity of 88.6 km/h (55 mi/h), or 104.7 km/h (65 mi/h)—if that is the speed limit—and then to accelerate to the design velocity.

For the current experiment, it was assumed that the vehicles in the automated lane would have acceleration characteristics similar to the acceleration characteristics of the simulator vehicle. Several simulator trials were conducted to determine how long it took for the simulator vehicle to accelerate from 88.6 km/h (55 mi/h) to the three automated-lane design velocities that were to be used in this experiment—i.e., 104.7 km/h (65 mi/h), 128.8 km/h (80 mi/h), and 153.0 km/h (95 mi/h). The results of these trials are shown in table 1. [Note that in making the calculations for table 1, it was assumed that the average length of a vehicle was 4.42 m (14.5 ft).]

Once the times required to accelerate to the three design velocities had been determined empirically, the distances traveled by the automated strings of vehicles, and by the entering vehicle while it is accelerating to each of the design velocities, were calculated. The differences in the distances for the automated vehicles and the entering vehicle would be the smallest inter-string separation that would be required to allow the entering vehicle to accelerate to the design velocity without affecting the traffic flow in the automated lane. Note that this separation is clearly an underestimate—it does not include any consideration of how long it will take for the driver of the entering vehicle to change lanes from the unautomated lane to the automated lane. The smallest inter-string

Table 1. Smallest inter-string gaps and maximum traffic flow possible with the empirically determined acceleration times required for the entering vehicle to reach each of the three design velocities.

(1)	Design velocity in automated lane.	104.7 km/h (65.0 mi/h)	128.8 km/h (80.0 mi/h)	153.0 km/h (95.0 mi/h)
(2)	Time required for entering vehicle to accelerate to design velocity.	7.8 s	14.3 s	37.4 s
(3)	Distance traveled by vehicle traveling at design velocity during time required for entering vehicle to accelerate to design velocity.	226.6 m (743.6 ft)	511.4 m (1677.9 ft)	1588.3 m (5211.1 ft)
(4)	Distance traveled by entering vehicle while it is accelerating to design velocity.	215.2 m (706.0 ft)	439.3 m (1441.3 ft)	1351.6 m (4434.4 ft)
(5)	Smallest inter-string gap that would allow entering vehicle to accelerate to design velocity without affecting traffic flow in automated lane.	11.5 m (37.6 ft)	72.1 m (236.6 ft)	236.7 m (776.7 ft)
(6)	Smallest inter-string gap time that would allow entering vehicle to accelerate to design velocity without affecting traffic flow in automated lane.	0.39 s	2.02 s	5.57 s
(7)	Maximum number of strings (of four vehicles) per 1.61 km (1 mi) when intra-string vehicle gap is set at 0.0625 s and inter-string gap is set at smallest distance that would allow entering vehicle to accelerate to design velocity without affecting traffic flow in automated lane.	46.53	16.68	6.13
(8)	Hourly traffic capacity (i.e., maximum number of vehicles per hour), with strings of four vehicles, when intra-string gap is set at 0.0625 s and inter-string gap is set at smallest distance that would allow entering vehicle to accelerate to design velocity without affecting traffic flow in automated lane.	12,097	5,337	2,329

separations derived for table 1 were used in selecting the inter-string separations that were tested in this experiment.

In addition, table 1 shows the maximum number of strings of four vehicles that could be accommodated per mile in a single automated lane. The table also shows the hourly traffic capacity for the automated lane (i.e., the maximum number of vehicles that could move past a fixed point in one hour, with strings consisting of four automated vehicles) that could be achieved if enough space were left between each pair of strings to allow a vehicle to enter between them.

It should be noted that, contrary to what might be expected, if enough space was left between each pair of strings to allow a vehicle to enter between them, the hourly traffic capacity for the single automated lane would be much higher if the design velocity was 104.7 km/h (65 mi/h) than it would be if the design velocity was higher. The traffic capacity if the design velocity was 104.7 km/h (65 mi/h) would be more than twice the capacity achieved if the design velocity was 128.8 km/h (80 mi/h), and five times the capacity if it was 153.0 km/h (95 mi/h).

DRIVING SCENARIO

The driver sat in the driver's seat in the simulator vehicle. Before the start of each experimental trial, this vehicle was positioned on a freeway entry ramp. When the trial started, the driver drove onto the freeway and, when it was safe, moved into the center lane. For the purposes of this experiment, the action of driving into the center lane was taken as constituting a request for entry to the automated lane. After the driver had been in the center lane traveling at 88.6 km/h (55 mi/h) for approximately 15 s, the automated system issued an *Enter* command. This command, which began with a countdown, was timed so that the driver would hear the actual *Enter* command just as the back bumper of the last vehicle in an automated string cleared the front bumper of the simulator vehicle. On hearing the command, the driver had to move the vehicle into the automated lane. If the driver failed to take action before the next string of vehicles went past in the automated lane, it was necessary to wait until another instruction message was issued by the AHS before making another attempt to enter the automated lane. Three entry opportunities were allowed per trial. [Note: in the 144 trials conducted in this experiment, there was only one trial in which a driver failed to enter the automated lane.]

When the driver had driven into the automated lane, the transfer of control from the driver to the AHS was effected in one of two ways: either the transfer was manual—with the driver indicating that the automated system should take control of the vehicle by pressing an *On* button—or it was partially automated—with the AHS taking control as soon as all four wheels of the driver's vehicle had crossed the lane marker between the center and the automated lanes. Whichever transfer method was used, when the system had taken control, it began to accelerate the driver's vehicle until it reached the same speed as the other vehicles in the automated lane. The system also positioned the vehicle at the head of the next string of vehicles.

DRIVING SITUATION

When investigating the transfer of control between the AHS and a driver, many different variables must be considered, either as variables to manipulate, variables to control, or variables to measure. The taxonomy of these variables developed by Bloomfield et al. was used as a guide in selecting the driving situation simulated in this experiment.(2)

This driving situation can be characterized as follows:

Each driver drove in dry weather conditions, at midday, on a straight three-lane freeway that was 15.25 km (9.47 mi) long. The left lane was automated, the center and right lanes were unautomated, there was no transition lane, and there were no barriers between the automated and unautomated lanes. The lane widths were the current standard 3.66-m (12-ft) freeway width, and a standard road surface was used.

The driver's task was to drive from the entry ramp into the right lane of the freeway, move into the center lane, and then, on hearing an *Enter* command, drive into the automated lane and transfer control of the vehicle. When the system had taken control, it positioned the vehicle at the head of the next string of vehicles in the automated lane.

Up to the point that control was transferred to the AHS, the driver controlled the velocity of the simulator vehicle. The average velocity of the other unautomated vehicles was fixed at 88.6 km/h (55 mi/h), and the density of these vehicles was 6.21 v/km/ln (10 v/mi/ln)—the lower of the two densities used in the first two experiments of the series.(2) With this density, the mean headway time for vehicles in the unautomated lanes was 6.55 s. [Note that the mean headway time is the difference in arrival time of two consecutive vehicles at a particular observation point on the highway. Mean headway time includes both the length of the first vehicle and the gap between it and the following vehicle.] The programming steps used to generate vehicles in this experiment were the same as those used in the first two experiments of the series.(2)

In the automated lane, the automated vehicles were traveling in strings of one, two, or three vehicles. The separation between the strings of vehicles in the automated lane and the velocity of the vehicles in that lane were both varied—the values that were selected are listed in the subsection on Experimental Design that immediately follows this subsection. The separation between the vehicles within strings was 0.0625 s.

When under automated control, the driver's steering wheel was prevented from moving, and the accelerator and the brake pedals were disconnected.

EXPERIMFNTAL DESIGN

As in the first two experiments in this series, a conventional factorial experimental design was used.(2) However, in this experiment, the method of transferring control of the vehicle was a between-subjects factor, while the design velocity for the automated lane and the size of the gap between the strings of automated vehicles were both within-subjects variables. Details of these independent variables are given below.

Method of Transferring Control of Vehicle

Two methods of transferring control from the driver to the AHS were used: 12 of the 24 drivers used a manual method; the other 12 used a partially automated method.

With both methods, the driver drove into the center lane, maintained a velocity of 88.6 km/h (55 mi/h), and waited until the AHS had determined that it would be appropriate to enter the automated lane and had issued an *Enter* command. The driver heard this *Enter* command just as the back of the last vehicle in an automated string, traveling in the automated lane, cleared the front of the simulator vehicle. On hearing the command, the driver was instructed to drive into the automated lane.

Then, with the manual method, the driver transferred control to the system by pressing the *On* button of the simulator vehicle's cruise control. In contrast, with the partially automated method, the AHS took control as soon as all four wheels on the simulator vehicle had crossed the lane marker between the center and the automated lanes.

Design Velocity

As in the first two experiments in the series, the following three design velocities were used: (a) 104.7 km/h (65 mi/h); (b) 128.8 km/h (80 mi/h); and (c) 153.0 km/h (95 mi/h).[2] However, for the current experiment, design velocity was a within-subjects variable—it had been a between-subjects variable in the earlier experiments.

Inter-String Gap

Two different separations between the strings of vehicles in the automated lane were used with each of the three automated lane velocities.

For the two faster design velocities—128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h)—the shorter of the two separations was the smallest inter-string separation that would allow the entering vehicle to accelerate to the design velocity without affecting the traffic flow in the automated lane—the values are given in table 1 (row 6)—and the longer of the two separations was the smallest inter-string separation with 2.0 s added—to allow for the lane change that the driver had to make.

As row 6 of table 1 shows, for the slowest design velocity—104.7 km/h (65 mi/h)—an inter-string separation of only 0.4 s would allow the entering vehicle to accelerate to the design velocity without affecting the traffic flow in the automated lane. It is impractical to use such a short gap—since the driver would clearly be unable to change lanes within this time. Instead, a 2.0-s separation was used as the shorter of the two separations. However, for this design velocity, the longer separation was 2.4 s, which is the smallest inter-string separation plus 2.0 s—as it was for the two faster velocities. Table 2 shows the inter-string gaps, in terms of both time and distance, for the three design velocities.

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

Design velocities	Inter-string gaps	
[in km/h (mi/h)]	Shorter gap	Longer gap
104.7 (65)	2.0 s [58.15 m (190.67 ft)]	2.4 s [69.74 m (228.80 ft)]
128.8 (80)	2.0 s [71.53 m (234.67 ft)]	4.0 s [143.05 m (469.33 ft)]
153.0 (95)	5.5 s [233.58 m (766.33 ft)]	7.5 s [318.52 m (1045.00 ft)]

Assignment and Counterbalancing of Experimental Conditions

There were 12 combinations of conditions (2 control transfer methods x 2 inter-string gaps x 3 design velocities). The effect of varying the control transfer method was determined by making between-subjects comparisons, while the effects of varying both the differential velocity and the separation distance were determined by making within-subjects comparisons.

The 24 drivers who participated in the experiment were divided into 2 groups of 12. For each driver in the first group, control was transferred to the AHS automatically as soon as the vehicle entered the automated lane. Each driver in the second group transferred control to the AHS manually.

The 6 combinations of inter-string gap and design velocity were presented to each of the 12 subjects in both groups using the counterbalanced random orders of presentation shown in table 3.

EXPERIMENTAL PROCEDURE

Initial Procedure

At the start of the experiment, each driver listened to an audio tape containing recorded introductory material. The driver was told that the experiment involved first driving in the simulator and then completing several vision tests and a questionnaire. The driver was informed that this experiment is part of an on-going FHWA program that is exploring ways of designing an AHS, determining how it might work, and how well drivers would handle their vehicles in such a system. It was made clear that the experiment was a test of the AHS, not a test of the driver. The text of this introductory information is presented in appendix 1, along with a complete description of the experimental protocol.

Pre-Experimental Simulator Procedure

Next, the driver was taken to the Iowa Driving Simulator, was asked to sit in the driver's seat, adjust the seat, put on the seat belt, and adjust the mirrors. The driver was shown the simulator emergency button, and was instructed on its use.

There were two familiarization trials. In the first of these trials, the driver drove along a country road with no other traffic present. At the start of the second familiarization trial, the driver's

Table 3. The counterbalanced order in which the 24 drivers in the 2 groups received the 12 combinations of method of transferring control, inter-string gap time, and design velocity.

Group	Driver	Counterbalanced order					
		Block 1			Block 2		
Group 1	M1	Cond 1	Cond 6	Cond 2	Cond 4	Cond 3	Cond 5
	F1	Cond 5	Cond 4	Cond 3	Cond 2	Cond 1	Cond 6
	M5	Cond 3	Cond 5	Cond 1	Cond 6	Cond 2	Cond 4
	F5	Cond 4	Cond 2	Cond 5	Cond 3	Cond 6	Cond 1
	M9	Cond 2	Cond 1	Cond 6	Cond 5	Cond 4	Cond 3
	F9	Cond 6	Cond 3	Cond 4	Cond 1	Cond 5	Cond 2
	M2	Cond 5	Cond 6	Cond 1	Cond 3	Cond 2	Cond 4
	F2	Cond 1	Cond 3	Cond 5	Cond 6	Cond 4	Cond 2
	M6	Cond 4	Cond 5	Cond 3	Cond 2	Cond 1	Cond 6
	F6	Cond 2	Cond 1	Cond 4	Cond 5	Cond 6	Cond 3
	M10	Cond 6	Cond 4	Cond 2	Cond 1	Cond 3	Cond 5
	F10	Cond 3	Cond 2	Cond 6	Cond 4	Cond 5	Cond 1
Group 2	M3	Cond 9	Cond 12	Cond 8	Cond 10	Cond 7	Cond 11
	F3	Cond 11	Cond 8	Cond 9	Cond 7	Cond 10	Cond 12
	M7	Cond 8	Cond 11	Cond 10	Cond 12	Cond 9	Cond 7
	F7	Cond 10	Cond 7	Cond 12	Cond 9	Cond 11	Cond 8
	M11	Cond 12	Cond 10	Cond 7	Cond 11	Cond 8	Cond 9
	F11	Cond 7	Cond 9	Cond 11	Cond 8	Cond 12	Cond 10
	M4	Cond 10	Cond 7	Cond 11	Cond 8	Cond 12	Cond 9
	F4	Cond 7	Cond 11	Cond 9	Cond 12	Cond 8	Cond 10
	M8	Cond 11	Cond 12	Cond 7	Cond 9	Cond 10	Cond 8
	F8	Cond 8	Cond 9	Cond 12	Cond 10	Cond 11	Cond 7
	M12	Cond 12	Cond 8	Cond 10	Cond 7	Cond 9	Cond 11
	F12	Cond 9	Cond 10	Cond 8	Cond 11	Cond 7	Cond 12

Key:

1 — Automated: 2.0 s & 104.7 km/h (65 mi/h)
2 — Automated: 2.4 s & 104.7 km/h (65 mi/h)
3 — Automated: 2.0 s & 128.8 km/h (80 mi/h)
4 — Automated: 4.0 s & 128.8 km/h (80 mi/h)
5 — Automated: 5.5 s & 153.0 km/h (95 mi/h)
6 — Automated: 7.5 s & 153.0 km/h (95 mi/h)
7 — Manual: 2.0 s & 104.7 km/h (65 mi/h)
8 — Manual: 2.4 s & 104.7 km/h (65 mi/h)
9 — Manual: 2.0 s & 128.8 km/h (80 mi/h)
10 — Manual: 4.0 s & 128.8 km/h (80 mi/h)
11 — Manual: 5.5 s & 153.0 km/h (95 mi/h)
12 — Manual: 7.5 s & 153.0 km/h (95 mi/h)

vehicle was positioned on a freeway entry ramp. The traffic density in the right and center lanes of this freeway was 6.21 v/km/ln (10 v/mi/ln). The driver was asked to drive down the ramp and merge into the right lane. Once there, 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. In addition, each driver in the manual transfer group was asked to use the cruise control during the second familiarization trial. Driving in these trials, each of which lasted 2 or 3 min, gave each driver an opportunity to become familiar with the simulator.

Experimental Procedure and Instructions

After the familiarization trials, the driver heard a second audio tape containing instructions for the experimental trials. These instructions, which are given in appendix 1, gave the driver 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 simulator vehicle would be on the entry ramp of the freeway.
- The speed limit in the unautomated lanes would be 88.6 km/h (55 mi/h).
- The driver was to drive into the right lane, then move to the center lane when it was safe.
- Once in the center lane, the driver was to drive at 88.6 km/h (55 mi/h). [Note: although the driver was asked to drive at 88.6 km/h (55 mi/h), as long as the velocity of the simulator vehicle was between 80.64 km/h (50.09 mi/h) and 96.48 km/h (59.93 mi/h), the vehicle was allowed into the automated lane.]
- The AHS would determine when it was appropriate for the driver to enter the automated lane, then would issue an *Enter* command.
- On hearing the command, the driver was to drive into the automated lane.
- For the drivers in the partially automated transfer group (group 1), the system would take control as soon as the simulator vehicle had crossed the white line between the center and automated lanes.
- For the drivers in the manual transfer group (group 2), after driving into the automated lane, the driver was to transfer control of the vehicle by pressing the *On* button on the cruise control.
- Once it had control, the AHS would increase the velocity of the simulator vehicle until it reached the design velocity, and would position the vehicle at the head of the next string of vehicles in the automated lane.
- Then, the simulator vehicle would travel under the control of the AHS for a few minutes.

Then the driver took part in six experimental trials. Each trial took between 3 and 5 min to complete. There was a brief break between trials while the simulator was reset.

Post-Simulator Procedure

Each subject completed a questionnaire dealing with the driving simulator, this experiment, and the AHS. [A copy of this questionnaire is presented in appendix 2.]

This was followed by the administration of the series of tests in which aspects of the driver's vision were assessed. A Titmus Vision Tester was used to test: (a) far foveal acuity; (b) near foveal acuity; (c) stereo depth perception; (d) color deficiencies; (e) lateral misalignment; and (f) vertical misalignment. Then, two newly developed perimetry tests that determine the driver's static and dynamic peripheral sensitivity were administered.[5]

SECTION 3: RESULTS

FOCUS OF DATA ANALYSIS

Objective

The objective of this experiment was to determine the conditions under which a driver in the unautomated lane could safely enter the automated lane and transfer control of the vehicle to the automated system, with a minimum of interference in the flow of traffic in both the automated and unautomated lanes. The data analysis focused on the:

- Moment that control of the vehicle was transferred from the driver to the AHS, and on the periods of time just before and just after this moment.

- Actions carried out by the driver and their effect on the driver's vehicle and on nearby vehicles, and on whether these actions had any effect on the efficiency of the AHS, and/or on safety—either actual safety (i.e., did they cause any collisions) or perceived safety.

The Entering and Potential Influence Time Periods

This experiment focused on the time between the moment that the *Enter* command was issued to the driver and the moment that the simulator vehicle achieved the design velocity and became the lead vehicle of a string of automated vehicles. This time can be divided into two distinct time periods, each of which consisted of two intervals. The beginning and end points of the two periods and four intervals were marked by the following five critical moments:

(1) The moment that the *Enter* command was issued.
(2) The moment that the driver began the lane change from the center to the automated lane (i.e., the moment that the first wheel of the driver's vehicle touched the white line between the center and automated lanes).
(3) The moment that the lane change from the center to the automated lane was completed (i.e., the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes).
(4) The moment that control of the vehicle was transferred to the AHS.
(5) The moment that the driver's vehicle attained the design velocity and became the lead vehicle of the following string of vehicles.

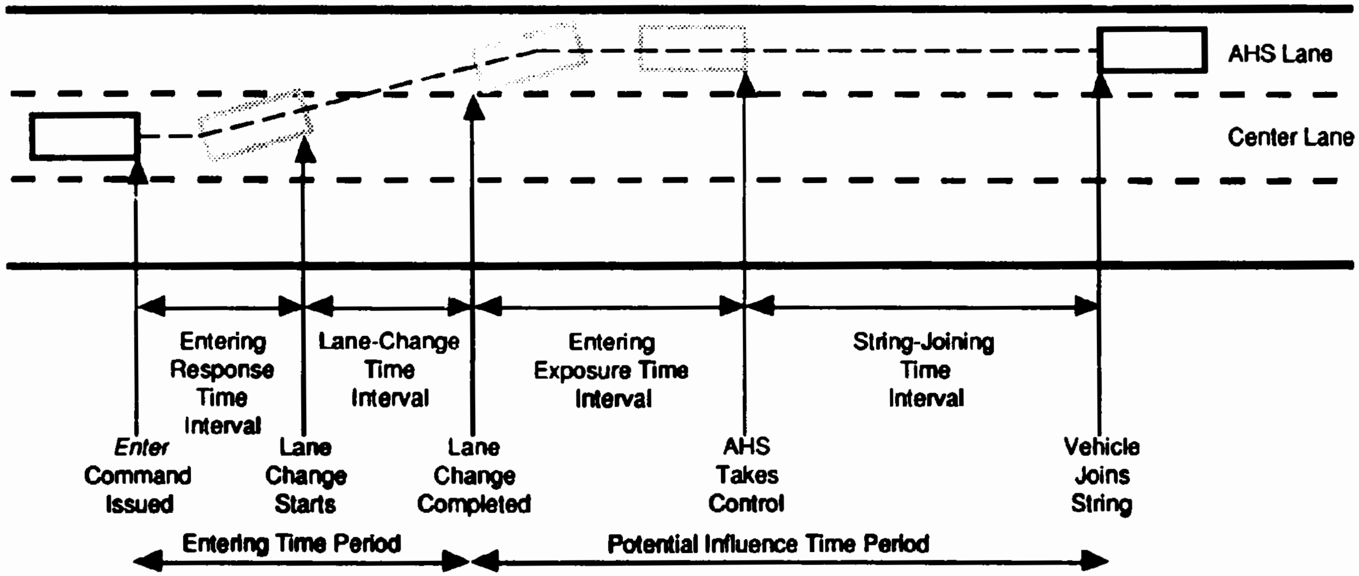


Figure 2. Track of entering vehicle during critical moments and time periods.

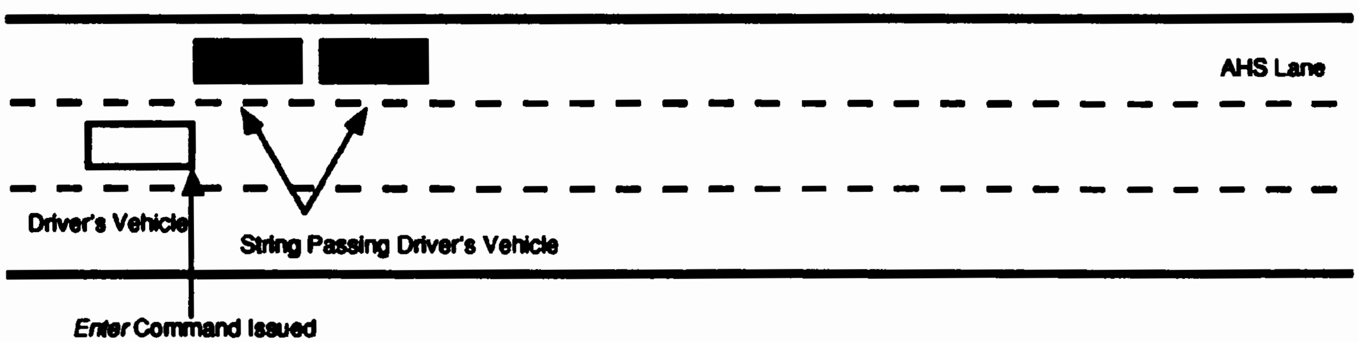


Figure 3. Position of on-coming string of automated vehicles at moment *Enter* command is issued.

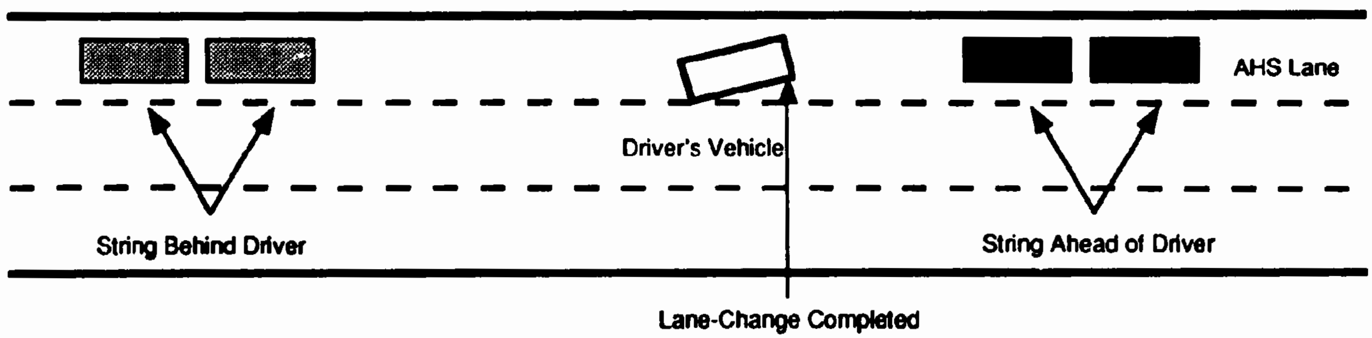


Figure 4. Position of on-coming string of automated vehicles when lane change is completed.

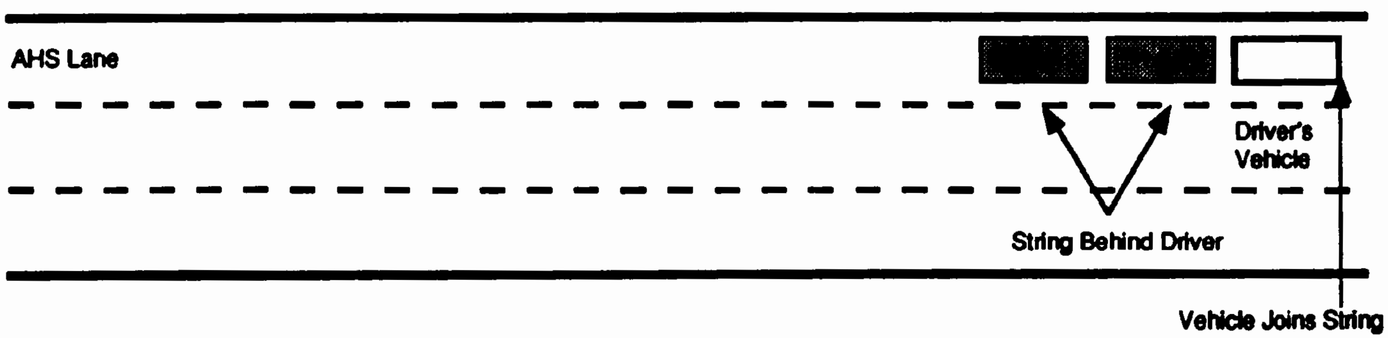


Figure 5. Position of on-coming string of automated vehicles at moment driver's vehicle joins string.

Figure 2 shows the track of the driver's vehicle throughout the five critical moments, two time periods, and four intervals. Figures 3, 4, and 5 illustrate three of the critical moments: figure 3 shows the relationship of the driver's vehicle to the string of automated vehicles that were passing it at the moment that the *Enter* command was issued; figure 4 shows the moment at which the driver's vehicle completed the lane change; and figure 5 shows the moment that the driver's vehicle joined the string as the new lead vehicle.

The two time periods and four intervals that are marked off by these critical moments are as follows:

(1) Entering Time Period—this lasted from the moment that the *Enter* command was issued until the moment that the driver's vehicle completely entered the automated lane. During the entering time period, the simulator vehicle was in the unautomated lane under the control of the driver traveling at approximately 88.6 km/h (55 mi/h)—there was a 16.1-km/h (10-mi/h) velocity differential between the driver's vehicle and the vehicles in the automated lane during this time period. The entering time period consisted of the following two intervals:

(1.1) Entering Response Time Interval occurred between the moment that the *Enter* command was issued and the moment that the driver began to enter the automated lane—i.e., the moment that the first wheel of the driver's vehicle touched the white line between the center and automated lanes.

(1.2) Lane-Change Time Interval occurred between the moment that the driver began to enter the automated lane and the moment that the lane change was completed—i.e., between the moment that the first wheel of the driver's vehicle touched the white line between the center and automated lanes and the moment that the fourth wheel crossed that same line.

(2) Potential Influence Time Period—this occurred between the moment that the driver's vehicle completely entered the automated lane and the moment that it became the lead vehicle of the string of vehicles that was directly following it. During the potential influence time period, the simulator vehicle was in the automated lane—first, during the entering exposure time interval, under the control of the driver; second, during the string-joining time interval, under the control of the AHS—and it was the period of time during

which the driver's vehicle could have influenced the velocity of the following string, producing possible time delays. It consisted of the following two intervals:

(2.1) Entering Exposure Time Interval occurred between the moment that the driver's vehicle entered the automated lane—i.e., the moment that the fourth wheel of the vehicle crossed the white line between the center and automated lanes—and the moment that control of the vehicle was transferred to the AHS. [Note that the entering exposure time was zero for the drivers in the partially automated transfer group.]

(2.2) String-Joining Time Interval occurred between the moment that the AHS took control of the vehicle and the moment that the vehicle became the lead vehicle of the string of vehicles immediately behind it in the automated lane—i.e., the moment that the driver's vehicle achieved the design velocity and the gap between it and the vehicle immediately behind it became 0.0625 s.

As mentioned above, the entering time period started at the moment that the *Enter* command was issued, and the potential influence time period ended at the moment that the driver's vehicle achieved the design velocity. Both of these time periods had to be considered in determining whether the inter-string gaps used in the current experiment were long enough to allow the driver's vehicle to enter the automated lane and join the string behind without causing delays to the automated vehicles behind it—the results of this determination, and the steps involved in making it, are discussed in section 4 of this report (see the subsection on implications for AHS efficiency).

Data Items

The times at which each of the critical moments defined in the previous subsection occurred were recorded. Then, the lengths of time between the critical moments were calculated. These times were the primary measures used in the analysis. The full list of the data items that was recorded or calculated in this experiment is as follows. [Note: the numbered items are the five critical moments identified above.]

- Track of the vehicle relative to the roadway.
- The moment that the driver implicitly requested entry to the AHS (by driving into the center lane).

(1) The moment that the *Enter* command was issued.

(2) The moment that the driver began the lane change from the center to the automated lane [i.e., the moment that the first wheel of the driver's vehicle touched the white line between the center and automated lanes].

- Driver's entering response time [i.e., the length of time between the system issuing the *Enter* command and the driver starting to move into the automated lane].
- Velocity of the driver's vehicle when it left the center lane.
- Distance between the driver's vehicle and the nearest vehicles ahead of and behind it in the automated lane when it began to enter the automated lane.

(3) The moment that the lane change from the center to the automated lane was completed [i.e., the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes].

- Velocity of the driver's vehicle when it entered the automated lane.
- Distance between the driver's vehicle and the nearest vehicles ahead of and behind it in the automated lane when the lane-change maneuver was completed.
- Whether the driver failed to enter the automated lane on the first, second, or third attempt.

(4) The moment that either the driver relinquished control of the vehicle—if the driver transferred control manually—or the system took control of the vehicle—if the partially automated method of transferring control was used.

- Distance between the driver's vehicle and the nearest vehicles ahead of and behind it in the automated lane when transfer of control occurred.

(5) The moment that the driver's vehicle attained the design velocity and became the lead vehicle of the following string of vehicles.

- Whether there were any inappropriate lane incursions [i.e., incomplete lane changes].
- Steering wheel deviations.
- Whether the driver's vehicle collided with any other vehicles.
- Design velocity of the vehicles in the automated lane.

Visual Capabilities Testing

The Titmus Vision Tester was used to administer a series of standard visual tests. As in the previous experiments in the series, none of the drivers taking part in this experiment were found to have any visual problems that were not remedied by the wearing of corrective lenses.[2]

Each driver was also given two newly developed tests—they were tested with a perimeter that explored static and dynamic peripheral sensitivity out to 21° of eccentricity, under binocular viewing conditions. As in the first experiment in the series, an initial comparison of the data from the drivers who took part in this experiment with data from ophthalmalogical patients examined in the University of Iowa Hospitals indicated that the peripheral sensitivities of the drivers were typical of normal subjects drawn from the population of 25 to 34 year olds.(2)

DATA ANALYSIS

Organization

The effects of the three independent variables—the method of transferring control from the driver to the AHS, the design velocity of the vehicles in the automated lane, and the inter-string gap—were assessed. In each case, an analysis of variance (ANOVA) was carried out.

The data analysis in the first five subsections below focuses on variations in the duration of the entering response time interval, the lane-change time interval, the entering exposure time interval, and the string-joining time interval, and variations in the possible time delay produced during the potential influence time period that might be attributable to variations in the method of transferring control, the inter-string gaps, or the design velocity. Then in the sixth subsection, collisions are considered.

Entering Response Time

The first experimental question asked was:

- *Does the Entering Response Time (i.e., the length of time between the moment that the AHS issued the* Enter *command and the moment that the driver started to move the vehicle into the automated lane) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

An ANOVA was conducted on the entering response times of the 24 drivers. As can be seen from the summary for this ANOVA, shown in table 4, there was insufficient evidence to show that the entering response time was affected by variations in the three main effects—the method of transferring control, the size of the inter-string gap, or the design velocity. However, one of the interactions—that between the transfer method and the design velocity—was statistically significant; this interaction is explored in figure 6.

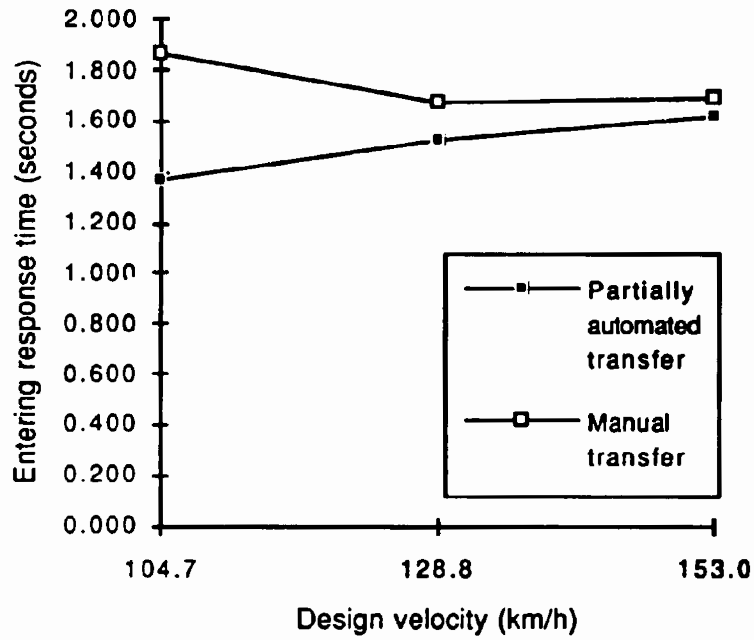


Figure 6. Entering response time as a function of design velocity for the partially automated and manual methods of transferring control.

Table 4. Summary of the ANOVA conducted to determine whether the driver's entering response times were affected by variations in the method of transferring control (T), the size of the inter-string gap (G), or the design velocity (V).[1]

Source	df	SS	MS	F	P
Method of Transfer (T)	1	2.0107	2.0107	2.64	0.1184
Subjects (within T) [S (w/T)]	22	16.7542	0.7616		
Size of Gap (G)	1	0.0201	0.0201	0.10	0.7500
T x G	1	0.2207	0.2207	1.15	0.2962
G x S (w/T)	22	4.2397	0.1927		
Design Velocity (V)	2	0.0993	0.0496	0.34	0.7110
T x V	2	1.2242	0.6121	4.24	0.0207
V x S (w/T)	44	6.3534	0.1444		
G x V	2	0.1330	0.0665	0.21	0.8142
T x G x V	2	0.2919	0.1459	0.45	0.6387
G x V x S (w/T)	41	13.2021	0.3220		

[1] There were three missing data points in these analyses.

Figure 6 plots the entering response time as a function of design velocity for both the partially automated and manual methods of transferring control. The figure shows that the average entering response time was between 1.5 s and 1.7 s when the velocity in the automated lane was set at the two higher design velocities—128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h)—whichever method of transferring control was used. However, when the velocity in the automated lane was set at the lowest of the three design velocities—104.7 km/h (65 mi/h)—the entering response time was significantly faster for the drivers who transferred control of the vehicle to the AHS using the partially automated method (their average response time was 1.37 s) than for the drivers who transferred control manually (their average response time was 1.87 s).

Lane-Change Time

The second experimental question was:

- *Does the **Lane-Changing Time** (i.e., the length of time from the moment that the driver began to drive the vehicle into the automated lane until the moment that the lane-change maneuver was completed) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

The summary of the ANOVA conducted on the lane-change times of the 24 drivers is given in table 5. As the table shows, design velocity was the only variable to affect the lane-change times. Post hoc analysis, using the Tukey Studentized Range Test, showed that the average lane-change

Table 5. Summary of the ANOVA conducted to determine whether the lane-change times were affected by variations in the method of transferring control (T), the size of the inter-string gap (G), or the design velocity (V).[1]

Source	df	SS	MS	F	P
Method of Transfer (T)	1	0.1853	0.1853	0.44	0.5142
Subjects (within T) [S (w/T)]	22	9.2751	0.4216		
Size of Gap (G)	1	0.0111	0.0111	0.08	0.7748
T x G	1	0.1130	0.1130	0.85	0.3654
G x S (w/T)	22	2.9092	0.1322		
Design Velocity (V)	2	0.4970	0.2485	4.17	0.0219
T x V	2	0.0127	0.0064	0.11	0.8988
V x S (w/T)	44	2.6199	0.0595		
G x V	2	0.3502	0.1751	0.96	0.3928
T x G x V	2	0.5363	0.2682	1.46	0.2431
G x V x S (w/T)	41	7.5085	0.1831		

[1] There were three missing data points in these analyses.

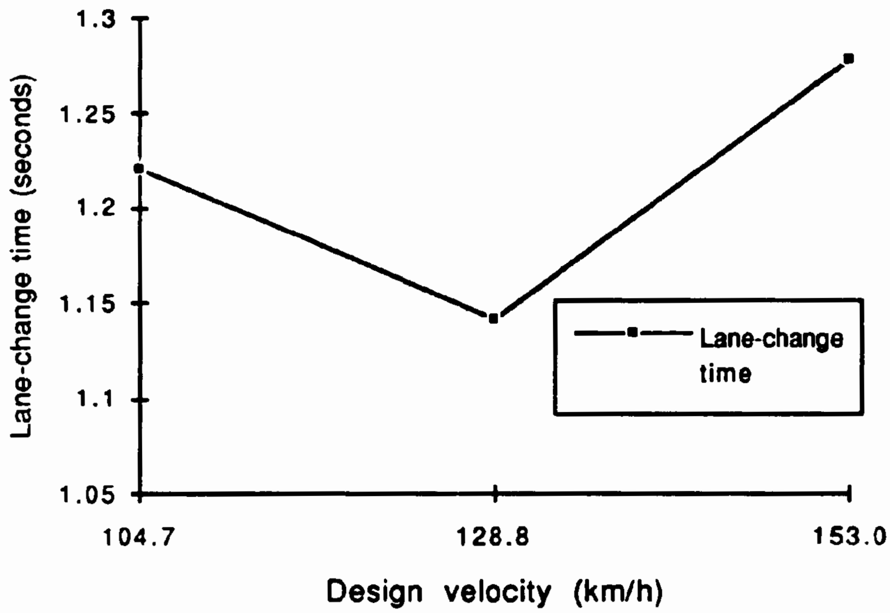


Figure 7. Lane-change time as a function of design velocity.

time for the 104.7-km/h (65-mi/h) condition was not significantly different from the times for the two faster design velocities. The same analysis showed that the average lane-change time for the 128.8-km/h (80-mi/h) design velocity condition—1.14 s—was significantly shorter than that for the 153.0-km/h (95-mi/h) condition—1.28 s. The effect of design velocity on lane-change time is shown in figure 7.

Entering Exposure Time

The third experimental question was:

- *Does the Entering Exposure Time (i.e., the length of time between the moment that the lane-change maneuver was completed and the moment that control was transferred to the system) vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

The ANOVA summary table for entering exposure times is presented in table 6.

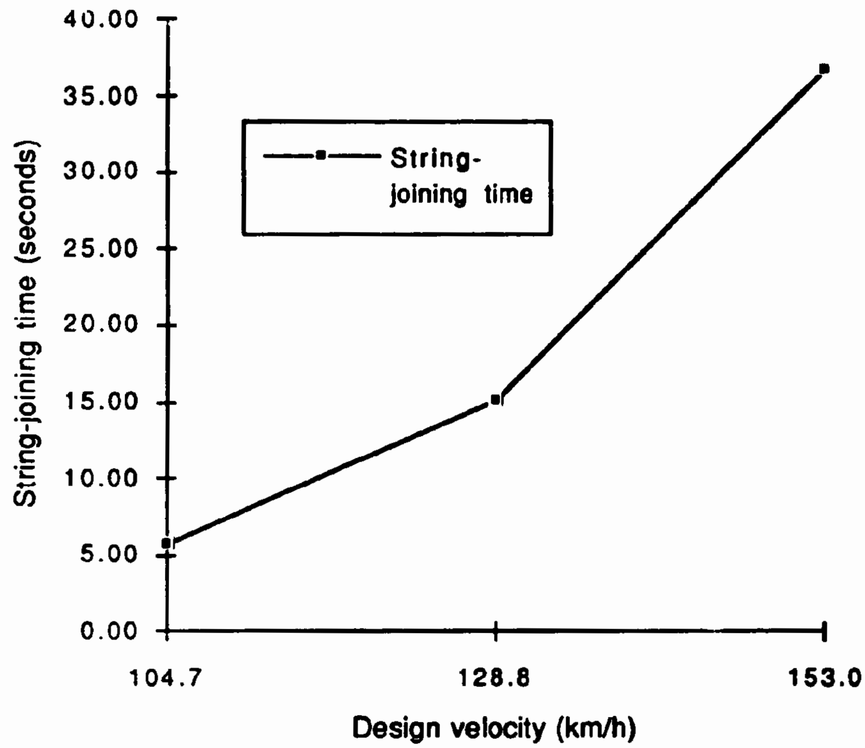


Figure 9. String-joining time as a function of design velocity.

significant effect on the string-joining time. The rapid increase in string-joining time that occurred as the design velocity increased is shown in figure 9. Post hoc analysis indicated that the 5.67-s string-joining time obtained with the 104.7-km/h (65-mi/h) design velocity was significantly smaller than the 14.55-s time obtained with the 128.8-km/h (80-mi/h) design velocity, and that this latter time was, in turn, significantly smaller than the 36.07-s string-joining time obtained with the 153.0-km/h (95-mi/h) design velocity.

Possible Time Delay

The fifth experimental question asked was:

- *Does the Possible Time Delay incurred during the entry maneuver vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-*

string gap, (c) the design velocity, or (d) some combination of two or more of these variables?

Bloomfield et al. introduced the concept of delay time—using it to refer to the time that the string of vehicles immediately behind the driver's vehicle was delayed because of the activities of the driver's vehicle as it left the automated lane.(2) Their concept is similar to the possible time delay concept used for the current experiment, where control was transferred from the driver to the AHS when the driver's vehicle entered the automated lane. Here, the possible time delay is the amount of time that the string of vehicles immediately behind the driver's vehicle could have been delayed because of the activities of the driver's vehicle as it entered the automated lane—i.e., during the time from the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes until the moment that the vehicle became the lead vehicle of the string of vehicles immediately behind it in the automated lane.

The possible time delay, T_p, is given by the following equation:

$$T_p = (d_1 - d_2) / V$$

where:

d_1 — was the distance traveled by the automated vehicles ahead of the driver's vehicle during the time period between the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes and the moment that the driver's vehicle became the new leader of that string of vehicles.

d_2 — was the distance traveled by the driver's vehicle during the time period between the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes and the moment that the driver's vehicle became the new leader of that string of vehicles.

V — was the design velocity.

The possible time delay in each trial was calculated using this formula. Then, an ANOVA was carried out on these time delays. The summary of this ANOVA is presented in table 8. It shows that there were statistically significant differences in the average possible time delay for the design velocity conditions. The table also shows that there was a significant difference in the possible time delay for the two methods of transferring control. Post hoc analysis, again using the Tukey Studentized Range Test, indicated that the possible time delays for all three design velocities were statistically different from each other. The effects of both design velocity and method of transfer are shown graphically in figure 10.

Table 8. Summary of the ANOVA conducted to determine whether the possible time delay was affected by variations in the method of transferring control (T), the size of the inter-string gap (G), or the design velocity (V).[1]

Source	df	SS	MS	F	P
Method of Transfer (T)	1	2.0038	2.0038	6.73	0.0166
Subjects (within T) [S (w/T)]	22	6.5511	0.2978		
Size of Gap	1	0.0502	0.0502	0.57	0.4567
T x G	1	0.0001	0.0001	0.00	0.9808
G x S (w/T)	22	1.9253	0.0875		
Design Velocity (V)	2	716.5778	358.2889	2604.89	0.0001
T x V	2	0.4935	0.2467	1.79	0.1785
V x S (w/T)	43	5.9144	0.1375		
G x V	2	0.3016	0.1508	1.28	0.2898
T x G x V	2	0.2361	0.1181	1.00	0.3768
G x V x S (w/T)	40	4.7213	0.1180		

[1] There were five missing data points in these analyses.

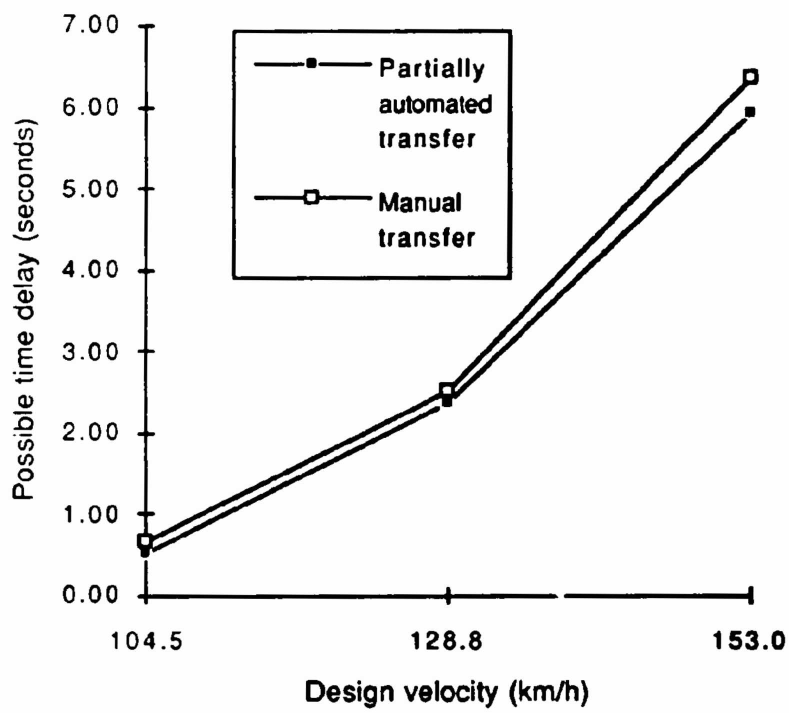


Figure 10. Possible time delay as a function of design velocity for the partially automated and manual methods of transferring control.

The possible time delays were relatively small for the 104.7-km/h (65-mi/h) design velocity condition—0.53 s for the partially automated transfer and 0.66 s for the manual transfer method. There were modest increases in the possible time delay as the design velocity increased to 128.8 km/h (80 mi/h)—2.36 s for the partially automated transfer and 2.52 s for the manual method. Then, there were more substantial increases for the 153.0-km/h (95-mi/h) condition—5.94 s for the partially automated transfer and 6.37 s for the manual method.

[Note: see the subsection on implications for AHS efficiency that appears in section 4 of this report for the determination of whether the inter-string gaps used in the current experiment were long enough to allow the driver's vehicle to enter the automated lane and join the string behind without actually causing delays to the automated vehicles behind it.]

Collisions

The sixth experimental question was:

- *Does the driver's ability to avoid **Collisions** with other vehicles vary as a function of (a) the method by which control was transferred from the driver to the AHS, (b) the inter-string gap, (c) the design velocity, or (d) some combination of two or more of these variables?*

There were no collisions in any of the trials for this experiment.

Questionnaire Data

There were two versions of the questionnaire used in this experiment—one for each transfer condition. The first 24 questions were identical for both versions—then there was one additional question, question #25, added for drivers in the manual transfer condition. A copy of the questionnaire is presented in appendix 2.

After questions 1 through 19, 23, and 25, a 102-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 50 reflects a response that favors the extreme to the left—the closer the score is to 0, the more it favors the extreme position. A score between 52 and 102 reflects a response that favors the extreme to the right—the closer the score is to 102, the more it favors the extreme position. The neutral point was 51.

A series of ANOVA's was conducted to examine whether the responses to questions 1 through 19, 23, and 25 were affected by the age of the driver, the gender of the driver, or the method used to transfer control from the driver to the AHS. 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 ANOVA's 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 9 are collapsed over age, gender, and the method of transfer.

As can be seen from table 9, the average responses of the drivers all fell on the right of the response bar for all six questions. For four of the questions, the responses were strongly to the right—suggesting that the drivers enjoyed driving in the simulator (question 1), found the view

Table 9. Simulator realism.

Question	Overall Mean
1. How much did you enjoy driving the simulator? L. Not at all R. A great deal	90.2
2. How did driving in the simulator compare to driving in your car? L. Very different R. Very similar	59.0
3. How realistic was the view out of the windshield in the simulator? L. Very artificial R. Very realistic	72.8
4. How realistic were the sounds in the simulator? L. Very artificial R. Very realistic	59.7
5. How realistic was the vehicle motion in the simulator? L. Very artificial R. Very realistic	74.1
6. While driving the simulator, did you feel queasy or unwell? L. Felt unwell R. Felt fine	82.5

through the windshield to be realistic (question 3), found the vehicle motion to be realistic (question 5), and did not have any feeling of queasiness (question 6). For the other two questions—comparing driving in the simulator to driving in the driver's own car (question 2), and asking how realistic the sounds in the simulator were (question 4)—though the responses were to the right, they were relatively close to the neutral point.

AHS Message The next two questions dealt with the AHS *Enter* command. The ANOVA's carried out on these two questions failed to show any statistically significant differences in the responses to them. As a result, the average response data presented in table 10 are collapsed over age, gender, and the method of transfer. The table indicates that the drivers found that the *Enter* command was very easy to understand and was given with sufficient time to enable them to respond.

Table 10. AHS message.

Question	Overall Mean
7. Was the message giving you the command to enter the automated lane easy to understand? L. Hard to understand R. Easy to understand	97.1
8. Did you have enough time to react to the message telling you to enter the automated lane? L. Insufficient time R. Sufficient time	91.3

Safety and Control Questions 9, 10, and 11 dealt with safety and control, and the ANOVA's carried out on these questions also failed to show any statistically significant differences in the responses to them. Once again, the average response data presented in table 11 are collapsed over age, gender, and the method of transfer. The mean responses of the drivers for all three questions indicate that they felt safe in the automated lane, they had control of the vehicle as they changed lanes, and they felt that they were in control of the situation.

Table 11. Safety and control.

Question	Overall Mean
9. How safe did you feel when you drove into the automated lane? L. Very unsafe R. Very safe	84.4
10. Did you control your car poorly or well as you changed lanes from manual to the automated lane? L. Very poorly (controlled) R. Very well (controlled)	84.7
11. To what extent did you feel in control of the situation when you drove into the automated lane and transferred control of your vehicle to the Automated Highway System? L. Not at all R. To a great extent	74.9

Inter-String Gap and Design Velocity The next two questions that deal with AHS velocity and inter-string gaps were analyzed with ANOVA's. No statistically significant differences in the responses to these questions were found—consequently, the average response data presented in table 12 are collapsed over age, gender, and the method of transfer. For question 12, concerning the gap between the driver's vehicle and the vehicles ahead, the responses were to the left—indicating that the drivers would have preferred longer gaps. For question 13, the responses were to the right—indicating that they would have preferred the velocity in the automated lane to have been faster.

Table 12. Inter-string gap and design velocity.

Question	Overall Mean
12. When your car was under automatic control, the distance between you and the car in front and behind was varied from trial to trial—which separation distance did you prefer? L. Prefened longer distance R. Preferred shorter distance	36.1
13. When your car was under automatic control, were you comfortable with the speed, or would you have preferred to have traveled faster or slower? L. Would prefer much slower R. Would prefer much faster	68.5

Attitude Toward the AHS The next set of six questions dealt with attitudes towards the AHS. There were no statistically significant differences for five of the questions and, as a result, the mean responses to these questions are presented in table 13 (a)—these responses show that the drivers who took part in this experiment preferred the automated to the manual lanes (question 14), thought that the manual lanes were more challenging (question 15), were in favor of the AHS being installed on the local interstate freeway (question 16), thought that the AHS would be somewhat safer than the current freeways (question 18), and thought that the AHS would reduce stress (question 19).

The responses to the sixth question (question 17), where a significant interaction between gender and the method of transferring control was found, are shown in table 13 (b)—they are arranged in a two-by-two contingency table. All these drivers indicated that they preferred the automated lanes: but much stronger preferences were expressed by the males who experienced the partially automated transfer method than the males who manually transferred control (90.3 vs. 67.5); while this result was reversed with the female drivers—with much stronger preferences being expressed by the females who manually transferred control than the females who experienced the partially automated transfer method (91.3 vs. 66.7).

Table 13 (a). Attitude toward the AHS (questions 14, 15, 16, 18, and 19).

Question	Overall Mean
14. You spent some time in the manual lanes and some time in the automated lane—which did you prefer? L. Strongly preferred manual R. Strongly preferred automatic	74.2
15. Was it more challenging to be in the automated lane or the manual lanes? L. More challenging in manual lanes R. More challenging in automated lanes	13.7
16. How would you feel if an Automated Highway System was installed on I-380 between Iowa City and Waterloo? L. Very unenthusiastic R. Very enthusiastic	82.3
18. If an Automated Highway System was installed, would you feel safer driving on I-380 than you do now without the System? L. Much safer with current freeways R. Much safer with Automated Highway System	64.7
19. How will the installation of an Automated Highway System affect the stress of driving? L. Will greatly decrease stress R. Will greatly increase stress	30.1

Table 13 (b). Attitude toward the AHS (question 17).

Question 17. If an Automated Highway System was installed on I-380, would you prefer driving in the automated lanes or in the manual lanes? L. Strongly prefer manual lanes R. Strongly prefer automated lanes	Male	Female
Partially Automated Transfer	90.3	66.7
Manual Transfer	67.5	91.3

<u>Cruise Control</u> Questions 23 and 25 dealt with cruise control. No statistically significant differences were found when ANOVA's were used to analyze the responses to them. The mean responses to question 23 are presented in table 14—the drivers indicated that they used cruise control quite often. As question 25 was not presented to the drivers in the partially automated group, table 14 gives the mean response to this question of only the drivers in the manual transfer group—these drivers thought that the way that the cruise control button was used to transfer control to the AHS was similar to the way they normally used it.

Table 14. Cruise control.

Question	Overall Mean
23. How often do you use the cruise control on your vehicle? L. Hardly ever R. Very often	74.4
	Manual Transfer
25. How does using the cruise control button to transfer control to the Automated Highway System compare with the way in which you normally use cruise control in your own vehicle? L. Very different R. Very similar	75.1

SECTION 4: DISCUSSION

EXPLANATIONS

The objective of this experiment was to determine the conditions under which a driver in the unautomated lane could safely enter the automated lane and transfer control of the vehicle to the automated system, with a minimum of interference to the flow of traffic in the automated lane.

Each experimental trial began with the simulator vehicle positioned on a freeway entry ramp. When the trial started, the driver drove onto the freeway and moved into the center lane. After the driver had been in the center lane traveling at 88.6 km/h (55 mi/h) for approximately 15 s, the automated system issued an *Enter* command—it was timed so that the driver would hear the command to enter just as the back bumper of the last vehicle in an automated string cleared the front bumper of the driver's vehicle. Then the driver had to drive into the automated lane. Once there, the control of the vehicle was transferred to the AHS, either manually or in a partially automated manner. When the system had control, it began to accelerate the driver's vehicle until it reached the same speed as the other vehicles in the automated lane, at which time the vehicle had become the lead vehicle of the next string.

The method of transferring control, the velocity of the vehicles in the automated lane (the design velocity), and the gap between the strings of vehicles in the automated lane (the inter-string gap) were varied from trial to trial. A group of 24 younger drivers (aged between 25 and 34) took part in the experiment. The data obtained were analyzed to determine whether the method of transferring control, the design velocity, or the inter-string gap had affected driving performance. The particular driving performance measures that were examined in these analyses were: the entering response time, the lane-change time, the entering exposure time, the string-joining time, and the delay time.

Entering Response Time

The entering response time was the time between the moment that the *Enter* command was issued and the moment that the driver began to enter the automated lane. The command to enter was issued at the moment that the back bumper of the last vehicle in an automated string, traveling in the automated lane, cleared the front of the driver's vehicle. The driver was instructed to drive into the automated lane quickly on hearing the command.

cult to explain why this difference occurred—and it should be pointed out that the difference was so small that it is unlikely to be of any importance operationally.

Entering Exposure Time

The entering exposure time was the time between the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes and the moment that control of the vehicle was transferred to the AHS.

When control was transferred to the AHS using the partially automated method, the transfer occurred as soon as the driver's vehicle entered the automated lane—therefore, the entering exposure time was zero for the drivers using this method and, inevitably, was smaller than the 1.16-s mean exposure time obtained with the drivers in the manual transfer group. The reduction in exposure time that was achieved by using the partially automated transfer condition is likely to be of practical importance—the sooner the vehicle is under the control of the AHS, the greater the portion of the inter-string gap that can be used to accelerate to the design velocity, and the smaller the delay time, the more efficient the AHS will be.

String-Joining Time

The string-joining time was the time between the moment that the AHS took control of the vehicle and the moment that the vehicle became the lead vehicle of the string of vehicles immediately behind it in the automated lane.

In every trial, the driver's vehicle entered the automated lane at approximately 88.6 km/h (55 mi/h), then accelerated to the design velocity—inevitably, the string-joining time increased as the design velocity increased. The increase was from 5.67 s to 14.55 s to 36.07 s as the design velocity increased from 104.7 km/h (65 mi/h) through 128.8 km/h (80 mi/h) to 153.0 km/h (95 mi/h).

Possible Time Delay

The possible time delay was the amount of time that the string of vehicles immediately behind the driver's vehicle could have been delayed because of the activities of the driver's vehicle as it entered the automated lane—i.e., during the time from the moment that the fourth wheel of the driver's vehicle crossed the white line between the center and automated lanes until the moment that the vehicle became the lead vehicle of the string of vehicles immediately behind it in the automated lane. The analysis of the possible time delay data showed that statistically significant differences were obtained when the method of transferring control was varied and when the design velocity conditions were varied. Both of these effects were to be expected: the possible time delays were incurred during the entering exposure time—which was significantly affected by the method of transferring control—and during the string-joining time—which was affected by the design velocity.

SAFETY IMPLICATIONS

Collision Data

In the first 2 experiments in this series, there were 3 collisions, and all occurred in the 120 trials when the design velocity in the automated lane was 153.0 km/h (95 mi/h).[2] In contrast, there were no collisions in any of the 144 trials in the current experiment.

Questionnaire Data

Additional information on safety was obtained from the responses of the drivers to the questionnaire—three of the questions in the questionnaire related to the driver's impressions and perceptions of the safety of the entry maneuver.

The responses to these questions suggested that all of the drivers, no matter which transfer of control group they were in, felt safe when they drove into the automated lane (question #9), that they controlled the vehicle well as they changed lanes from the manual lane to the automated lane (question #10), and that they felt that they were in control when they transferred control of the vehicle to the AHS (question #11).

These subjective responses on safety support the objective data on safety—in this experiment, the AHS operations appear to have been safe.

IMPLICATIONS FOR AHS EFFICIENCY

Whenever a vehicle enters the automated lane to join the AHS, the timing of the entry maneuver will be of critical importance. If it enters rapidly, a vehicle will have a minimal effect on the string of vehicles immediately behind it—the time delay introduced by the entering vehicle will be held to a minimum, and the negative impact on the efficiency of the system will be minimized.

Design Velocity

The generic AHS configuration used in this experiment is representative of several possible AHS configurations that allow vehicles to enter the automated lane with a velocity that is slower than the preferred design velocity.

In an AHS configuration that utilized multiple automated lanes, if the design velocity increased from lane to lane—with the lowest design velocity in the lane closest to the unautomated lane and the highest in the automated lane furthest from the unautomated lane—it would be relatively easy for a vehicle entering the AHS to get into a high-velocity automated lane without causing delays for the vehicles behind it. It is conceivable that multiple automated lanes might be built in some cities, particularly those that already have existing extensive multiple-lane freeways—e.g., Atlanta, Georgia; Chicago, Illinois; Los Angeles and San Francisco, California; Seattle, Washington; and Washington, D.C. However, it is likely that the cost of expanding existing freeways in high-land-use areas will prohibit the building of an AHS with multiple automated lanes in the many U.S. cities that currently have freeways with only two or three lanes in each direction. Furthermore, with regard to interstate highways—most of which are only two lanes in each direction—if there is sufficient funding to develop multiple lanes all over the U.S. freeway system, there will be little need to create an AHS, as in the majority of locations, the simple addition of two or three lanes would be enough to reduce congestion.

In AHS configurations with only one automated lane—like the configuration used in this experiment as well as in the previous experiments in this series—it will be desirable to have a vehicle enter the automated lane while the automated vehicles continue to move at the design velocity, with only minor adjustments. To do this without delaying the automated vehicles that will be behind the entering vehicle, there must be a large enough gap between the strings of vehicles in the automated lane to allow a vehicle to enter the lane at a velocity of 88.6 km/h (55 mi/h) or 104.7 km/h (65 mi/h)—if that is the speed limit—and then accelerate to the design velocity.

The possible time delays obtained in this experiment were influenced by both the design velocity and the method by which control was transferred to the AHS. Since the partially automated transfer method was more efficient than the manual method at all three design velocities, the possible time delays associated with the partially automated method were used in determining the answer to the seventh experimental question, which was:

- *Does the entry maneuver cause the string of vehicles immediately behind the driver's vehicle to slow down, and, if so, what is the potential effect on AHS efficiency?*

To determine whether the inter-string gaps used in the current experiment were long enough to allow the driver's vehicle to enter the automated lane and join the string behind without causing delays, it was necessary to consider the differences between the design velocity in the automated lane and the velocity of the driver's vehicle during both the entering time period and the potential influence time period. The steps involved in this determination were:

(1) Determine the length of the entering response time interval—from the data for the partially automated transfer method used for figure 6.

(2) Determine the length of the lane-change time interval—from the data for the partially automated transfer method used for figure 7.

(3) Add (1) and (2) to obtain the length of the entering time period.

(4) Determine the difference in the distance traveled during the entering time period by the simulator vehicle and the automated vehicle ahead of it by multiplying the length of the entering time period in (3) by the differential between the velocity of the driver's vehicle during the entering time period and the design velocity. [Note: for this calculation, it was assumed that the entering vehicle would be traveling at 88.6 km/h (55 mi/h) during the entering time—in fact, in this experiment, if the driver drove the simulator vehicle at any velocity between 80.64 km/h (50.09 mi/h) and 96.48 km/h (59.93 mi/h), it was allowed into the automated lane.]

(5) Determine the possible time delay—from the data for the partially automated transfer method used for figure 10.

(6) Calculate the possible delay distance by multiplying the possible delay time in (5) by the design velocity.

(7) Assume the average length of a vehicle is 4.42 m (14.5 ft).

(8) Express the intra-string gap of 0.0625 s as a distance for each design velocity.

(9) Determine the minimum inter-string distance by adding (4), (6), (7), and (8).

(10) Divide the minimum inter-string distance found in (9) by the design velocity to obtain the minimum inter-string time required for the driver's vehicle to join the string without causing a delay for the string of vehicles it joins.

(11) Compare the required minimum inter-string time found in (10) to the inter-string gaps used in the experiment.

used the partially automated transfer method, there was an elapsed time of approximately 2.6 s (1.4 s of response time plus 1.2 s of lane-change time) from the moment that the *Enter* command was issued until control of the vehicle was transferred to the AHS; while for the drivers using the manual transfer method, the elapsed time was 4.3 s (1.9 s of response time, plus 1.2 s of lane-change time, plus 1.2 s of exposure time).

These times could be greatly reduced if control of the driver's vehicle were to be transferred to the AHS before the opportunity to move into the automated lane occurred—the delay time would be minimized. This expectation has already been tested in the experiment that followed the current experiment in the series. In this recently completed experiment, entering the AHS was explored further—the results of this test will be reported when data analysis for this experiment is completed.

APPENDIX 1: EXPERIMENTAL PROTOCOLS

Two protocols were used for this experiment. They are presented here.

PROTOCOL FOR GROUP 1 (PARTIALLY AUTOMATED TRANSFER)

[Group 1 consists of the following subjects: M1, F1, M2, F2, M5, F5, M6, F6, M9, F9, M10, and F10.]

[Introduction]

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

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

[*E* turns on tape containing Background Information.]

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

Narrator (on tape): Thank you for coming here today. You will be here for about 2 hours. First, I will give you some introductory information about the study in which you are about to take part. Then, your research host will take you to the driving simulator, where the main part of the study will take place. In the simulator, you will drive the simulator vehicle several times. After you have driven in the simulator, your research host will bring you back to this room, and ask you to fill out a questionnaire. Then, your eyesight will be tested.

N: The study in which you are participating is part of an on-going investigation of Automated Highway Systems. We are conducting the investigation for the FHWA (the Federal Highway Administration). The FHWA is responsible for safety and travel effectiveness on our highways. In this investigation, the FHWA is trying to determine how to design an Automated Highway System in order to reduce congestion and to increase highway safety. We are conducting a series of studies using the Iowa Driving Simulator. We will explore how an Automated Highway System might work, and how well drivers would handle their vehicles in such a system. The data provided by you, and others, will aid us in making accurate and responsible recommendations

[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.

[At this point, *E* will take the *D-S* to the simulator bay, stopping at the bathroom on the way, if necessary.]

[Entering the Simulator]

[Seat *D-S* in car.]

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. If there is 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. First, you will drive in a rural setting on a regular two-lane road. The next time you drive, you will be on a segment of freeway. These two drives will allow you to become familiar with simulator driving.

E: Do you have any questions?

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

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

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

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

E: How are you doing?

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

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

[*D-S* drives simulator on freeway in Familiarization Drive #2.]

[During the drive...]
—*E:* Please would you move into the center lane when it is safe to do so.

[Also, during the drive...]
—*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?

<u>[Instructions for Experimental Trials]</u>

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

Narrator (on tape): From now on, you will drive on a three-lane freeway—a three-lane freeway on which the Automated Highway System has been installed. On this freeway, the left-most lane is reserved for automated traffic only. All the vehicles in this lane are under the control of the

Automated System. They have been arranged in strings—there may be one, two, three, or four vehicles traveling together in each string. The traffic in the automated lane will be traveling faster than the vehicles in the other two lanes, which are not automated.

N: At the start of each drive, your vehicle will be on the entry ramp of the freeway. Your task is to join one of these automated strings of vehicles. Don't worry, the system will help you to do this.

N: You will start by driving from the entry ramp into the right lane of the freeway. While you are in the right and center lanes, you will drive among vehicles that are not under automated control—they will behave in the way that traffic usually behaves on a freeway. The speed limit in these two lanes will be 55 miles an hour.

N: Your next task will be to move from the right lane to the center lane, when it is safe to do this. When you get to the center lane, please drive at 55 miles an hour and keep in the lane. The system will check your vehicle to determine whether it has the special equipment needed to drive in the automated lane. It will also determine which string of vehicles you should join.

N: While this is going on, you should continue to drive in the center lane at 55 miles an hour. When the system has decided it is appropriate for you to move into the automated left lane, you will hear a tone. After the tone, you will hear my voice informing you that you should enter the automated lane. This is what you will hear:

> [Tone and voice inserted here.
> "After the countdown, enter the automated lane.
> Four...Three...Two...One...*Enter.*"]

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

N: While you are listening to this message, you should maintain a speed of 55 miles an hour. If you go too fast or too slowly, your vehicle will not be able to enter the automated lane safely, and you will hear the following warning:

> [Voice inserted here.
> *"Don't enter! Don't enter! Don't enter!"]*

N: Remember, as soon as you hear the *Enter* command, you drive into the automated lane. If you take too long to move into it, after I give you the *Enter* command, you will not be able to enter safely, and you will hear the same *Don't enter!* warning.

N: If your first attempt to enter the automated lane is unsuccessful, you must wait until you hear the *Enter* message again. You will be allowed three attempts to get into the automated lane in each drive.

N: When you successfully enter the automated lane, the system will take control of your vehicle automatically. It will take control at the moment that your vehicle completely crosses the lane marker. By moving into the automated lane as soon as you hear the *Enter* command and transferring control quickly, you will give the system as much time as possible to take control of your vehicle before the next string of vehicles comes along. When the system has taken control of your vehicle, you will hear a second tone. This will also be followed by a message—informing you that the system has taken control. This is what you will hear:

[Tone and voice inserted here.
"Your vehicle is now under the control of the automated system."]

N: Then, the system will automatically control your speed and the speed of the string behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

N: Once you become the lead vehicle of the string, the distance between your car and the last vehicle of the string ahead will stay constant. The much shorter distance between your car and the car behind, will also stay 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 would stay a constant distance behind. In the same way, the vehicle behind you will slow down automatically, and remain at a constant distance behind you. The system will control your vehicle until the end of the drive.

N: I will repeat what you should do to enter the automated lane. While you are listening to the countdown, a string of vehicles will pass you. You must wait until you hear the *Enter* command, but then, as soon as you do hear the word *Enter* you should drive into the automated lane. The system will take control automatically as soon as your vehicle has completely crossed the lane marker. Then you will hear a second tone, followed by a message informing you that the system has taken control. It will control your speed and the speed of the string of vehicles behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

N: If you have any questions, please ask your research host. Remember, this is a test of the Automated Highway System, not a test of you, the driver.

[Tape ends]

E: Do you have any questions about the study? Or about what you have to do? [Be prepared to repeat any part of the instructions for entering the automated lane.]

[*E* answers *D-S's* questions.]

[Experimental Trials]

E to Simulator Operator: Please start the first drive.

[When visuals appear....]
—*E to D-S:* We are about to start the first drive. You are on an entry ramp. When you start the vehicle, you have to drive into the right lane, then move to the center lane as soon as you can. In the center lane, you should drive as close to 55 miles an hour as you can, while you wait for the *Enter* command.

E: Do you have any questions?
[If "Yes," *E* answers questions. Then...]
—*E:* You can start the drive now.

[*D-S* drives simulator in Experimental Drive #1.]

E: How are you doing? Please talk about your experience of getting into the automated lane. Do you have any comments or questions?

E to Simulator Operator: Please start the second drive.

[*D-S* drives simulator in Experimental Drive #2.]

E: How are you doing? How did that compare to the drive before? Do you have any comments or questions?

E to Simulator Operator: Please start the third drive.

[*D-S* drives simulator in Experimental Drive #3.]

E: How are you doing? How did that compare to the drives before? Do you have any comments or questions?

E to Simulator Operator: Please start the fourth drive.

[*D-S* drives simulator in Experimental Drive #4.]

E: How are you doing? How did that compare to the drives before? Do you have any comments or questions?

E to Simulator Operator: Please start the fifth drive.

[*D-S* drives simulator in Experimental Drive #5.]

E: How are you doing? How did that compare to the drives before? Do you have any comments or questions?

E to Simulator Operator: Please start the sixth drive.

[*D-S* drives simulator in Experimental Drive #6.]

E: How are you doing? How did that compare to the drives before? That was the last drive. 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* hands the questionnaire to the *D-S* and remains in the room while it is completed. When it is completed....]:

(a) *E* looks at the response to question #7—if the response is less than three-quarters of the way towards the "easy to understand" marker, *E* asks the *D-S* , "Did you have problems with the content or the clarity of the message?"

(b) *E* looks at the response to question #8—if the response is less than three-quarters of the way towards the "sufficient" marker, *E* asks the *D-S*, "How much more warning would you like?"

(c) *E* looks at response to question #23—if the response is positive (i.e., if the subject says that he/she has had an accident involving a moving vehicle, *E* asks for details—how many accidents, when did it (they) occur, under what circumstances, what happened?)

E: How well did the instructions prepare you for carrying out the study?

[Record answer.]

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

[Vision Testing—Titmus Vision Tester]

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 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.

[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.

[*E* operates computer to present the test stimuli to the driver.]

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: 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.

[*E* allows the driver 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 driver is unable to see the granularity of the screen, he/she will be examined by Dr. Wall in the Ophthalmology Department.]

[*E:* reviews the procedure with the driver.]

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 that the subject is holding the light pen perpendicular to the screen and that 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 test is complete]

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

[*E:* prepares stimuli for the motion test.]

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

[*E* checks that the subject is holding the light pen perpendicular to the screen and that 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.

[Test ends.]

[Payment]

E: Would you be interested in participating in another study investigating Automated Highway Systems?
[*E* records answer.]

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

PROTOCOL FOR GROUP 2 (MANUAL TRANSFER)

[Group 2 consists of the following subjects: M3, F3, M4, F4, M7, F7, M8, F8, M11, F11, M12, and F12.]

[Introduction]

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

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

[*E* turns on tape containing Background Information.]

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

Narrator (on tape): Thank you for coming here today. You will be here for about 2 hours. First, I will give you some introductory information about the study in which you are about to take part. Then, your research host will take you to the driving simulator, where the main part of the study will take place. In the simulator, you will drive the simulator vehicle several times. After you have driven in the simulator, your research host will bring you back to this room, and ask you to fill out a questionnaire. Then, your eyesight will be tested.

N: The study in which you are participating is part of an on-going investigation of Automated Highway Systems. We are conducting the investigation for the FHWA (the Federal Highway Administration). The FHWA is responsible for safety and travel effectiveness on our highways. In this investigation, the FHWA is trying to determine how to design an Automated Highway System in order to reduce congestion and to increase highway safety. We are conducting a series of studies using the Iowa Driving Simulator. We will explore how an Automated Highway System might work, and how well drivers would handle their vehicles in such a system. The data provided by you, and others, will aid us in making accurate and responsible recommendations about how the Automated Highway System should be designed and operated. 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 today 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 will enter the freeway as you do now—first moving into the right lane and then to the center 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 will be instructed to enter that lane, and to transfer control of your vehicle to the system. Then, the Automated Highway System will move you rapidly along in the automated lane, steering your car and controlling its speed automatically.

N: To get the feel of driving in the simulator, today you will start by driving the simulator vehicle on a rural road and a regular freeway. After that, you will drive the simulator vehicle on the Automated Highway System several times. Each time you drive on the automated system, you will start on the entry ramp of a freeway, drive into the right lane, and move into the center lane. You will continue to drive in the center lane while the system determines when it will be appropriate for you to enter the automated lane. When the system has completed this determination, and it is appropriate for you to enter the automated lane, you will hear a message containing an *Enter* command. On hearing the command, you will drive into the automated lane and transfer control of your vehicle to the system. Once the system has control of your vehicle, it will adjust your speed, and the speed of the other automated vehicles, until you become the lead vehicle of a string of vehicles in the automated lane.

N: You will receive more details about how to drive into the automated system when you are in the simulator vehicle. If you have any questions, please feel free to ask your research host about them. Thank you again for coming today. We hope that you enjoy driving in the simulator.

[Tape ends]

E: Do you have any questions?

<u>[Signing of the Consent Forms]</u>

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.

[At this point, *E* will take the *D-S* to the simulator bay, stopping at the bathroom on the way, if necessary.]

[Entering the Simulator]

[Seat *D-S* in car.]

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. If there is 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. First, you will drive in a rural setting on a regular two-lane road. The next time you drive, you will be on a segment of freeway. These two drives will allow you to become familiar with simulator driving.

E: Do you have any questions?

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

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

[Towards the end of the drive...]

—*E:* As y approach the barn, the simulator operator will stop the vehicle—you should not slow down.

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

E: How are you doing?

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

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

[*D-S* drives simulator on freeway in Familiarization Drive #2.]

[During the drive...]
—*E:* Please would you move into the center lane when it is safe to do so.

[Also, during the drive...]
—*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?

[Instructions for Experimental Trials]

E: Please listen carefully to the instructions on this tape.

[*E* turns on tape containing Instructions.]

Narrator (on tape): From now on, you will drive on a three-lane freeway—a three-lane freeway on which the Automated Highway System has been installed. On this freeway, the left-most lane is reserved for automated traffic only. All the vehicles in this lane are under the control of the automated system. They have been arranged in strings—there may be one, two, three, or four vehicles traveling together in each string. The traffic in the automated lane will be traveling faster than the vehicles in the other two lanes, which are not automated.

N: At the start of each drive, your vehicle will be on the entry ramp of the freeway. Your task is to join one of these automated strings of vehicles. Don't worry, the system will help you to do this.

N: You will start by driving from the entry ramp into the right lane of the freeway. While you are in the right and center lanes, you will drive among vehicles that are not under automated control—they will behave in the way that traffic usually behaves on a freeway. The speed limit in these two lanes will be 55 miles an hour.

N: Your next task will be to move from the right lane to the center lane, when it is safe to do this. When you get to the center lane, please drive at 55 miles an hour and keep in the lane. The system will check your vehicle to determine whether it has the special equipment needed to drive in the automated lane. It will also determine which string of vehicles you should join.

N: While this is going on, you should continue to drive in the center lane at 55 miles an hour. When the system has decided it is appropriate for you to move into the automated left lane, you will hear a tone. After the tone, you will hear my voice informing you that you should enter the automated lane. This is what you will hear:

> [Tone and voice inserted here.
> "After the countdown, enter the automated lane.
> Four...Three...Two...One...*Enter*."]

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

N: While you are listening to this message, you should maintain a speed of 55 miles an hour. If you go too fast or too slowly, your vehicle will not be able to enter the automated lane safely, and you will hear the following warning:

> [Voice inserted here.
> *"Don't enter! Don't enter! Don't enter!"*]

N: Remember, as soon as you hear the *Enter* command, you drive into the automated lane. If you take too long to move into it, after I give you the *Enter* command, you will not be able to enter safely, and you will hear the same *Don't enter!* warning.

N: If your first attempt to enter the automated lane is unsuccessful, you must wait until you hear the *Enter* message again. You will be allowed three attempts to get into the automated lane in each drive. When you successfully enter the automated lane, and your vehicle has completely crossed the lane marker, you should press the *On* button of the cruise control to transfer control to the system, as soon as possible. The *On* button of the cruise control is located to the left of the center panel of the steering wheel. [E points out the position of the cruise control and the position of the *On* button to the D-S.] By moving into the automated lane as soon as you hear the *Enter* command and transferring control quickly, you will give the system as much time as possible, to take control of your vehicle, before the next string of vehicles comes along. When the system has taken control of your vehicle, you will hear a second tone. This will also be followed by a message—informing you that the system has taken control. This is what you will hear:

> [Tone and voice inserted here.
> "Your vehicle is now under the control of the automated system."]

N: Then, the system will automatically control your speed and the speed of the string behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

N: Once you become the lead vehicle of the string, the distance between your car and the last vehicle of the string ahead will stay constant. The much shorter distance between your car and the car behind, will also stay 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 would stay a constant distance behind. In the same way, the vehicle behind you will slow down automatically, and remain at a constant distance behind you. The system will control your vehicle until the end of the drive.

N: I will repeat what you should do to enter the automated lane. While you are listening to the countdown, a string of vehicles will pass you. You must wait until you hear the *Enter* command, but then, as soon as you do hear the word *Enter* you should drive into the automated lane. As soon as your vehicle has completely crossed the lane marker, you press the *On* button of the cruise control to transfer control to the system. Then you will hear a second tone, followed by a message informing you that the system has taken control. It will control your speed and the speed of the string of vehicles behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

N: If you have any questions, please ask you research host. Remember, this is a test of the Automated Highway System, not a test of you, the driver.

[Tape ends]

E: Do you have any questions about the study? Or about what you have to do? [Be prepared to repeat any part of the instructions for entering the automated lane.]

[*E* answers *D-S's* questions.]

[*E* again points out the position of the cruise control and the position of the *On* button.]

E: This is the cruise control. Please note the position of the *On* button.

[Experimental Trials]

E to Simulator Operator: Please start the first drive.

[When visuals appear...]

E to D-S: We are about to start the first drive. You are on an entry ramp. When you start the vehicle, you have to drive into the right lane, then move to the center lane as soon as you can. In the center lane, you should drive as close to 55 miles an hour as you can, while you wait for the *Enter* command.

E: Do you have any questions?
[If "Yes," *E* answers questions.]

Then:
—*E:* Don't forget, when you get into the automated lane, you should press the *On* button immediately—to transfer control to the automated system.

E: You can start the drive now.

[*D-S* drives simulator in Experimental Drive #1.]

E: How are you doing? Please talk about your experience of getting into the automated lane. Do you have any comments or questions?

E to Simulator Operator: Please start the second drive.

[*D-S* drives simulator in Experimental Drive #2.]

E: How are you doing? How did that compare to the drive before? Do you have any comments or questions?

E to Simulator Operator: Please start the third drive.

[*D-S* drives simulator in Experimental Drive #3.]

E: How are you doing? How did that compare to the drives before? Do you have any comments or questions?

E to Simulator Operator: Please start the fourth drive.

[*D-S* drives simulator in Experimental Drive #4.]

E: How are you doing? How did that compare to the drives before? Do you have any comments or questions?

E to Simulator Operator: Please start the fifth drive.

[*D-S* drives simulator in Experimental Drive #5.]

E: How are you doing? How did that compare to the drives before? Do you have any comments or questions?

E to Simulator Operator: Please start the sixth drive.

[*D-S* drives simulator in Experimental Drive #6.]

E: How are you doing? How did that compare to the drives before? That was the last drive. Do you have any comments or questions?

The remainder of the protocol for Group 2 consisted of the following:

- Debriefing.
- Vision Testing with the Titmus Vision Tester.
- Vision Testing with the Spatial Localization Perimeter.
- Payment.

Since the procedures and instructions for these sections were identical to those used for Group 1, they are not repeated here.

APPENDIX 2: QUESTIONNAIRE

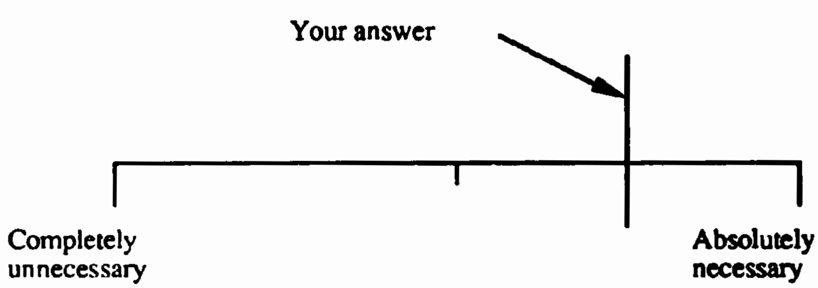
[Note: there were two versions of the questionnaires used in this experiment—one for each transfer condition. The first 24 questions were identical for both versions—then there was one additional question, question #25, added for drivers in the manual transfer condition.]

Questionnaire

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:



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1. How much did you enjoy driving the simulator?

Not at all — A great deal

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

Very different — Very similar

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

Very artificial — Very realistic

4. How realistic were the sounds in the simulator?

Very artificial — Very realistic

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

Very artificial — Very realistic

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

Felt unwell — Felt fine

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

Hard to understand — Easy to understand

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

Insufficient time — Sufficient time

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

Very unsafe — Very safe

10. Did you control your car poorly or well as you changed lanes from the manual lane to the automated lane?

Very poorly (controlled) — Very well (controlled)

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

Not at all — To a great extent

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

Strongly preferred longer distance — Strongly preferred shorter distance

13. 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

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

Strongly preferred manual lanes — 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

24. Have you had any accidents involving moving vehicles?

(a) Yes

(b) No

[And, for drivers in the manual transfer group only]

25. How does using the cruise control button to transfer control to the Automated Highway System compare with the way in which you normally use cruise control in your own vehicle?

Very different — Very similar

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