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IN-VEHICLE NAVIGATION DEVICES: EFFECTS ON SAFETY AND DRIVER PERFORMANCE

FINAL TECHNICAL REPORT

MAY 1990

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

Office of Safety and Traffic Operations Research and Development

Washington, D.C. 20590

FOREWORD

This study was conducted at the Turner-Fairbank Highway Research Center, McLean, Virginia utilizing the Federal Highway Administration's Highway Driving Simulator. Seven generic in-vehicle navigation devices were tested to determine their effects on the safety of drivers' performance. The performance of younger, middle-aged and older drivers was analyzed.

Study findings indicate that, of the devices tested, (1) audio devices were somewhat safer to use than visual devices (2) moderate display complexity was generally preferable to higher display complexity, and (3) higher levels of complexity affected performance of older drivers to a greater extent than younger or middle aged drivers.

The results of this study will be of interest to researchers, planners and others working in the Intelligent Vehicle/Highway System area. In the interest of information dissemination, this report is being distributed nationally to key members of the IVHS research and planning community.

Robert J. Betsold
Director, Office of Safety
and Traffic Operations
Research and Development

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16. Abstract

Seven navigational devices were tested in the Federal Highway Administration Highway Driving Simulator (HYSIM) for their effects on safe driving performance. Younger, middle-aged, and older drivers navigated a 26-mi (41.8-km) route through simulated streets of Detroit, MI, using one of seven devices. A control group used strip maps. The other six used either an audio or visual device which was of either low, medium, or high complexity. The difficulty of the driving task (workload) was increased in three successive sections by adding crosswinds, another vehicle, gauge-monitoring, and mental arithmetic problems, and by narrowing the lanes. Measures included speed, average and variance of lateral placement, heart rate, and reaction time to gauge changes. Results indicate an interaction of age group and level of difficulty, such that higher levels of difficulty affected older drivers to a greater extent. Device differences suggest that audio devices are somewhat safer than visual devices, and moderate levels of complexity are preferable to higher levels. The complex visual device had the longest reaction times and the slowest speeds in sections where navigation tasks were performed.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

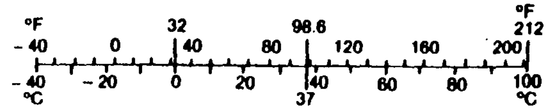
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	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	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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IN-VEHICLE NAVIGATION DEVICES: EFFECTS ON THE SAFETY OF DRIVER PERFORMANCE

INTRODUCTION

Traffic congestion is a serious and growing national problem. In 1975, for example, 41 percent of the travel on urban freeways during peak hours occurred under congested conditions; that number rose to 55 percent in 1983. Current urban freeway congestion is estimated at 1.2 billion vehicle-hours of delay per year.(1) Vehicle delay on freeways is expected to increase by over 400 percent between 1985 and 2005; on other roads, the increase is expected to be over 200 percent.(2)

The problems of urban congestion cannot be solved merely by building more roadways. An integrated approach utilizing supply and demand techniques, advanced computer resources, and in-vehicle technology is required.(2)

One method to reduce congestion is to expedite route-choosing and -following techniques used by drivers. Errors in trip planning and route following account for approximately 20 percent of the miles driven, and approximately 40 percent of time spent driving.(3)

Among the many options contemplated to increase route-planning and -following efficiency, onboard guidance systems appear to hold considerable promise. The intent of onboard navigational devices is to reduce both congestion and the overall burden on the driver by simplifying the process of choosing and following a route. Such systems have been under development for some time. Among the earliest is the Experimental Route Guidance System (ERGS), a prototype designed by General Motors Corporation for the U.S. Department of Transportation.(4) ERGS utilized a simple onboard visual display to provide intersection-by-intersection guidance information received from roadside transmitters. A similar system, AUTOGUIDE, has been developed through the cooperative efforts of several British organizations, coordinated by the London Regional Office of the Department of Transport.(5)

A number of after-market electronic guidance systems are currently in the testing stage, and a few are commercially available. The Etak "Navigator", for example, has been tested in fleet operations, such as police departments, and can be purchased for privately owned vehicles.(6) The Etak unit, unlike ERGS and AUTOGUIDE, is completely self-contained, and navigates by dead-reckoning. Guidance is provided to the driver on a digitized map, complete with street names, displayed on a CRT screen.

Major automobile manufacturers have also pursued onboard navigational devices. Systems based on the dead-reckoning method were introduced by Toyota and Nissan in 1981.[7] These devices provided the driver only the distance and direction to a chosen destination. Newer systems, such as those developed by General Motors, Ford and Chrysler make use of satellites for navigation and vehicle tracking, and like Etak's Navigator, use map displays to guide the driver.[8, 9, 10] The early 1990's are commonly stated projections for availability of these devices as options with new vehicle purchases.

Future systems, which will provide a wide diversity of information in addition to onboard guidance, are now being planned at the national and multinational level. Under Japan's Comprehensive Automobile Control System (CACS), the proposed guidance unit will combine a dynamic map display with verbally presented information.[7] Although the in-vehicle devices being developed to provide navigational guidance will vary by manufacturer, national standards are planned.[11] In the largest scale effort of its kind to date, 28 nations of Western Europe have combined research efforts to develop an integrated system of traffic control to reduce congestion and improve safety.[12] The PROMETHEUS Research Project (PROgraM for European Traffic with Highest Efficiency and Unprecedented Safety) is scheduled to complete its research and development phase in 1994, with major emphasis on computer-aided driving. Onboard navigational guidance is a key component of this comprehensive approach. The United States Department of Transportation, in cooperation with private sector interests, is also actively investigating an Intelligent Vehicle/Highway System with similar objectives.[13] Given the range of efforts in onboard navigation systems, it is probable that devices to aid the driver in choosing and following the most efficient route will become commonplace.

Human factors considerations must guide the design of such devices to eliminate or significantly reduce unsafe operations, as well as optimize the system/driver interface. Although an onboard unit may aid drivers in a given task, its operation may also introduce significant hazards. One study for example, investigated the effect of cellular telephone use on lane placement deviations.[14] Drivers were required to enter long-distance telephone numbers while driving under conditions which were well-controlled, and nearly ideal. The authors estimated that given 12-ft (3.66-m) lanes, approximately 2 percent of drivers would leave their lane while making a call; given 10-ft (3.05-m) lanes, this number would rise to almost 12 percent. The results imply that this activity adds sufficiently to the demands of the driving task that under actual roadway conditions, safe performance may be impaired.

As the above example illustrates, onboard systems operation competes with other elements of the driving task for the user's attention. Consequently, use of a guidance device may impose additional demands which could offset the benefits of assisted navigation.

A fundamental assumption of the present study is that use of any onboard device adds to the demands of the driving task; at some level of increase, use of the device may cause an unacceptable deterioration in driving safety. Among the most basic of design issues is the quantity and type of guidance information which should be provided, and the method by which it should be presented. Our purpose is to gauge the safety of drivers' performance during the use of guidance devices which vary in complexity and mode of presentation.

WORKLOAD

The issue posed here is grounded in an area of human factors research referred to as workload. The concept has its foundation in the measurement of human capacity to perform physical work. When cognitive and perceptual variables are of interest, the term refers to mental workload.

In this context it is assumed that the human operator has a limited capacity to perceive and process information, select appropriate responses, and execute those responses adequately. The "quantity" of resources tapped in the successful performance of any task is represented by workload.(15)

Workload is assumed to increase as greater demands, such as increased task difficulty, requirements for simultaneous performance of subordinate functions, or environmental stressors, are placed on the operator. With low to moderate increases in workload, performance may remain stable, because the operator can compensate by increasing the effort (i.e., devoting a greater share of resources) expended on the task. Beyond this point, performance begins to deteriorate, and additional load results in severe performance decrements.(16)

In the choice of a system configuration to be used to perform a task, or some function which is part of a larger task, the demands imposed by use of the system itself must be considered. This is particularly so when the demands of the task are variable, and may at times require use of the system operator's "reserve" capacities in response to high demand situations, such as emergencies.(16) In terms of our present concerns, one must measure the effects of the workload imposed on the driver when using an onboard guidance system to determine its potential to interfere with safe operation of the vehicle under various conditions.

The emphasis in workload literature typically (and appropriately) is placed on assessment techniques; various performance measures, auxiliary tasks, subjective rating schemes, and physiological responses are used to differentiate levels of workload and detect related performance effects. This is obviously a critical aspect of the present study as well. However, of necessity, the authors also approached the topic from a different perspective: that of inducing load. The effects of generic guidance devices were investigated via the Federal Highway Administration Highway Driving Simulator (HYSIM). In the validation study of this system the authors determined that the rather sterile "environment" presented in the HYSIM resulted in task loading which, relative to driving in actuality, was generally too low.[17] Thus, a primary preliminary concern was to alter the workload of the simulator driving task to more closely correspond to the actual demands of driving. A search of the literature was conducted to establish an appropriate set of driving-related loading techniques which could be applied within the limits of the system's capabilities.

It should be noted at the outset that the distinction between the use of workload measures and the introduction of loading factors at times appears arbitrary, and the two are not necessarily mutually exclusive. This is most clear in the use of subsidiary tasks used in conjunction with a primary performance task (e.g., driving). Deterioration of performance on such secondary tasks is typically taken as a measure of the workload of the primary task. Several researchers caution that in the choice of task one must avoid interference with the primary task, a phenomenon known as "intrusion".[16, 18] This is based on the assumption that when an appropriate secondary task is introduced the primary task can remain isolated, for example, by instructing subjects to give it priority.[15] This assumption has been questioned. It can be argued that the additional task interacts with, and alters the nature of the primary task. Intrusive effects, which imply increased load, can thus yield information about the demands of the primary task.[15] In the review that follows, both alterations of primary task variables, and use of subsidiary tasks, are explored for the increases in overall workload they may produce.

Driving is comparable to other tasks which involve the interaction of an operator with a machine component. The types of activities performed in such tasks have been categorized as "universal operator behaviors" of four types: motor, perceptual, mediational, and communications.[18,19] The last, communications, typically plays a minor role in the driving task, and will not be specifically addressed. The others, though there is considerable overlap, define primary skill areas which are tapped in driving.

PSYCHOMOTOR

All aspects of vehicle control are psychomotor in nature. Potential increases in psychomotor load may be linked to several variables. For example, on narrow roads, or approaching bridges, the frequency of drivers' steering movements increases, presumably to maintain stricter control of the vehicle's position within the lane.[20] Road curvature affects workload more directly; the sharper the curve, the more corrections per unit time are required to avoid lane encroachment.[21] Environmental conditions may also affect the difficulty of vehicle handling. Wierwille and his colleagues have researched the effects of wind on both driving and piloting tasks.[22,18] In one study, conducted in a simulator, the application point of crosswind gusts was varied from near the front wheel, rearward to the center of the vehicle. The differential effects of wind placement were evident in measures of lateral deviation, yaw deviation, and steering reversals.

PERCEPTUAL

Driving is heavily dependent on visual input. Anything that increases the demand for visual attention increases driving workload. For example, under conditions of high traffic density, and potential conflict with other vehicles, drivers were found to increase the proportion of visual attention directed toward the forward view, and to "narrow" the scope of attention to the center of the roadway. In operational terms, under conditions of high visual demand, drivers had little "spare capacity", and thus decreased the frequency with which they checked rear and side view mirrors and glanced at dashboard displays.[23] Similar results were reported in a study with a very different methodology. Subjects drove through a series of curves in a driving simulator; an auxiliary visual search task was presented during the drive. Viewing ratio (percentage of time spent looking at the auxiliary display) was dependent on driving difficulty as measured by the sharpness of the curves negotiated, and variability of lane position and speed increased in the presence of the perceptual task. Thus, even though the subjects modulated their visual attention according to driving demand, their performance was degraded.[21]

Many piloting tasks are also dependent on visual input, though the emphasis is more on display panels rather than the forward view. To increase the workload of a simulator study Wierwille et al. varied the rate and number of danger conditions as indicated on flight instruments. Pilots had to respond by pushing a button associated with each instrument to correct the condition. Reaction time to a target display, which was the primary task measure, increased monotonically over three levels of loading.[17]

COGNITIVE

Higher level information-processing involving problem solving and decision making are ongoing mediational, or cognitive, activities. Experimentally inducing cognitive load frequently involves the introduction of tasks which, though artificial in nature, may be related to normal operator functions. For example, in one study of cognitive load pilots were presented with wind triangle navigation problems which varied in the number and complexity of arithmetic and geometric operations required. Response times to solve the problems, as well as the error rate, reliably distinguished among the differing load levels.[24] In driving studies, tasks requiring cognitive resources have typically been less realistic, but have been found effective nonetheless. Numeric tasks in various forms, for example, have proved useful in several studies. Mental addition and a changed digit task were used, respectively, with "average" drivers and "advanced" drivers with special training.[25] These tasks were performed alone and while driving a route which included both a residential area and a business district. Task errors increased progressively from the task alone, to residential, to business district conditions, and accelerator pedal reversals, measured only during testing of advanced drivers, increased in the addition task/driving condition. Each of these results suggests greater load related to both the task requirement and driving conditions.

In another study, inserting a delayed digit-recall task increased the time it took subjects to drive a circuit marked with pylons. The same effect was found by inserting a noise stress factor. When both task and noise were combined, drivers struck significantly more pylons.[26]

CHOICE OF LOADING TECHNIQUES

A number of factors were found to be appropriate to the driving task, and consistent with the proposed test of onboard navigational systems. For psychomotor load, crosswind effects produced in a simulator have been shown to adequately increase the difficulty of control tasks. Varying the road geometry, in terms of curvature and lane width would also be effective. Use of curves, however, was limited by the choice of test devices. One device uses a CRT screen on which a map is displayed; maps are available for only a small number of cities. To properly simulate use of the device, it was necessary to match the projected roadway to one of the available maps. Thus it was necessary to use an "existing" pattern of roads, and control of workload by the manipulation of curvature was not possible. Lane width could be varied however, because details of this sort cannot be readily distinguished on the CRT map.

As noted previously, there is overlap in the categories of operator behaviors. The input which leads to psychomotor responses is multidimensional, consisting of visual, kinesthetic, and to a lesser extent, auditory cues. The presence of other vehicles, discussed as a demand on visual attention, also increases psychomotor demand. HYSIM cannot simulate a high density traffic situation, however vehicles of different types can be introduced singly to increase the demands of driving, in terms of both perceptual and psychomotor workload.

Choice of additional techniques to vary perceptual load were somewhat more restricted. Although intrusiveness is essentially equated with workload in the present context, basic physical limitations must be taken into account. As an extreme example, use of a response requiring simultaneous use of both hands in conjunction with the primary driving task would be an inappropriate method of increasing psychomotor load. Such a technique produces what is referred to as peripheral interference.[27] Regarding perceptual load, it is physically impossible to focus the eyes on two locations at the same time. Because driving is so dependent on visual input, and visual attention is necessary for use of certain navigational aids, no auxiliary task which requires prolonged focus was considered acceptable. In contrast, monitoring of dashboard displays by occasional scanning is a normal aspect of driving. This is particularly so if the driver has reason to expect a problem of some sort. This routine subtask of driving was incorporated as a load factor by instructing subjects to monitor the oil and temperature gauges for abnormal readings which, if ignored, would lead to serious mechanical failure.[18] Upon detection of an aberrant reading, subjects pushed a button to "correct" it.

Choice of a cognitive loading task was also somewhat limited, and necessitated a technique which would not interfere with either normal visual input, or physical control of the vehicle. A mental arithmetic task, related to remaining fuel and allowing for verbal presentation and response, was chosen.

Each loading technique was designed to allow a variable level of difficulty. This permitted an interactive effect of the individual techniques that yielded a greater increase in task loading than would have been possible otherwise. For example, baseline psychomotor conditions included 12-ft (3.66-m) lanes, no other vehicle, and no wind disturbance. A moderate difficulty condition was created by reducing lane width, and adding an automobile and light crosswinds. A truck, heavy crosswinds, and further reduced lane width, were combined to produce an even higher level of psychomotor workload.

Manipulation of workload levels was held constant across subjects, with the type of navigational device as the primary between-subjects variable. In this way the effects of the different devices under varying conditions of workload could be gauged.

CHOICE OF WORKLOAD MEASURES

Examples of workload measures are evident in the previous discussion. As might be interpreted from that discussion, there is no particular technique which is generally accepted as the correct measure of workload. Instead there appears to be an emerging consensus that global, general purpose measure are of limited usefulness.[15] Use of multiple measures, selected for their relatedness to critical aspects of task performance, appears as a most viable approach.

The measures used in this study were chosen consistent with HYSIM capabilities, and some demonstration of their sensitivity to workload in published research. Primary performance variables, i.e., those that relate to driving per se, have shown a reasonable level of reliability. Measures of lane maintenance have been found useful in discriminating workload related to visual attention and psychomotor demand.[26,28,14,29,22] Average lateral placement and variance of lateral placement were chosen as measures known to be reliable in the HYSIM. Speed measures have also met with success, though they area often more open to interpretation in field studies because of traffic variations, stopping times, etc.[25,21,26,30] Speed variables taken in the simulator should not suffer this problem because more precise control of these conditions is possible.

As stated earlier, primary task performance is not always degraded under conditions of increased load. A compensatory increase in effort can maintain performance at baseline levels. Under these conditions performance on subtasks may deteriorate as a result of workload.[18] For this reason, reaction time to the gauge-monitoring task was used as an additional measure of workload.

Theoretically, effort expended in task performance should be reflected in psychophysiological responses, such as pupil diameter, heart rate, muscle contractions, or brain wave activity. Of the numerous measures which have been used, only cardiac function and respiration are presently feasible in HYSIM, and the latter has proved less than reliable.[17]

Various measures of cardiac function are used because they are unobtrusive, simple to obtain, and intuitively appealing - heart rate should increase as workload, and thus effort, increases. Although there is support for this hypothesis, the results are inconsistent.[31,16] Heart rate variability, considered an improvement on simpler measures, has also produced some negative results.[32] Despite these inconsistencies Wierwille et al. suggest use of a cardiac measure (heart rate mean) of workload in psychomotor tasks which involve stress or danger.[18] It was included in this study as a supplementary measure, though it was not expected to display a high degree of sensitivity to changes in workload level.

Each of the workload measures, as well as loading techniques, are presented in detail in the Methods section of the report.

METHOD

SUBJECTS

Licensed drivers were either drawn from the subject listing maintained by the Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA, or recruited from the greater Washington Metropolitan area. The sample consisted of 126 subjects, balanced by gender, and with equal numbers in each of 3 age categories (Younger, average age 22.8 years; Middle, average age 37.6 years; and Older, average age 62.8 years). This allowed for 18 subjects in each of the 7 experimental conditions. Six subjects from each of the three age categories, equally split between males and females, ran in each condition.

APPARATUS

Simulator

Data were collected as subjects drove in the Federal Highway Administration's Highway Simulator (HYSIM). HYSIM is a fully interactive driving simulator utilizing computer-generated graphics for roadway delineation. A more complete description of the HYSIM is found in appendix A.

Guidance Units

Six electronic guidance units, three visual and three audio, were used in the study. The complex visual unit consisted of 4.9-in by 5.5-in (12.45-cm by 13.97-cm) screen showing a map of the area in the immediate vicinity of the driver (see figure 1). The driver is represented by an icon on the map, and the map "flows" by the icon as the driver proceeds through the road system. The direction in which the driver is going is always "up" on the display. The destination is represented by a second icon on the CRT map.

The medium complexity visual unit was a modification of the ERGS (see figure 2).[4] Only the words on the ERGS display were used in this condition. For example, if the driver was to make a left turn, the system would light up "TAKE THIRD LEFT" in the third block before the turn, "TAKE SECOND LEFT" in the second block before the turn, and "TAKE FIRST LEFT" in the block just before the turn.

The simple visual unit was also a modification of ERGS, utilizing only the arrows on the ERGS display (see figure 3). In the block just before the driver was to make a turn, the appropriate arrow was lit.

The audio guidance units were designed to parallel the visual systems. The complex audio system was a recorded series of statements, in a woman's voice, giving as much information as

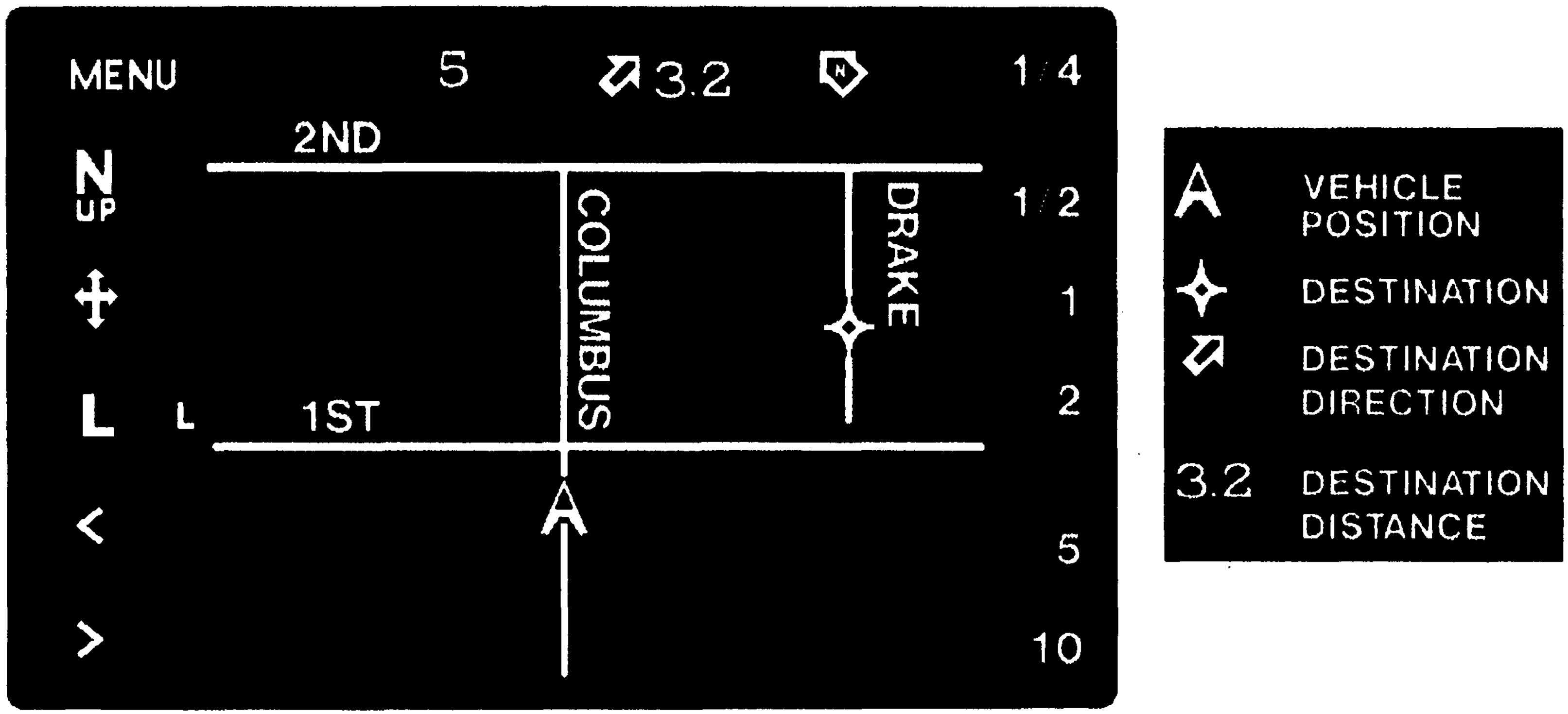


Figure 1. Sketch of complex visual guidance unit display. (The number at the top (5) and those along the right are map scales. Other icons were not needed.)

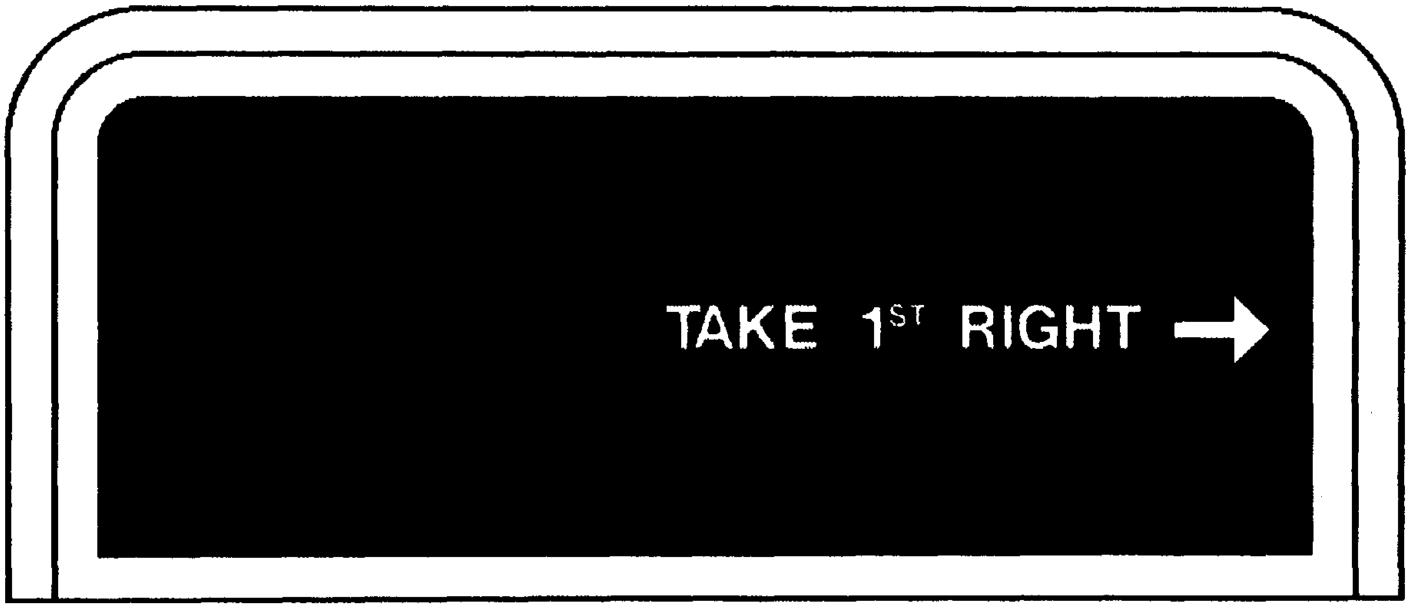


Figure 2. Sketch of medium visual guidance unit display.

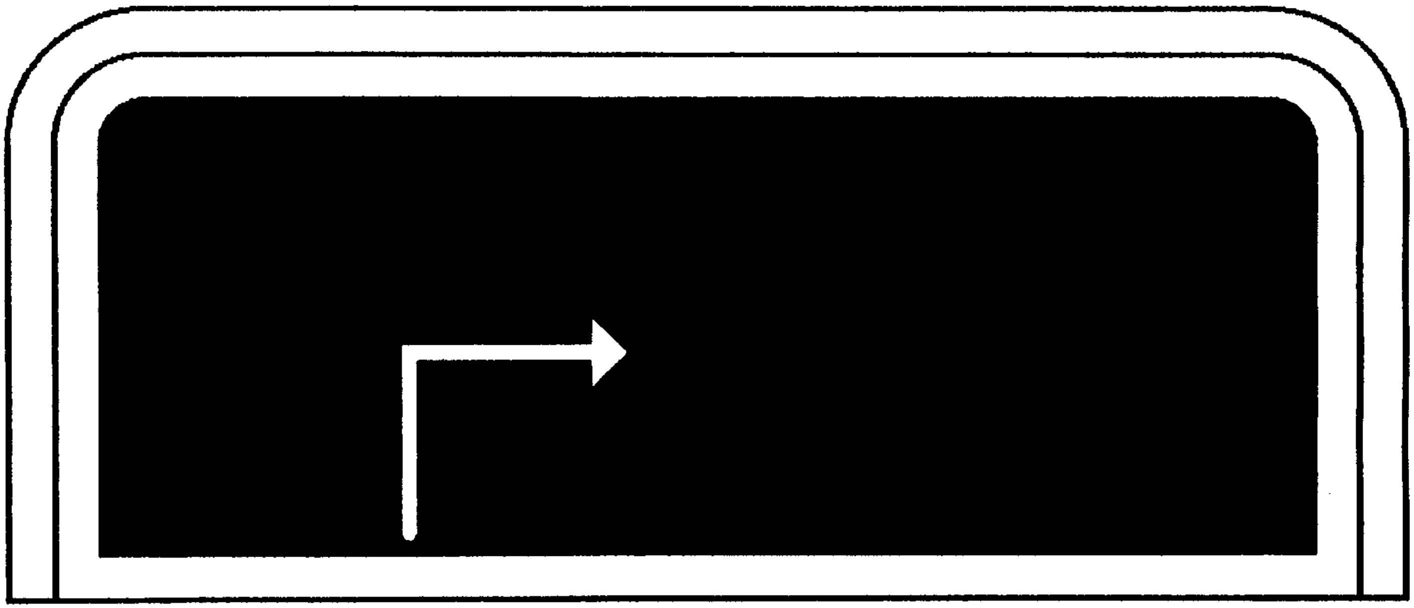


Figure 3. Sketch of simple visual guidance unit display.

was temporally feasible regarding the driver's whereabouts in the network. These messages occurred periodically along the drive. Thirty-four complex audio messages were used in the main drive. The text of these messages is found in appendix B. The medium complexity audio unit presented the same information as the medium complexity visual unit, but the recorded messages ("Take third left" etc.) were presented to the driver by a female voice.

The simple audio system also corresponded to the simple visual system. Instead of an arrow appearing half a block before a turn, the driver heard a female voice say "Left, left, left" (or "Right, right, right") half a block before the turn.

The seventh experimental condition, used as a control, was designed to give the best navigational information without electronics. Subjects in this condition were given a "strip" map (similar to those used by AAA) to guide them through the scenario. Each "strip" showed only the previous turn and next turn, and included written directions. Subjects turned to the next "strip" at the first stop sign after each turn. They were also permitted to look at the map at any other stop sign or red traffic light. The darkness of the car's interior helped to ensure that subjects did not look at the map wile driving. A sample page of the map used by subjects in the main drive is shown in appendix C.

SCENARIO

The scenario the subjects drove in the HYSIM was based on roads in the city of Detroit, Michigan. The HYSIM roads were identical to those in Detroit in name, orientation, length, and relationship to intersecting streets. Width and number of lanes were manipulated by the experimenters. Limitations on the size of the data set for the scenario precluded inclusion of streets parallel to the correct route; thus side streets which were not part of the route (i.e., wrong turns) ended in cul de sacs. This strategy not only brought the drivers back to the point at which they left the correct route, but also allowed for greater emphasis on the effect of the guidance units on driving performance, as opposed to their effectiveness in aiding route-following.

Signs in the main drive were developed using guidelines for urban signing from the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD).[33] Forty-five percent of the 381 cross streets in the 26-mi (41.83-km) main drive were identified by street signs. Other signs included standard regulatory, warning, and guide signs that might be found in an urban setting. The speed limit was 25 mi/h (40.23 km/h), throughout the drive, with a physical cap on the simulator car speed of 30 mi/h (48.27 km/h).

LOADING

All three types of loading (psychomotor, perceptual and cognitive) were changed during the main drive to increase the workload of the driving task. The first third of the drive had the lowest loading ("easy"), the second third of the drive had "moderate" loading, and the last third had the most loading ("hard"). The loading tasks are described in detail below, and are charted in table 1.

Table 1. Factors used to increase driving task load.

LOAD FACTOR	SECTION OF DRIVE		
	EASY	MODERATE	HARD
Lane Width	12 ft	10 ft	8 ft
Cross Winds	None	Light	Heavy
Other Vehicle	None	Sedan	Truck
Gauge Change	None	Gross	Small
Mileage Questions	Easy	Moderate	Hard

(1 ft = .3048 m)

Psychomotor

Three factors were involved in the psychomotor loading: lane width, intensity of crosswinds, and presence of another vehicle.

In the easy section the subject drove on two-lane streets with 12-ft-wide (3.66-m) lanes. There were no crosswinds and no other vehicle was present, thereby providing a "best case" scenario.

In the medium section, the subject drove on a four-lane street with lanes narrowed to 10 ft (3.05 m). Some light crosswinds were present, and the other vehicle involved was a late model sedan. Its apparent image was 6 ft (1.83 m) by 16.7 ft (5.09 m). The car, located in an adjacent lane, "tracked" the subject throughout this section of the drive. The speed of the car was matched to the subject's speed with slight variations. The position of the car varied from next to the driver, to about 20 ft (6.1 m) ahead of the driver. The driver could momentarily gain on the car by accelerating suddenly, although the car would quickly catch up. The obverse was true when the driver braked. The car never prevented the subject from turning, and dropped out of sight before turns and at other points in the scenario, then reappeared. The car was always present throughout the data collection zones, with one exception caused by a sharp jog in the road.

In the hard section of the drive the lanes were 8 ft (2.44 m) wide. The crosswinds increased in intensity and other the other vehicle was a 10-wheel dump truck. Its apparent image was 8 ft (2.44 m) by 24 ft (7.32 m). The truck tracked the subject in the manner described above for the car.

Prior to each appearance of the other vehicle, subjects were instructed to drive in a given lane, and to maintain that position until told otherwise. This was done for two reasons. First, it introduced a measure of control into the psychomotor loading. Once the vehicle appeared, it remained in the same lane, and some subjects may have tried to follow behind the vehicle, thus reducing the load. By requiring subjects to drive in the adjacent lane, this variable was consistent across the seven conditions for each subject. Second, in the low complexity conditions, subjects were given information as to where and in which direction to turn approximately half a block before the turn. This allowed little time to change lanes in preparation for the turn compared to the medium and high complexity guidance conditions. This method allowed for appropriate lane choice well in advance for all conditions, and reduced the probability of extreme maneuvers.

This may have reduced the navigation task for subjects who realized that the lane specified was the correct lane for the next turn. However, as noted previously, the focus of the study was not the navigation task per se, but the effect of the guidance units on the safety of drivers' performance.

Perceptual

The perceptual loading involved monitoring two of the gauges on the dashboard: oil (on the upper left hand portion of the dash) and temperature (on the upper right hand portion). A red button was placed on top of the dash to the left of the steering wheel (associated with the oil gauge), and a green button to the right (associated with the temperature gauge).

The task was to monitor these gauges, as the car had an oil leak and a faulty radiator. The subject was told that if either gauge went out of normal range, it should be reset as quickly as possible by pushing the button above it. Only one gauge changed at any given time, with the oil gauge always going low (left) and the temperature gauge always going high (right). The gauges changed in a randomly determined order, which remained constant over all subjects.

The difficulty of the gauge task varied in the three sections of the drive (see figure 4). In the easy section of the drive, both gauges remained in the midline state. In the moderate section of the drive, one of the gauges changed from fully in to fully out. in the hard section, one gauge changed from barely in to fully out. This latter difference was much more difficult to perceive than the full change in the medium section.

Cognitive

The cognitive loading task consisted of a tape-recorded series of mental arithmetic problems. The calculations involved a combination of distance to the next gas station, and remaining fuel. The mileage problems used, in the order presented, are given in appendix D.

In the easy section the question was phrased: "How far will you have to walk if the next gas station is X miles and you have enough gas to go Y?" The number for X and Y in this section of the drive were multiples of 5, and the difference between the two was a multiple of 10.

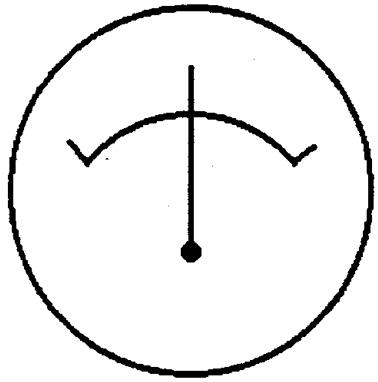
In the moderate section of the drive, the same question was used, but the X and Y values were more varied. The numbers required two-place subtraction, and in one case required carrying, i.e., 42 - 28 = 14.

In the hard section of the drive the phrasing of the question was changed to "How far will you have to walk if the next gas station is X miles, your car gets Y miles to the gallon and you have Z gallons?", thus requiring the subject to multiply and then subtract.

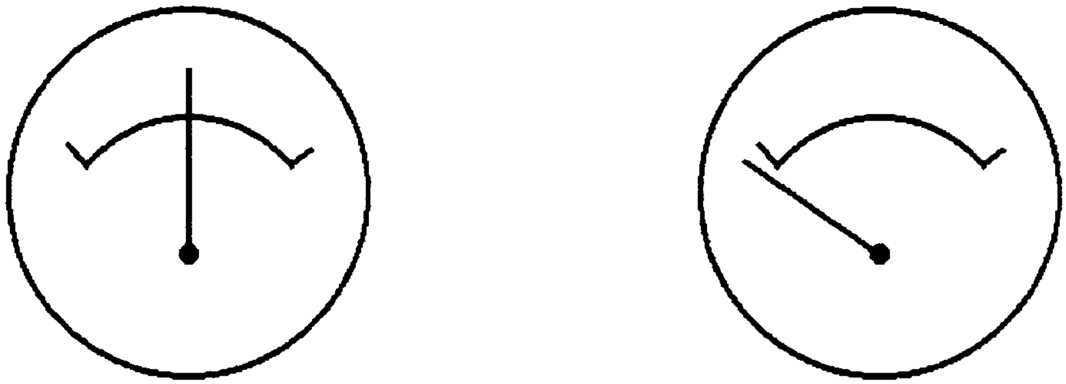
Subjects were not penalized for incorrect answers. Fourteen pilot subjects performed these calculations while seated at their desks. The average time in seconds from end of question to correct response was .91 for the easy, 3.35 for the medium, and 4.30 for the hard.

DATA ZONES

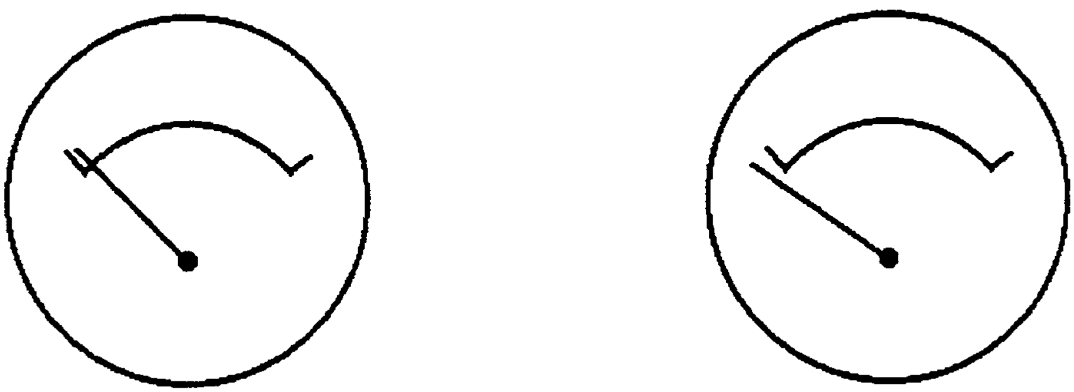
There were 15 data zones in the scenario, 5 in each third of the drive ("easy", "moderate", and "hard"). Twelve of these data zones included turns (4 in each third), and 3 were in straight segments of the drive (1 in each third). The straight zones were designed as control conditions which had no guidance information. The data zones which included turns were numbered



a. Easy: Gauges remained in midline position.



b. Moderate: Gauge changed from midline (left) to out (right).



c. Hard: Gauge changed from "just in" (left) to out (right).

Figure 4. Gauge changes used in perceptual load task.

from 1 through 12; with numbers 1 through 4 in the easy section, numbers 5 through 8 in the medium section and numbers 9 through 12 in the hard section. The straight segment data zones were designated by an alphabetic character: X (easy), Y (medium), or Z (hard).

Each data zone was divided into subzones: A, B, C, and D. In the "turn" data zones the breakdown into subzones was fairly complicated, and each subzone will be discussed separately. The subzones were devised to detect driving behaviors attributable to different types of loading, and interactions, if any, of load and the various guidance devices.

Please refer to figure 5 during the following explanation of data subzones.

Subzone A was 500 ft (152.40 m) long, ending at the start of subzone B. Because no stimulus occurred in this subzone, it was used as a baseline for subsequent subzones.

Subzone B was 900 ft (274.32 m) long, beginning with a gas-mileage problem, and ending at the start of subzone C. It was devised to measure the effects of the mileage question on the drivers' behavior. In the second and last thirds of the drive, the gauge changes occurred at the end of this subzone.

The length of subzone C varied dependent on the length of the two blocks before the turn (counting only streets on the same side as the turn). The start of the subzone was 300 ft (91.44 m) before the second street prior to the turn intersection. This was the point at which the last complex audio guidance message before a turn was given, and where the first message was given in both medium complexity conditions (audio and visual). In general, this subzone was where the navigational information was most needed.

Because the guidance units in the simple treatments gave navigational information only in the last block before the turn, subzone C was broken down into Ca and Cb for those treatments. Cb started when the information was given, usually 200 ft (60.96 m) before the intersection.

In all cases, data subzone C (or Cb in the simple treatments) ended 50 ft (15.24 m) before the intersection. This was due to software limitations which precluded accurate tracking of the vehicle as it neared the intersection. The point at which the measurement system in HYSIM would change its reference line from the street before the turn to the street after the turn could not be predicted. This limitation was not expected to affect the results because subjects would be unlikely to look at the displays of the visual guidance units while performing a turning maneuver.

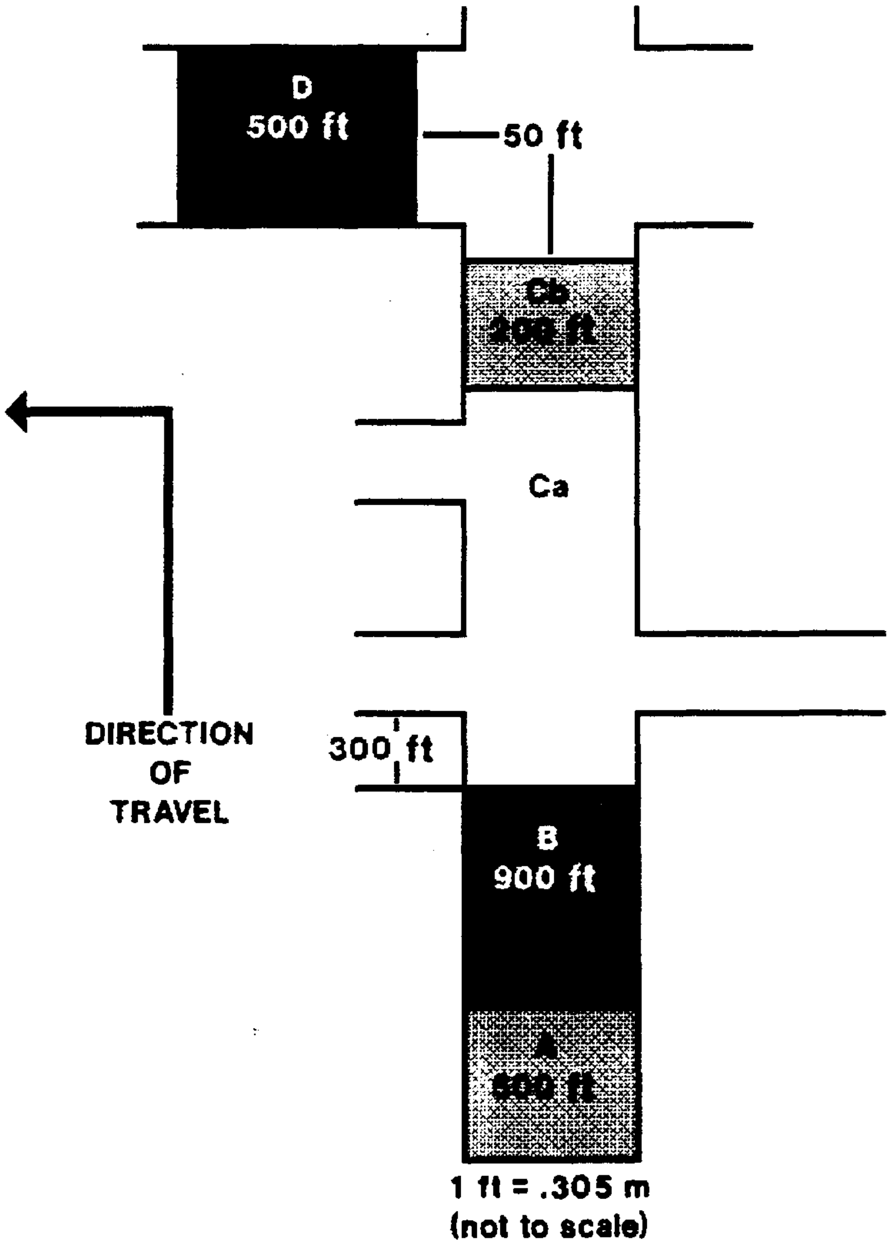


Figure 5. Definition of subzones in zones which included a turn.

Subzone D was 500 ft (152.40 m) long, which began 50 ft (15.24 m) after the turn was made. It was designed to determine any recovery effects. The gauge that previously had changed reset itself at the end of this data zone if the subject did not respond to the change.

In the straight section zones (X, Y, and Z), subzone A was from 0 to 500 ft (152.40 m) into the data collect area, subzone B encompassed the next 900 ft (274.32 m), subzone C encompassed the next 1100 ft (335.28 m), and subzone D was the last 500 ft (152.40 m). As in the turn zones, the gas-mileage problem was presented at the start of subzone B, and the gauge change occurred at the end of subzone B.

DEPENDENT VARIABLES

Data were collected in the simulator at a rate of once every .075 s, then averaged over each subzone.

Four basic types of data were collected during the drive: heart rate, speed, lateral placement, and reaction time to the gauge changes. The first three variables were collected in every subzone of each data zone; the fourth, reaction time, was only collected once in each data zone (because only one gauge change occurred). Further, there are no reaction time data for the first five zones (1, 2, 3, X, 4) which occurred in the easy section of the drive, because no gauge changes occurred in this section. Each variable is discussed separately below.

Heart Rate

Each subject's resting heart rate, in beats per minute, was measured by the experimenter during preliminary procedures. This information was entered in the subject's personal data file in the HYSIM computer, and was used as a baseline to produce the output for the heart rate data later analyzed. During the main drive, heart rate data were collected by means of a modified Gould Radial Pulse Sensor (Model #287163) attached to the subject's earlobe. The output from the sensor was connected to a Gould Biotech Amplifier (Model #13-4615-66) and processed by the HYSIM computer (see appendix A).

The data analyzed for heart rate information were adjusted for individual differences using the following formula:

$$\frac{(\text{Data heart rate}) - (\text{Base heart rate})}{(\text{Base heart rate})} \times 100$$

This yielded percent change in heart rate for each data point.

Speed

Four speed variables, minimum, mean, variance, and skew, were recorded in each subzone. Maximum speed was not collected because there was a speed cap in the simulator of 30 mi/h (48.27 km/h), and a ceiling effect was expected.

Lateral Placement

Values for lateral placement were keyed to the center of the "correct" lane (the lane in which the driver should have been), which was given the value of 0; deviations were measured based on the placement of the center of the HYSIM car, relative to the zero point. Deviations in the direction of the next turn were counted as positive, as were placements directed away from the simulated "other vehicle" in the medium and hard sections of the drive. For example, if the next turn was to the left, and the other vehicle was in the right lane, the left lane was the correct lane for the subject. Placements left of center, and away from the simulated vehicle, took positive values; placements right of center, and towards the other vehicle, were negative.

Because different lane widths were used in each third of the drive, the raw lateral placement data were converted to ratios that equalized the lateral placement scores, regardless of the lane width. All data points were divided by a number referred to as "leeway", which changed in each section of the drive. Leeway was the distance, when the 5-ft (1.52-m) wide car was centered in its lane, from the side of the car to the edge of the lane. Thus, the leeway in the easy section with 12-ft (3.66-m) lanes was 3.5 ft (1.07 m); in the medium section, with 10-ft (3.05-m) lanes, it was 2.5 ft (.76 m); and in the hard section with 8-ft (2.44-m) lanes, it was 1.5 ft (.46 m). As a result, any data over +/- 1 indicated the car was out of its lane.

All lateral placement statistics (average, variance, minimum, and maximum) were based on these converted data.

Reaction Time

Reaction time to gauge changes was collected, as described above, only once in each data zone of the medium and hard thirds of the drive. Reaction time was defined as the time from the changing of the gauge to the subject's response of pressing the appropriate button. If the subject did not respond to the gauge change, the gauge was reset automatically at the end of subzone D and the data point was coded as missing. The time at which this took place was dependent on the driver's speed.

PROCEDURE

Upon arriving at the research center, each subject completed an informed consent record (see appendix E) and a vision test, conducted with a Bausch and Lomb Ortho-Rater. A pulse reading was also taken to establish a baseline for heart rate data. The subject was then escorted to the HYSIM laboratory.

Initially the experimenter took the driver's position, while the subject was seated on the passenger's side. After a brief description of the HYSIM car controls, the instructions for the study were read to the subject (appendix F), and an overview map of the practice route was provided; subjects in the complex visual condition were shown a simplified map which was similar to the visual display. During the instructions, the use of the navigational device was explained; subjects in the control group were given strip maps of the practice route and told they could make any necessary notes.

The experimenter then drove for a short distance to demonstrate the driving characteristics of the system. Because of certain limitations in the graphics component, which affect the appearance of intersections, particular attention was given to turn maneuvers. Unlike the curved edges of an actual intersection, HYSIM displays edge lines which form 90 degree (1.57 r) angles. In order to perform a smooth, gradual turn, one must begin the turn a bit early, and cross over the edge lines, as though the roadway image were contoured as in the real world. After a demonstration of two turn maneuvers, the subject took the driver's position. The plethysmograph used to monitor heart rate was attached, and the subject was encouraged to make any necessary seat or steering wheel adjustments prior to beginning. The experimenter accompanied the subject during the practice session. Any additional training in the use of the guidance system, coaching in the operation of the vehicle, and explanation of the procedures was provided during this time. Other than the initial training and explanation provided, subjects were required to depend on the guidance units to determine their route. If an error was made (e.g. missed turn, or turned the wrong direction) the experimenter verbally assisted the subject in returning to the proper route.

The practice drive was a closed loop approximately 14 mi (22.53 km) in length. The session was similar to the main drive, but the lane width was always 10 ft (3.05 m), gas-mileage questions were of the easy category described above, gauge changes were from fully in to fully out, and the other vehicle present during part of the drive was the sedan. All subjects included in the test results drove a minimum of the first 9 mi (14.48 km) of the practice drive. Subjects were encouraged to continue the session until fully comfortable with the vehicle and procedures. Beyond the 9-mi (14.48-km) point, which included all variables in the main drive, the session was terminated when the experimenter and subject concurred that the subject was prepared for the main drive.

The subject was given a brief break while the main drive was loaded into the HYSIM. During this period subjects in the control group were given strip maps for the main drive.

Instructions were reviewed prior to the start of the main drive, and any remaining questions were addressed. During the drive the experimenter monitored the subject's progress from the control room adjoining the HYSIM laboratory. If any error was made in following the route, the experimenter verbally guided the subject out of the cul-de-sac, and back onto the appropriate path. In the event of a crash, an attempt was made to restart the drive at the point of the crash. In a small number of cases, the program was reloaded, and the experimenter drove the car back to the point of the crash. The subject was given a break during this time, and completed the drive. This was done to maintain a consistent level of exposure across all subjects.

RESULTS

GENERAL

The data were automatically collected by the HYSIM computer, then processed by the HYSIM staff to yield the subzone statistics described in the methods section. These were transferred by tape to the IBM mainframe computers at the National Institutes of Health, where they were further analyzed using the SAS statistical package.[34] The major analyses used PROC GLM of SAS to do a five-way analysis of variance with navigational device, age group, and sex as independent-group factors, and loading and subzone as within-group (repeated measures) factors. The loading factor was formed by averaging the measures across the turn zones within thirds of the drive. Thus, average speed in subzone D in the moderate loading section was the average of the average speeds in subzone D for Zones 5, 6, 7, and 8. This reduced idiosyncrasies imposed by the intersections, e.g., distances between intersections preceding the turn, and angle of the street at the turn.

Sometimes a third repeated-measures factor, referred to as "turn", was included in order to compare the three straight zones (X, Y, and Z) to the averages of the turn zones.

Given the large number of statistical tests to be conducted, the .01 level of significance was used. In most of the graphs of the data, each plotted mean is bracketed by a vertical bar indicating +/- standard errors of the mean. Non-pooled standard errors were used, the better to display differences in variability among the groups. Parameters on the graph, such as 'age' in figure 6, have been offset to improve readability of the figures.

HEART RATE

Analysis of the heart rate data found no device effects and no age effects, although there was a significant interaction of loading and subzone ($F = 5.37$, $df = 6/462$, $p = .0001$). Figure 6 shows this interaction. Note that even in subzone A, before any gas-mileage problems or gauge changes, there was an increase of about 5 percent over baseline. This was true even in the straight zones. It appears that driving in HYSIM, even in the best conditions, was more strenuous than sitting in a chair having one's pulse taken.

Profile contrasts, an option of the SAS analysis, indicated a significant rise between subzones A and B, and between subzones Ca and D. These are consistent with increased load as the turn approaches. There is no explanation why the heart rate does not increase from B to Ca.

To further investigate the loading-by-subzone interaction, separate analyses were computed for loading at each subzone. Significant loading differences were found in subzones A and D only. Unfortunately, the profile contrasts show that in both cases heart rate was higher in the easy loading section. Obviously, this is counter-intuitive. One would expect heart rate to increase as loading increased.

To investigate the effect of the simple devices, subzone Ca was compared to subzone Cb for the simple visual and simple audio devices. No overall treatment or age effects were found, and what effects were found were counter-intuitive, as in the larger analysis of variance. For instance, there was a loading by subzone effect such that increases in heart rate in the easy section were higher in Cb than in Ca, but approximately the same for both subzones in the moderate and hard sections. It could be expected that heart rate would increase as the turn approaches, but why should the effect disappear when the subjects reach the harder loading sections?

In summary, the heart rate measure responded to the loading within each zone (from A to D) but this may be influenced by the muscular exertion from talking (the increase from A to B) or from making the turn (the increase from C to D). It was not responsive to overall loading sections, nor did it differentiate among the navigational devices.

REACTIONS TO GAUGES

Gauges changed only during the middle and final third of the drive. Thus, each subject had 10 trials, including the

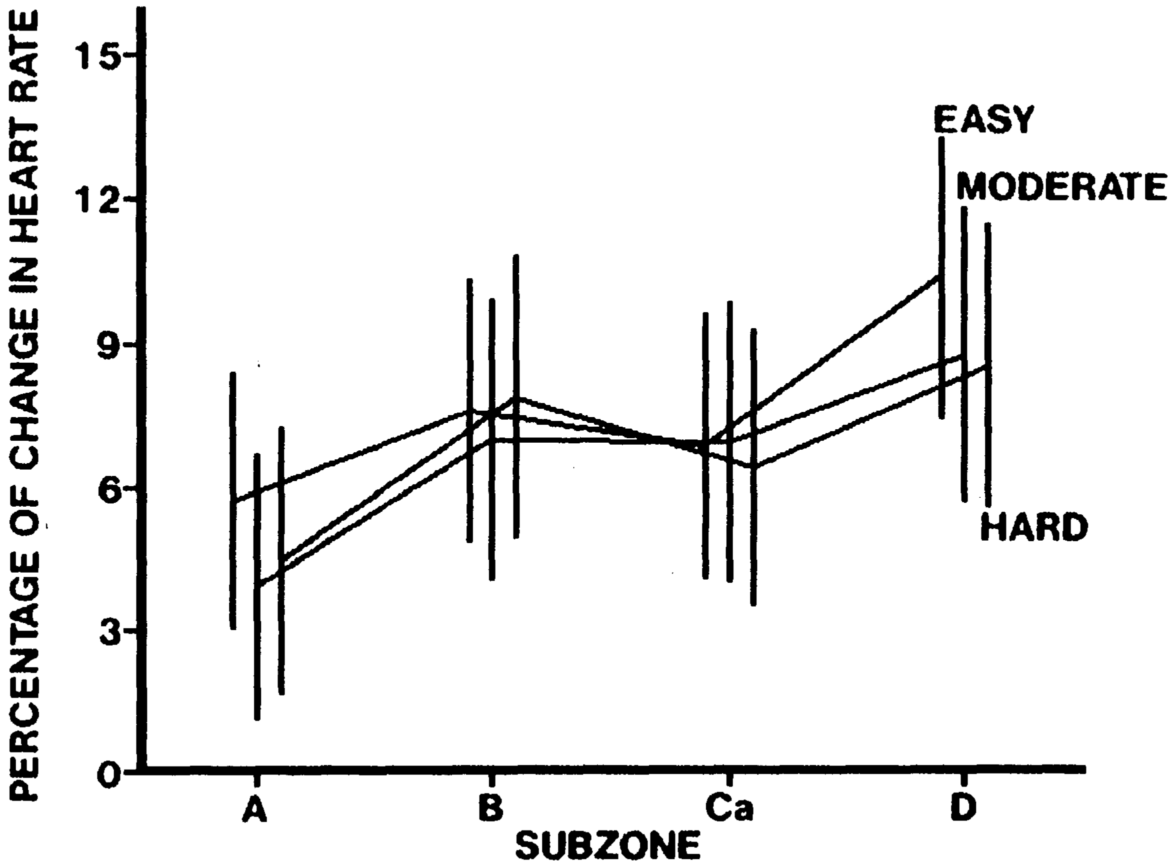


Figure 6. Averages of percentage of change in heart rate, broken down by subzone and loading. (Error bars indicate +/- 2 standard errors of the mean.)

straight zones, for a total of 1260 trials over the whole experiment. Of these, the subjects pressed the response button on 1052 trials, for a 'hit' percentage of 84. Subjects missed 201 trials, for a 'miss' percentage of 16. Seven trials were declared unknown because all the data for those zones were missing, generally due to subjects crashing or suffering from simulator sickness.

The 'miss' percentage was much larger than expected, resulting in a loss of 28 subjects in the analysis of variance. Because this design requires full data sets for each subject, the missing reaction times were assigned the time between the onset of the gauge change and the reset of the gauge by HYSIM. This equaled the time spent in subzones B, C, and D, the maximum possible if the subject had responded at the last second. This resulted in 126 subjects in the final analysis of variance, because the 7 unknown trials were absorbed in the process of averaging within loadings.

No sex or loading effects were found in the analysis, but there were significant turn effects, with significant interactions between turn and device, and between turn and age group. These interactions, and the overall turn effect, are illustrated in figures 7 and 8.

The reaction times in turn zones averaged 6.79 s longer than those in straight zones. This is the turn effect ($F = 31.14$, $df = 1/84$, $p = .0001$). However, as can be seen in figure 7 and in the turn-by-treatment interaction ($F = 4.98$, $df = 6/84$, $p = .0002$), differences were largest for the complex visual and map devices, 20 and 10 s respectively. All auditory devices and the simple visual device had a 2-s difference whereas the medium visual device had a difference of 6 s.

A possible explanation for this interaction lies in the subjects' use of street signs. In the map-control group, subjects could not make a turn without reading the signs; looking for street signs takes time away from looking at gauges. While this interpretation also seems reasonable for the complex visual group, it is inconsistent with results which will be discussed under the section related to navigational errors. A more likely explanation for this group is that time spent scanning the electronic map took time from watching for gauge changes.

Based on the navigational error results which will be discussed later, some subjects in the complex audio group may also have used the street signs for confirmation at the turn. But others may have used the pattern of the message to help them navigate without the street signs. The last message before each turn was, "You are crossing 'X'; the next street is 'Y' and then 'Z'. You should turn (left/right), (cardinal direction), onto 'Z'." The last sentence occurred only in messages just before

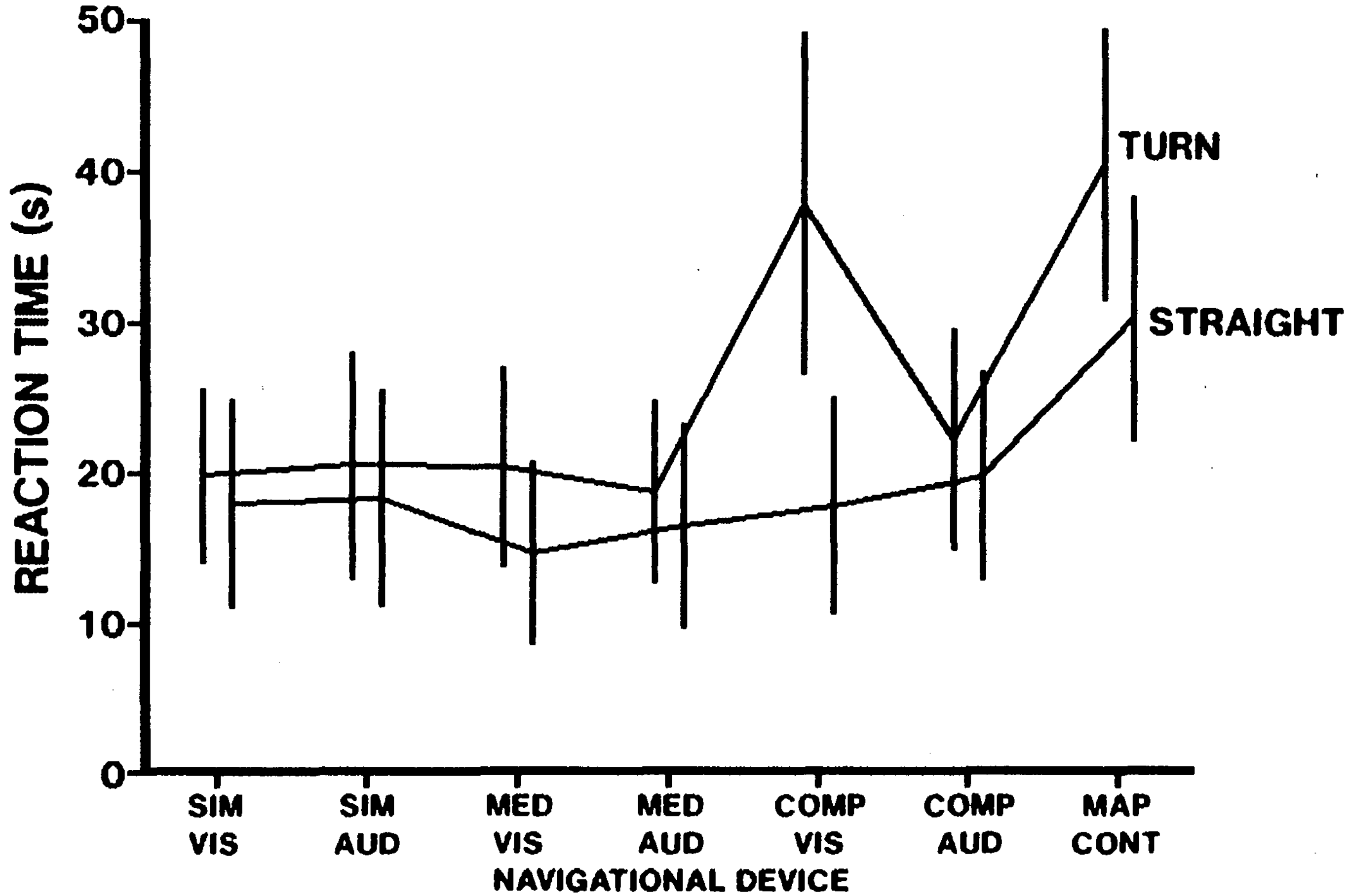


Figure 7. Averages of reaction times to gauges, broken down by device and type of zone. (Error bars indicate +/- 2 standard errors of the mean.)

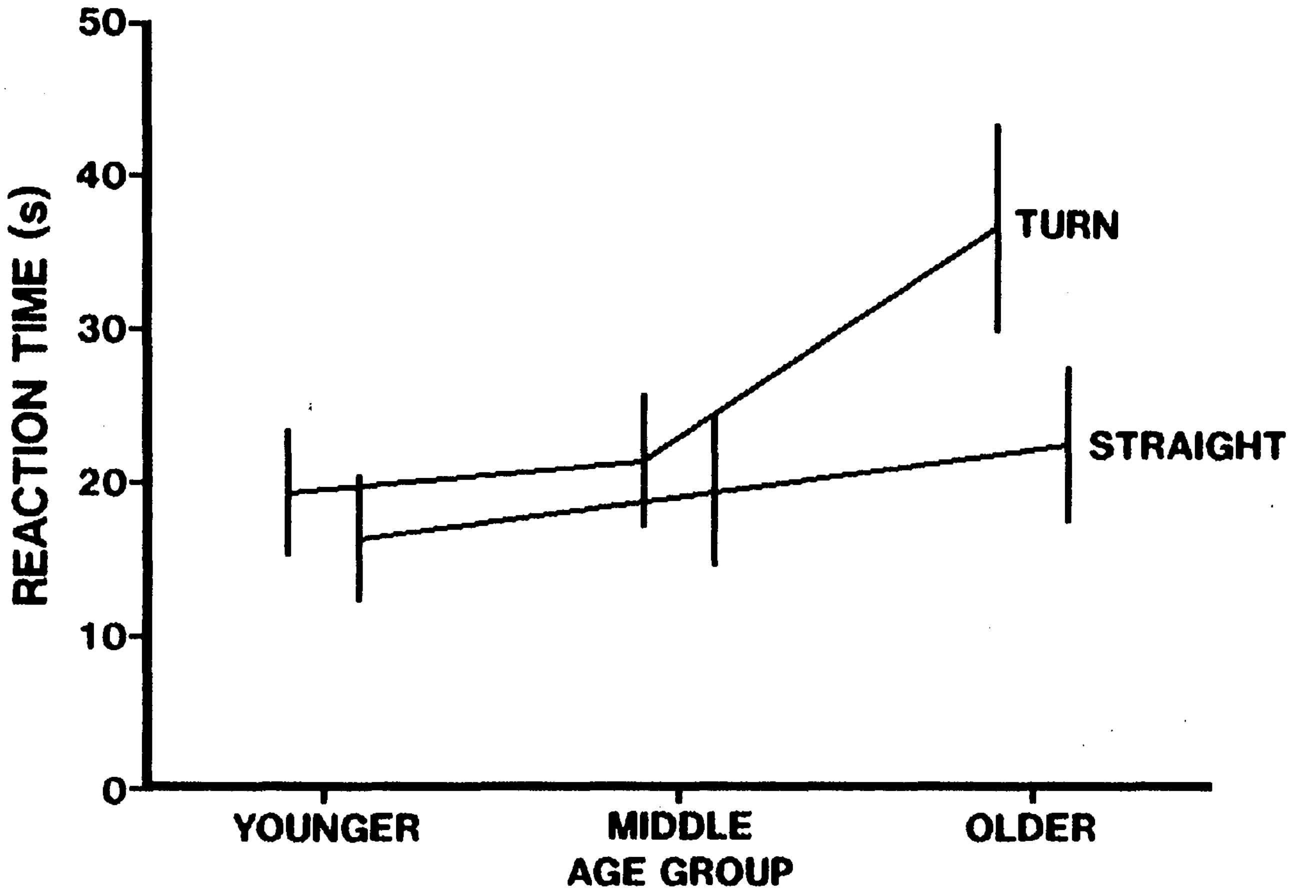


Figure 8. Averages of reaction times to gauges, broken down by age group and type of zone. (Error bars indicate +/- 2 standard errors of the mean.

the turn. Subjects may have realized that when they heard "You should turn. . .", the turn was two streets away.

Figure 8 shows the turn-by-age-group interaction (F = 11.5, df = 2/84, p = .0001). The overall turn effect is again evident along with an age effect which is linear except for the older subjects during turns, indicating that choice-points are particularly demanding for older drivers. This strong interaction emphasizes the need to include this group in driving studies.

Because there was a fairly large percentage of misses, a frequency analysis of hits versus misses was added, using PROC FREQ of SAS. The significant results are shown in figure 9, and follow the results of the reaction time analysis with a few exceptions. There were no overall effects for sex or loading (moderate section vs. hard section). There was an overall age effect (Chi-square = 35.53, df = 2, p = .000) in which the older subjects missed more than the other two groups, and there was a significant interaction between age group and device (Cochran-Mantel-Haenszel Chi-square = 37.26, df = 2, p = .000) which is evident in figure 9.

The analysis tested age group versus gauge-hit-or-missed for each device. The complex visual group had the largest differences (Chi-square = 30.16, p = .000), followed by the medium visual group (Chi-square = 12.49, p = .002), the medium audio group (Chi-square = 11.97, p = .003), and the map-control group (Chi-square = 11.93, p = .003). There were no significant age-group differences within the other three groups: simple visual, simple audio, and complex audio. The hit/miss pattern of the older subjects is similar to their reaction time pattern. On the other hand, the pattern of the middle-aged group is quite different. The middle-aged map-control subjects missed almost as many gauges as the older subjects, but the middle-aged subjects who used the medium visual or medium audio devices missed none, significantly less than either the older or the younger subjects using those devices.

SPEED

Averages of Speeds

As in the reaction time data, a turn factor was added to the analysis to compare the straight zones to the turn zones. This comparison is shown in figure 10. As expected, the straight zones showed relatively little change in speed, whereas in the turn zones the drivers slowed, especially before the turn (subzone C) and after the turn (subzone D). In the analysis of variance, this is shown in a significant turn effect (F = 478.7, df = 1/83, p = .0001), and a turn-by-subzone interaction effect (F = 670.7, df = 3/249, p = .000). Because this inter-

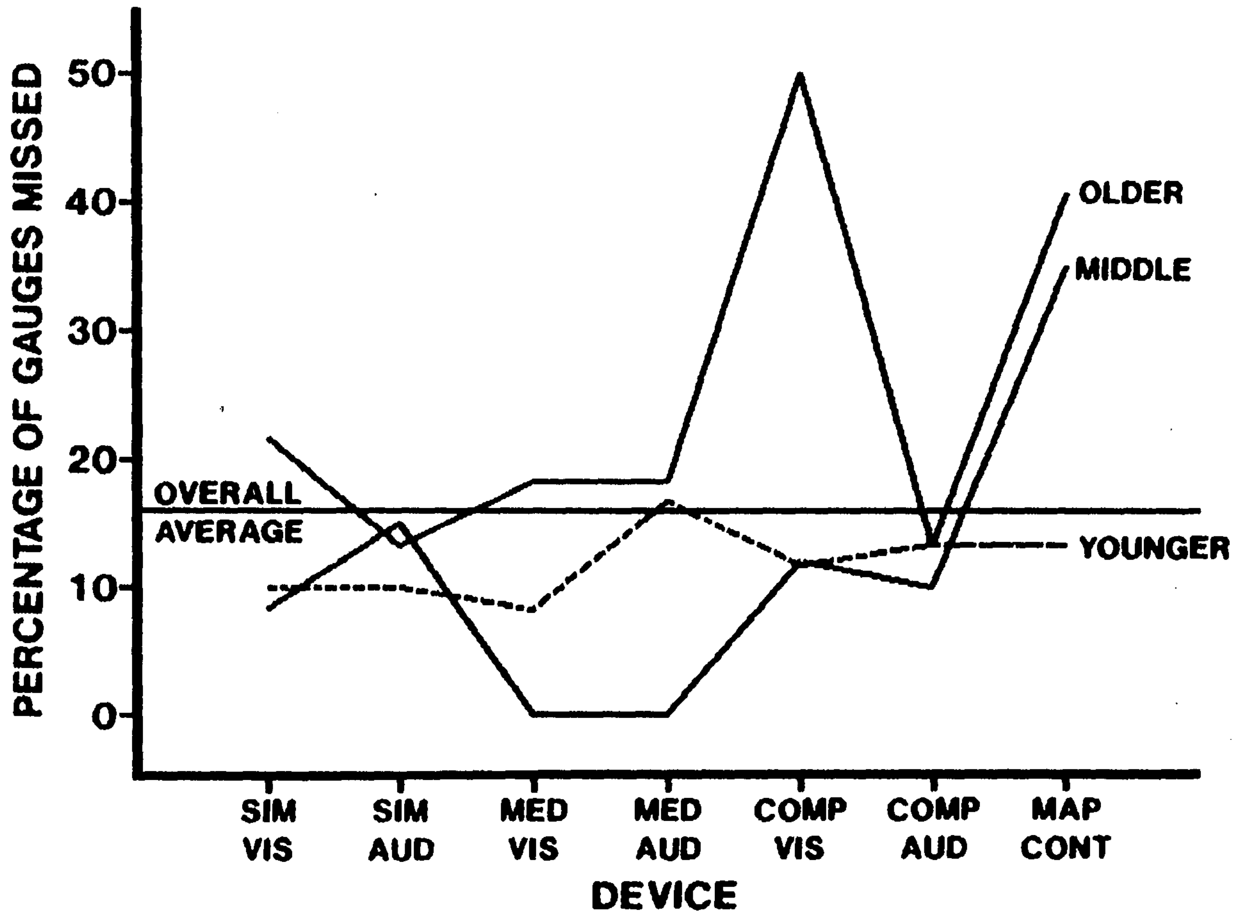
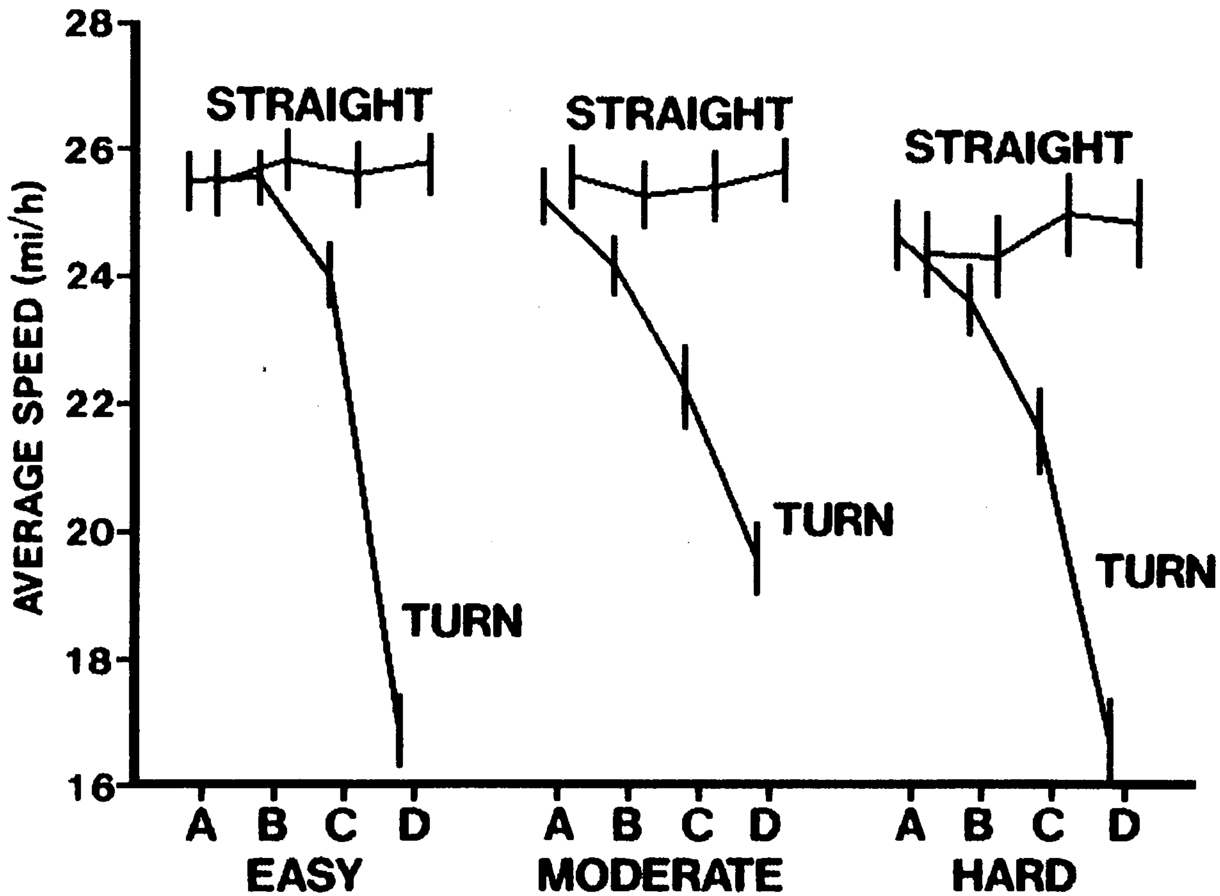


Figure 9. Percentage of gauges missed, broken down by device and age.



1 mi/h = 1.61 km/h

Figure 10. Average speeds, broken down by turn, loading, and subzone. (Error bars indicate +/- 2 standard errors of the mean.)

action was so large, separate analyses were computed for the turn zones and the straight zones. The simpler straight-zone analysis will be presented first.

There were no treatment, age-group, or sex differences in the analysis, either as main effects or as interactions with the within-subjects factors. It could have been expected that the groups using the simple and medium devices, which presented no navigational information during these zones, would have been faster than the map-control or complex visual groups, which had information available, or the complex audio group, which heard a message within subzone C of the straight zones. If drivers in these three groups took in any navigational information, it did not affect their speeds, perhaps because they did not have to act upon it.

The straight-zone analysis did uncover a significant loading effect ($F = 12.49$, $df = 2/166$, $p = .0001$), a significant subzone effect ($F = 4.23$, $df = 3/249$, $p = .0061$) and a significant interaction of the two ($F = 4.34$, $df = 6/498$, $p = .0003$). Profile contrasts indicated that speeds in the hard loading section were 1.2 mi/h (1.93 km/h) slower than in the moderate section. This was significant ($p = .0002$) whereas the difference between the easy and moderate sections (0.2 mi/h) (.32 km/h) was not ($p = .32$). Naturally, decreases in speed were expected as loading increased. Unfortunately, the techniques used did not give a linear function of speed to loading, as there was no significant decrease from the easy section to the moderate section.

To investigate the other significant straight-zone effects, the speeds were broken down by loading and analyzed separately. These analyses showed that there were no significant differences within subzones for the easy or moderate loading sections. This occurred only in the hard section ($F = 5.12$, $df = 3/252$, $p = .0019$), with an increase of 0.67 mi/h (1.08 km/h) between subzones B and C. As can be seen in figure 10, this is the largest change between subzones for all the straight zones. The most plausible explanation is that the gas mileage problems, which were heard at the beginning of subzone B, were sufficiently difficult in the hard zone to slow the driver. However, this does not explain why average speeds in subzone A were just as slow as in subzone B.

In the analysis of the speed data for the turn zones by themselves (collapsed into an average for each loading section), the largest effect was for subzone ($F = 901.84$, $df = 3/252$, $p = .000$), which is very evident in figure 10. There is also an obvious loading effect ($F = 66.1$, $df = 2/168$, $p = .0001$), and a strong loading-by-subzone interaction ($F = 153.98$, $df = 6/504$, $p = .000$) which is mainly due to slower than expected speed in subzone D of the easy loading section. The interaction is better shown in figure 11. The slopes of the lines for subzones A, B, and C are almost linear, but the slope for D is definitely not. If it were linear, the average for D (easy) would be 21 or 22 mi/h (33.79 km/h or 35.40 km/h) instead of 17 mi/h (27.35 km/h). One possible explanation is that the turns on two-lane streets were much more difficult than turns on four-lane streets, even though the two-lane streets were 2 ft (.61 m) wider per lane. It may be related to the corner problem mentioned before, where intersections were made without radii on the corners. Even though the subjects were instructed to 'cut off' the corners, through both example and practice, it remained an unnatural driving action. The experimenters remember many subjects who started a turn late and finished out of their proper lane. This was more likely on four-lane streets than on two-lane streets because subjects seemed more reluctant to go off the road entirely (as when making a late left turn on a two-lane street), and may have slowed more in the two-lane (easy-loading) section in order to stay in their lane.

Another possible explanation is that right turns are harder than left turns, and because the moderate section had only one right turn, its speeds in subzone D were higher. To decide between these possibilities, the average speeds in all 12 zones were inspected. Left turns were no different than right turns, a result which favors the former explanation.

This inspection also uncovered a relationship between speed in subzone D and the distance to the first stop sign after the turn. In at least two zones the sign was visible before the drivers completed zone D, decreasing their average speed and increasing the variance of their speed. This is illustrated in figure 12. The zones with the shortest distances are zone 4 in the easy section (580 ft) (176.78 m) and zone 12 in the hard section (590 ft) (179.83 m). Zones where the Stop sign was between 600 and 700 ft (182.89 m and 213.36 m) away may have been marginally affected. The third point from the left in figure 12 (zone 9, distance 636 ft; 193.85 m) is not significantly slower than zone 11 (distance = 1003 ft; 305.71 m), but the fourth point (zone 10, distance = 674 ft; 205.44 m) is.

Whatever the effect of the visible stop signs, the remainder of the zones in the easy section (1, 2, and 3) average 18.4 mi/h (29.61 km/h), still less than the 19.6 mi/h (31.54 km/h) average in subzone D in the moderate section. Even when subzone D is dropped from the analysis altogether, there is still a strong interaction between loading and subzone ($F = 48.4$, $df = 4/336$, $p = .0001$). It appears among subzones A, B, and C when comparing the easy and moderate sections. In the moderate section, speed drops more quickly in these subzones than it does in the easy section. The difference between A and B is obvious (see figure 10 and compare the slopes of the lines connecting A and B in turn sections of the easy and moderate zones), while the differences of the B-C slopes are not as

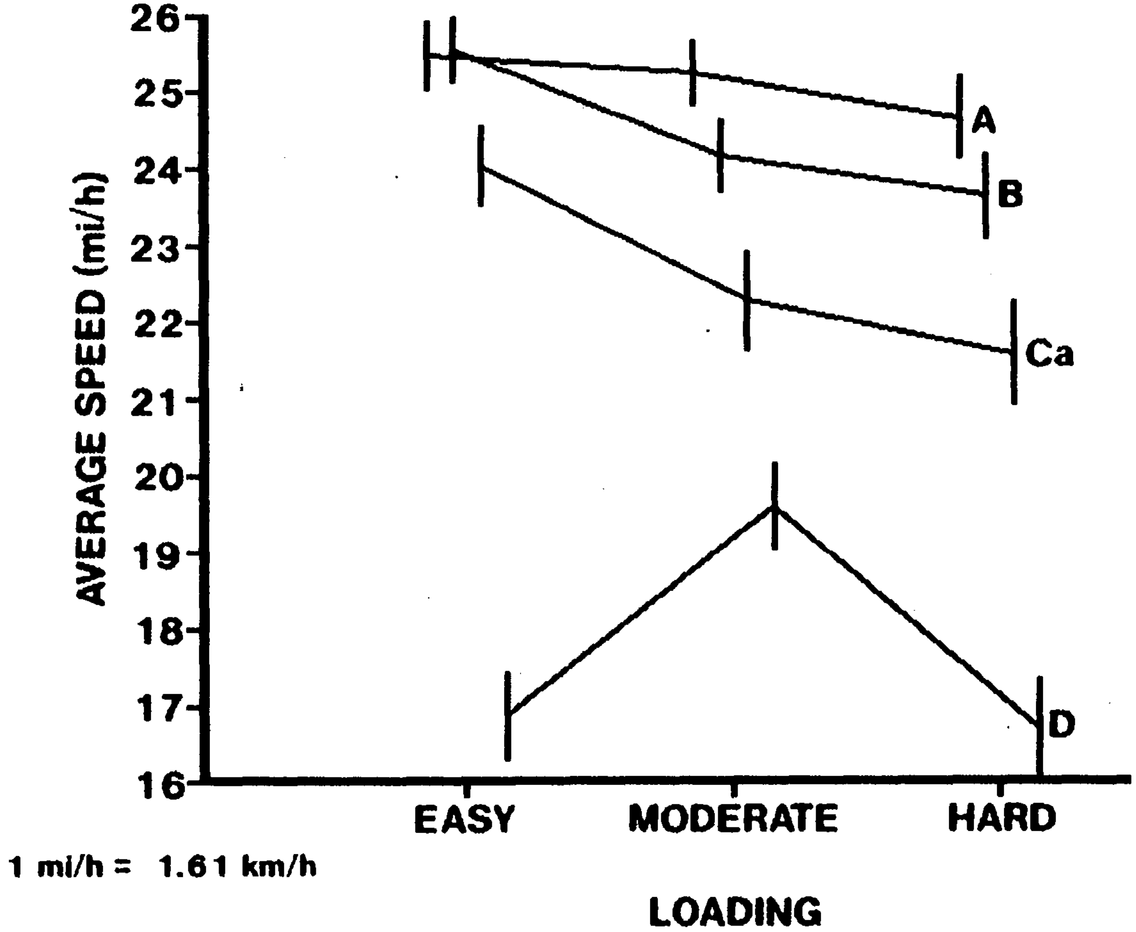


Figure 11. Average speed around turns, broken down by loading and subzone. (Error bars indicate +/- 2 standard errors of the mean.)

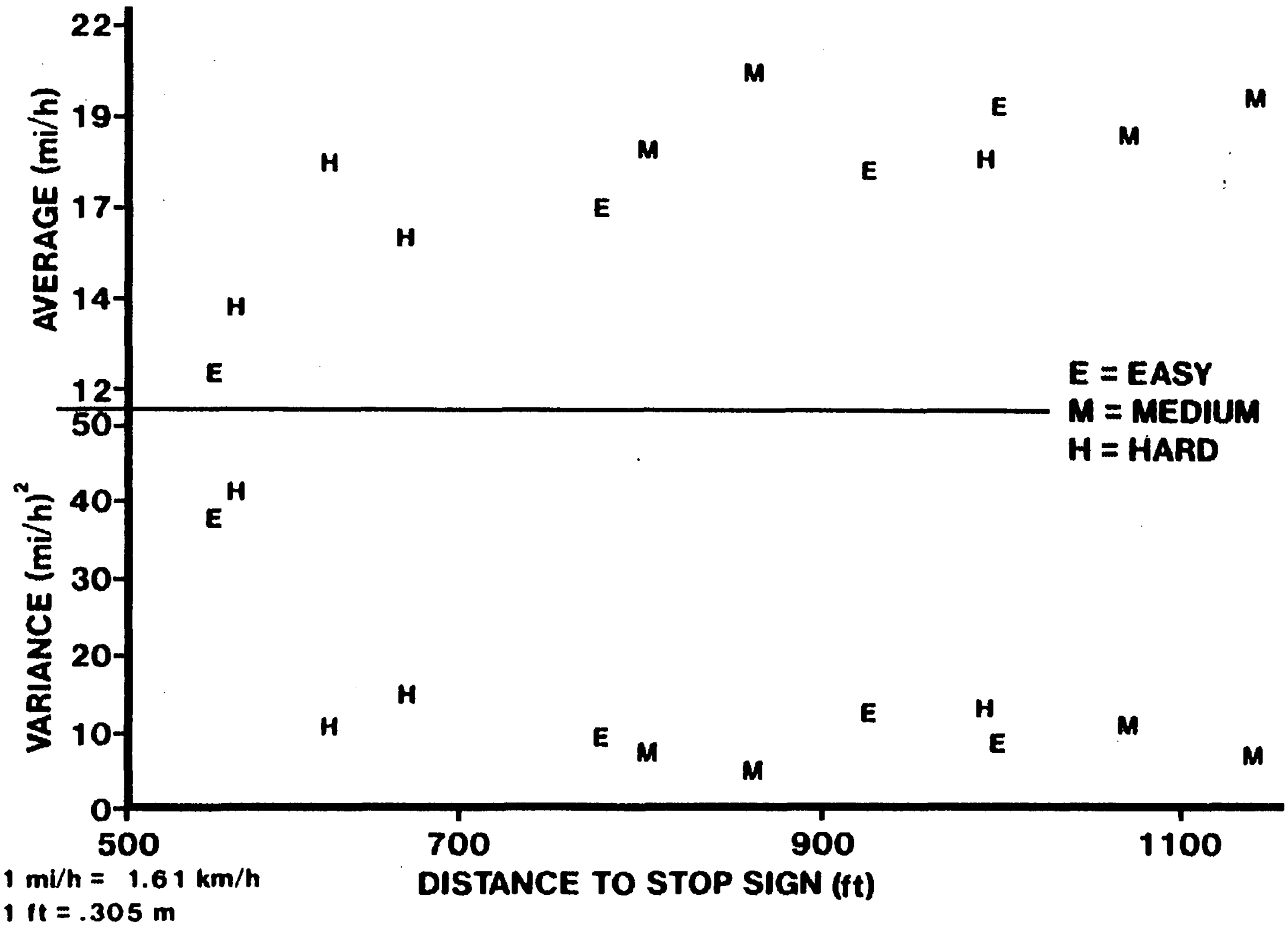


Figure 12. Effect of visible stop sign in zone D on average and variance of speed.

evident. However, the slowing in the moderate section (1.88 mi/h) (3.02 km/h) is significantly more than that in the easy section (1.51 mi/h) (2.43 km/h) ($F = 9.22$, $df = 1/84$, $p = .0032$). These effects can also be seen in figure 11 in the non-parallel lines between easy and moderate loading for subzones A, B, and C. One explanation for the A-B difference is that the easy gas-mileage problems had no effect on speed whereas the moderate problems, along with the other loading changes, did slow the drivers. Going from moderate problems to hard problems, on the other hand, had no effect ($F = 0.42$, $df = 1/84$, $p = .5188$).

Considering navigational device effects, there was a significant overall effect ($F = 9.58$, $df = 6/84$, $p = .0001$). In addition, there were significant interactions with loading ($F = 3.28$, $df = 12/168$, $p = .0003$), subzone ($F = 10.24$, $df = 18/252$, $p = .0001$), and the combination of loading and subzone ($F = 2.05$, $df = 36/504$, $p = .0004$).

Figure 13 illustrates the overall treatment differences and the subzone-by-device interaction. In all subzones, the complex visual group had the slowest speeds with one exception (in subzone A of the easy section). In subzone D it was significantly slower than all of the other groups. In subzone A it was significantly different from the simple audio group, but none of the others. In subzones B and C the differences depended on the loading section. This triple interaction is shown in figures 14, 15, and 16.

Before going into those specifically, two features of figure 13 should be emphasized. The first is the lack of change in both simple groups between subzones B and Ca. This is because in those two groups the 200 ft (60.96 m) nearest to the turn was separated out as subzone Cb, which did not exist for the other groups. Thus the slowing that occurred immediately before the turn was excluded from those two groups. A comparison of Ca and Cb for the simple groups will be presented later in the paper. The second feature is the large decrement for the complex visual group between subzones C and D (5.68 mi/h) (9.14 km/h). It could be argued that subjects in that group were looking for the stop sign more than the others since they had to set their next destination there, and would be more affected by the close stop sign problem mentioned above. The map-control group, which had to change maps at the stop sign, also showed a large decrement from Ca to D (5.14 mi/h) (8.27 km/h), although not as much as the complex visual group. On the other hand the complex visual group also had a larger decrement from B to Ca (3.60 mi/h) (5.80 km/h) than any other group, and here the stop sign has no effect.

Returning to the treatment differences in the previous paragraph, and looking first at subzone B, there were no significant treatment differences in the easy section ($F = 1.82$,

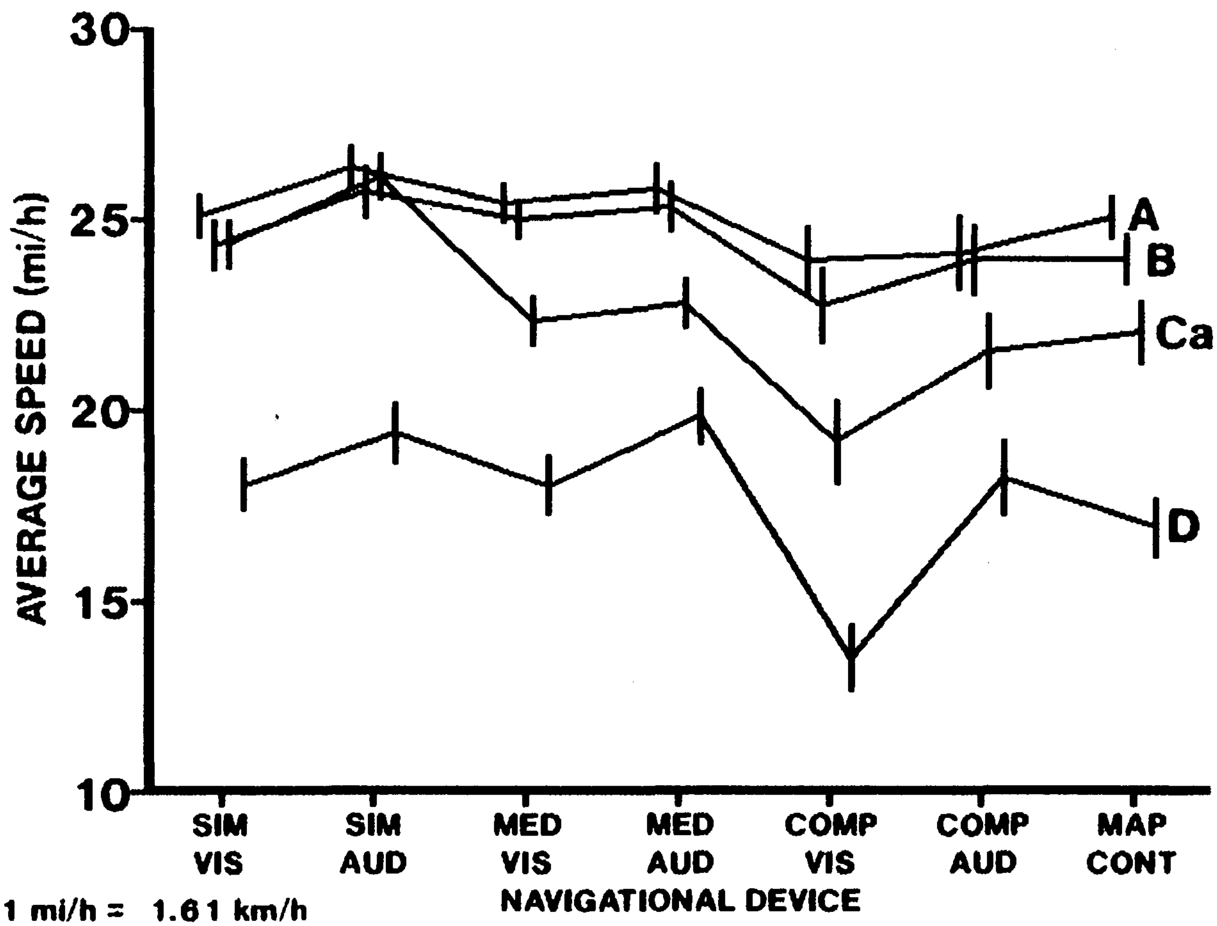


Figure 13. Average speed broken down by subzone and treatment. (Error bars indicate +/- 2 standard errors of the mean.)

df = 6/84, p = .1056), as seen in figure 14. The range among groups was 2.1 mi/h (3.38 km/h). In the moderate section (see figure 15) during subzone B, the complex visual group was significantly slower than the medium audio group according to the Ryan-Einot-Gabriel-Welsch Multiple F test (REGWF). The difference here was 2.7 mi/h (4.34 km/h), which is a marginal difference as indicated by the overall treatment effect (F = 2.38, df = 6/84, p = .0357). In the hard section, shown in figure 16, the complex visual group (21.3 mi/h) (34.29 km/h) is significantly slower than the simple audio (25.5 mi/h) (41.05 km/h), medium audio (24.8 mi/h) (39.91 km/h), and medium visual (24.4 mi/h) (39.28 km/h) groups (F = 4.39, df = 6/84, p = .0007).

For subzone C in the easy section (figure 14), the complex visual group (21.4 mi/h) (34.43 km/h) is slower than all other groups except the complex audio group (23.0 mi/h) (37.00 km/h), (F = 11.1, df = 6/84, p = .0001). Note that the complex visual is the only group that is slower than the map-control group. In the moderate section (figure 15), the complex visual group (18.8 mi/h) (30.25 km/h) is significantly slower than all other groups (F = 14.59, df = 6/84, p = .0001).

In general, the complex visual is slower than the other groups, and these differences increase over loading and subzone.

Turning to age-group effects in the speed data, there is an overall effect (F = 17.21, df = 2/84, p = .0001) in which, as expected, the younger drivers are fastest (23.59 mi/h) (37.96 km/h), then the middle-aged drivers (22.18 mi/h) (35.69 km/h), and the older drivers are slowest (20.92 mi/h) (33.66 km/h). These averages are for the turn zones, collapsed across loading sections and subzones.

There are also interactions of age group with subzone (F = 5.32, df = 6/252, p = .0001), and with loading and subzone (F = 2.32, df = 12/504, p = .0069). Figures 17, 18, and 19 show these interactions. The computed contrasts show age differences, in addition to those mentioned above, between subzones A and B, and between B and Ca. (These are not shown directly in the figures since the averages involved are collapsed across the loading factor.)

Between A and B, and the older and middle-aged groups slow significantly more (F = 6.98, df = 2/84, p = .0016) than the younger group. Speed reductions are 0.81, 0.86, and 0.35 mi/h (1.30, 1.38, .56 km/h) respectively. Between B and Ca, the older group slows significantly more (F = 16.08, df = 2/84, p = .0001) than the middle-aged and younger groups. Here the reductions are 2.61, 1.53, and 1.30 mi/h (4.20, 2.46, 2.09 km/h) respectively.

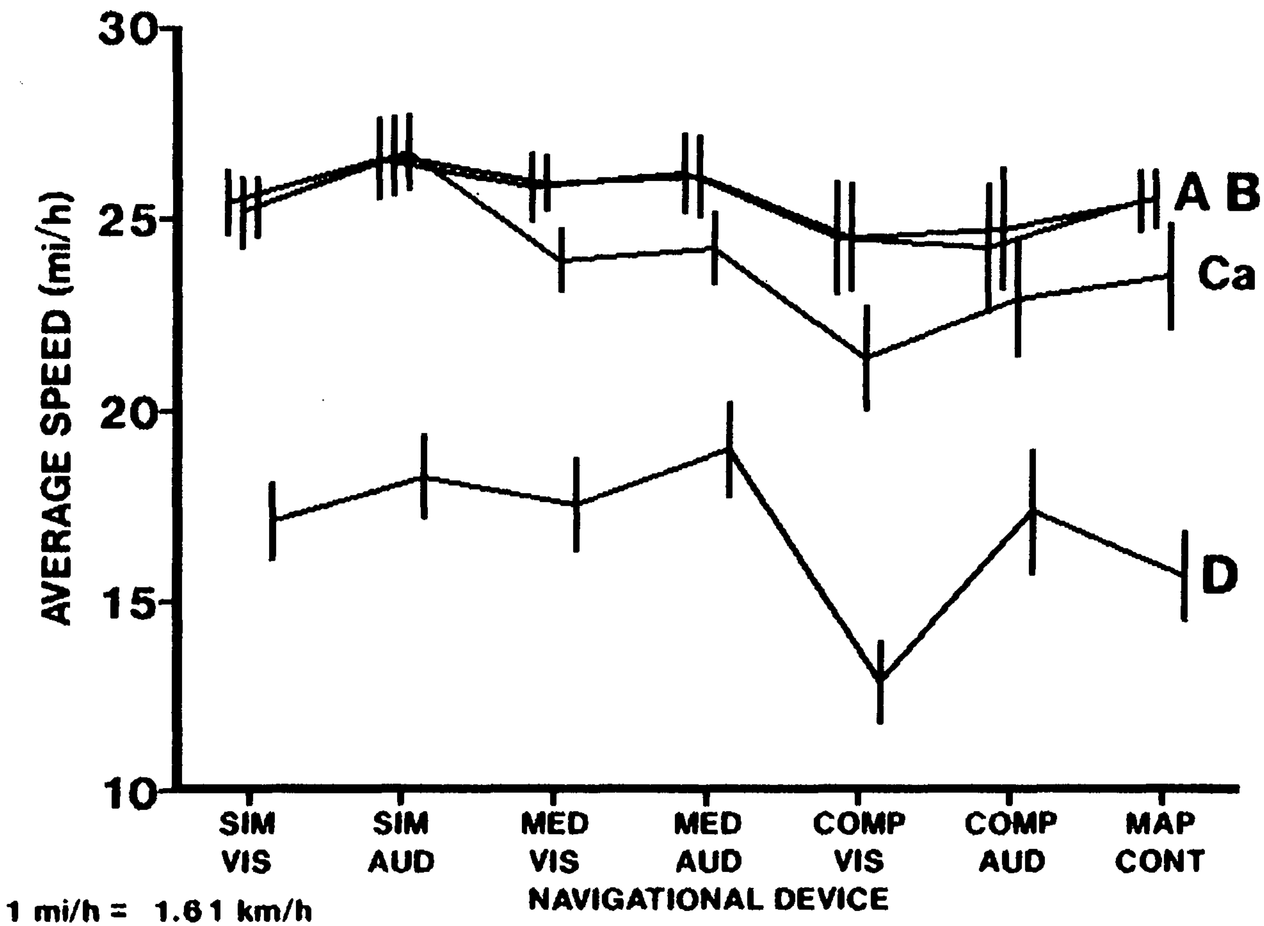


Figure 14. Average speed broken down by treatment and subzone, easy loading only.
(Error bars indicate +/- 2 standard errors of the mean.)

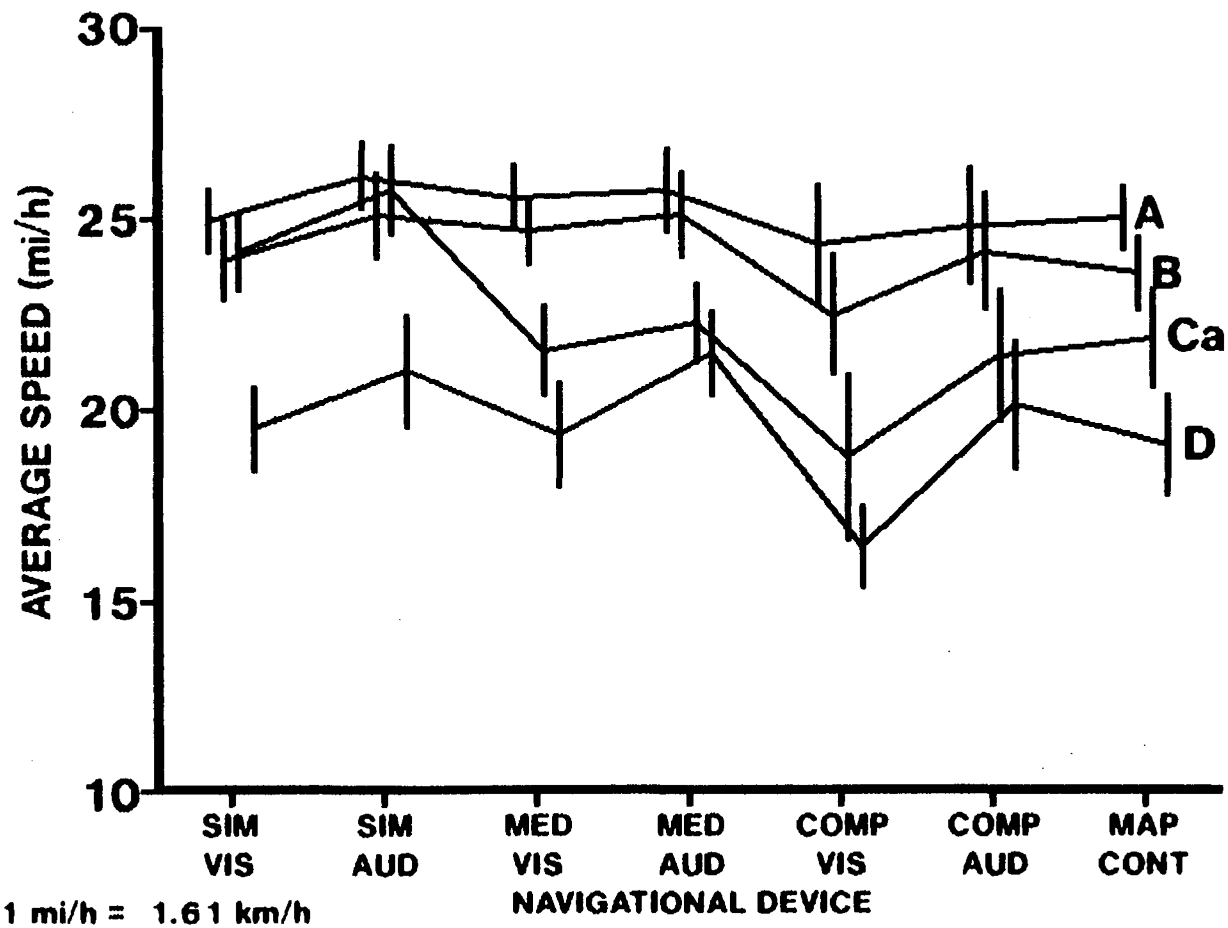


Figure 15. Average speed broken down by treatment and subzone, moderate loading only.
(Error bars indicate +/- 2 standard errors of the mean.)

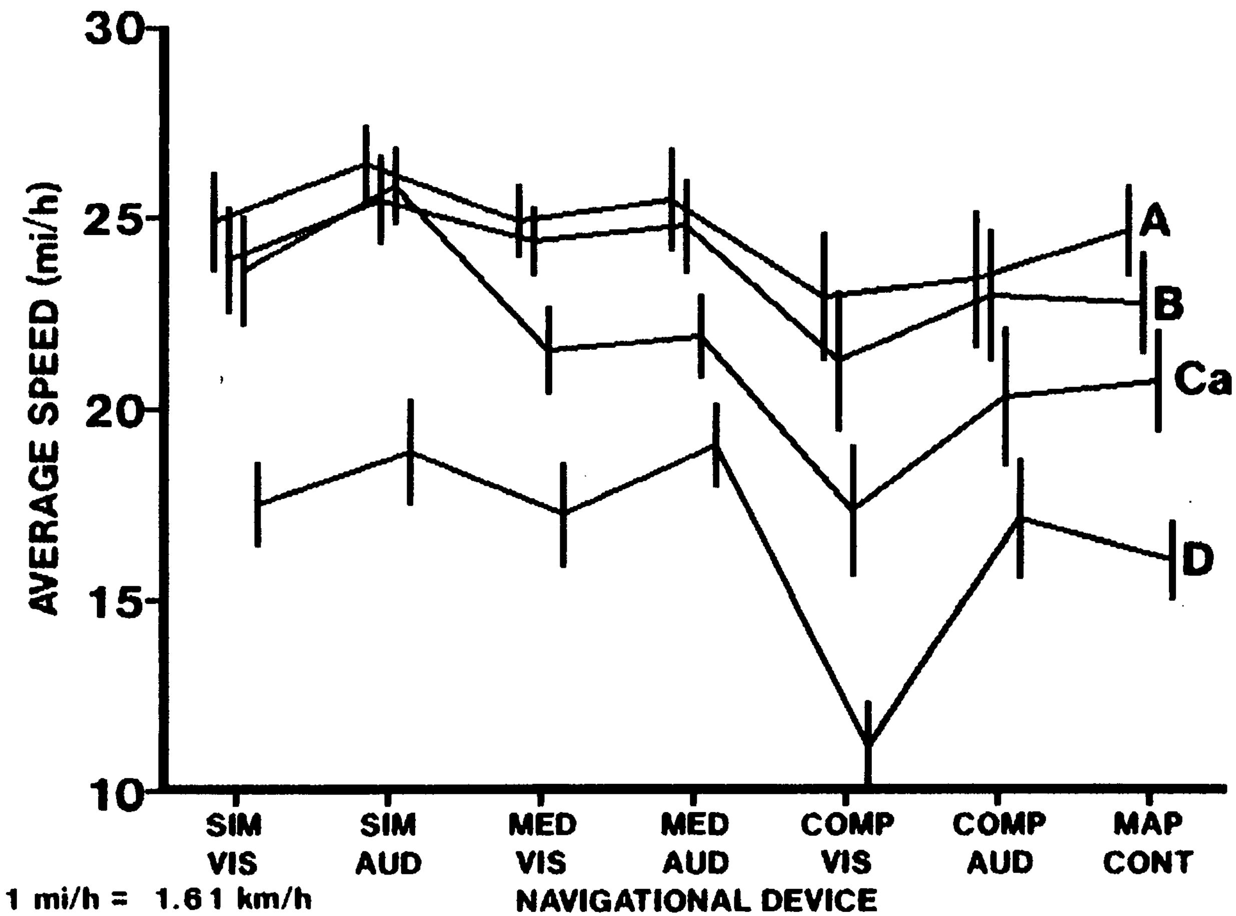


Figure 16. Average speed broken down by treatment and subzone, hard loading only.
(Error bars indicate +/- 2 standard errors of the mean.)

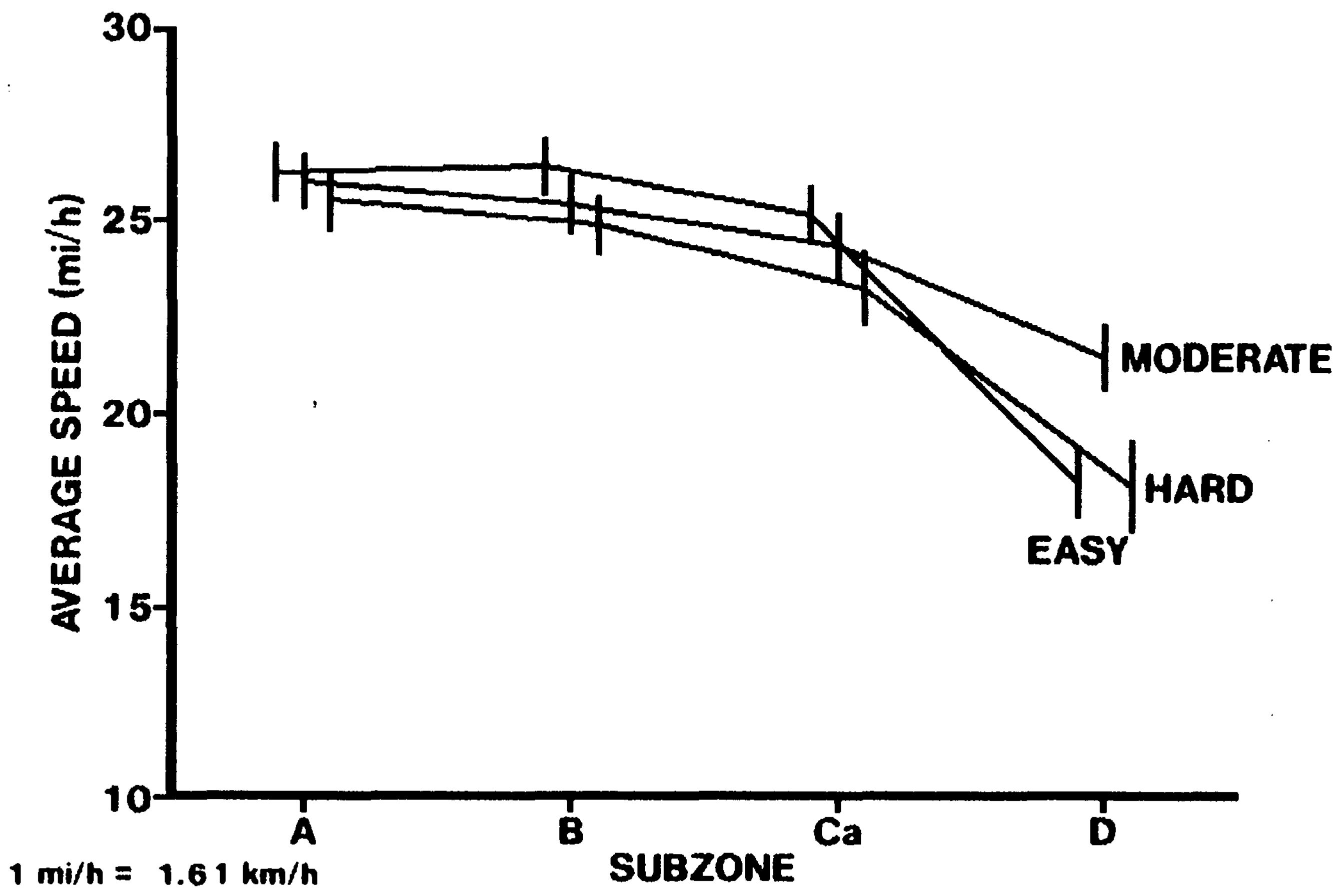


Figure 17. Average speed broken down by subzone and loading, younger only. (Error bars indicate +/- 2 standard errors of the mean.)

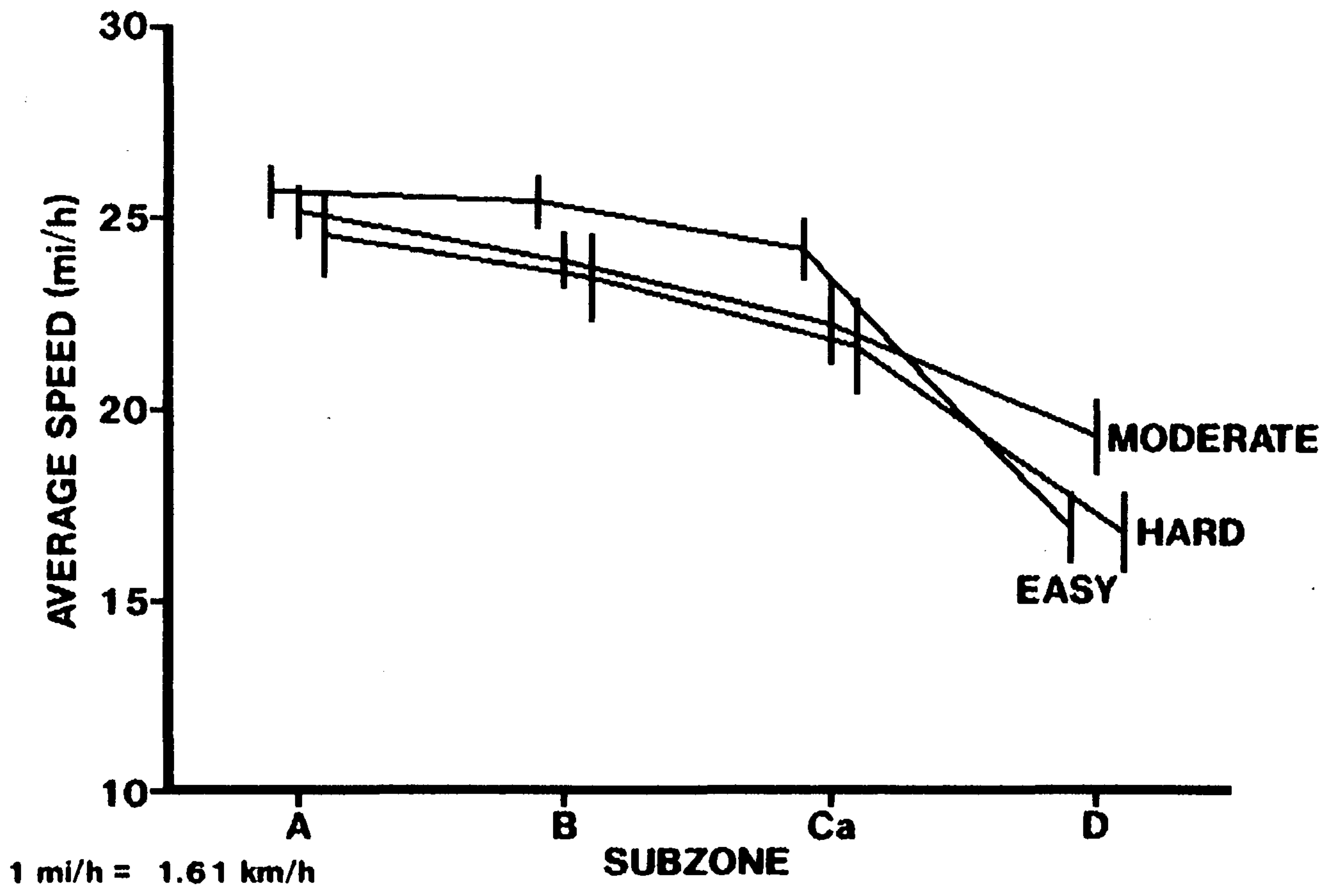


Figure 18. Average speed broken down by subzone and loading, middle only. (Error bars indicate +/- 2 standard errors of the mean.)

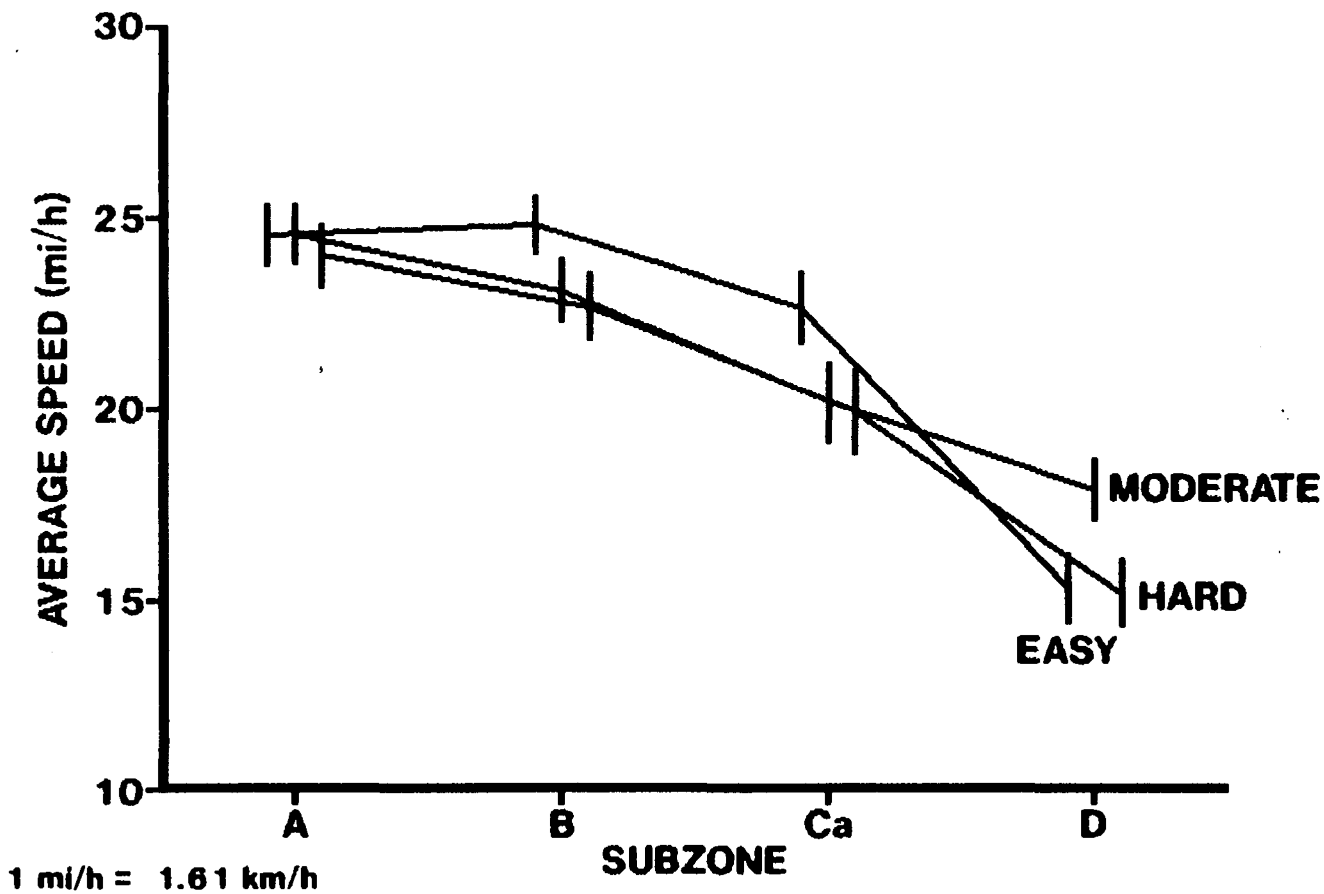


Figure 19. Average speed broken down by subzone and loading, older only. (Error bars indicate +/- 2 standard errors of the mean.)

Regarding the age-by-loading-by-subzone interactions, the two most significant contrasts related to that interaction are as follows: First, if one compares changes from A to B in the easy to changes from A to B in the moderate section, the older group slows more than the other two groups ($F = 8.59$, $df = 2/84$, $p = .0004$). Even though all groups slow more in the moderate section than in the easy section, the older group shows twice the effect of the younger group, with the middle group in between. Changes are 1.71, 0.74, and 1.00 mi/h (2.55, 1.19, 1.61 km/h) respectively. Second, if one compares change from B to Ca in the easy section to changes from B to Ca in the moderate section, the results are similar ($F = 5.24$, $df = 2/84$, $p = .0072$) except that the middle group is not different from either of the others. For the younger group the slowing in the moderate section was actually less than in the easy section, so their average contrast is -0.14 mi/h (-.23 km/h). For the middle and older groups the averages were 0.42 and 0.81 mi/h (.68 and 1.30 km/h) respectively.

Although these amounts are small, remember they are added to the overall age effects and the age-by-subzone effect. Moreover, the pattern of interactions emphasizes the additional problems experienced by the ageing driver. Referring to figures 17 and 19, the total effect can best be seen by looking at the line slopes from A to B to C (the top line is the easy section and middle line is the moderate section). Note how in figure 19, the older group shows greater slowing as they progress from A to B to C, especially compared to the smaller changes in the younger group, shown in figure 17.

Speed in Cb

For the simple visual and simple audio groups, subzone C was broken into two parts because they were not given any navigation information until approximately 200 ft (60.96 m) before the turn. Ca is the subzone from the usual start of C to where the navigation message started, the Cb is the remainder of C (remember that the 50 ft (15.24 m) nearest the turn was not included due to the indeterminacy problem mentioned previously). The average length of subzone Cb was 172 ft (52.43 m). Figure 20 includes Cb in the speed profiles of the two simple groups.

Compared to the other groups as a whole, the simple groups differ only in subzone Ca, where they are faster, as has been mentioned above. This difference is obvious because the drivers had to slow most in the 200 ft (60.96 m) before the turn, and this data is excluded from Ca in the simple groups. Comparing the two groups to each other, there were no treatment effects, even though, as figure 20 indicates, the simple audio group was faster in 12 of the 16 subzones.

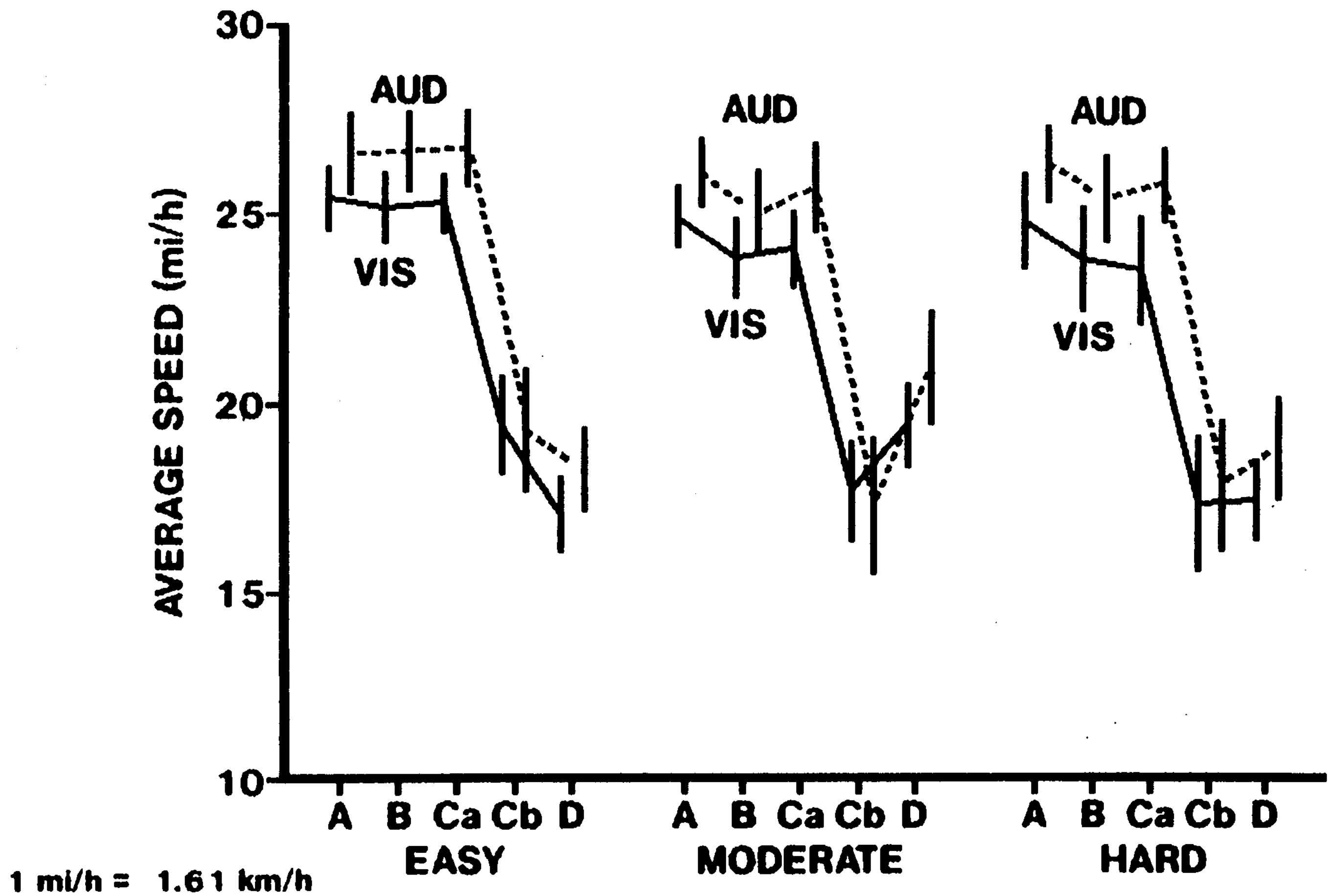


Figure 20. Average speeds for simple visual and simple audio devices, broken down by loading and subzone. (Error bars indicate +/- 2 standard errors of the mean.)

As in the larger speed analysis, there were significant age-group (F = 8.43, df = 2/24, p = .0017, loading (F = 6.34, df = 2/48, p = .0036), subzone (F = 296.75, df = 4/96, p = .0001), and loading-by-subzone (F = 31.51, df = 8/192, p = .0001) effects. In addition, there was a significant age-by-subzone effect (F = 3.77, df = 8/96, p = .0022).

The loading profile indicated no significant differences from the easy section to the moderate section, nor from the moderate section to the hard section, so the overall significance mentioned in the previous paragraph must be based on a significant difference between the easy and hard sections, indicating a minor overall loading effect for the simple groups.

The subzone profile indicated no significant slowing between B vs. Ca or Cb vs. D (over all loading sections), but as in the larger speed analysis there is a significant drop from A to B (F = 34.61, df = 1/24, p = .0001). The loading-by-subzone interaction must be considered here. As in the larger analysis there is more slowing in the moderate and hard sections than in the easy section (F = 9.85, df = 1/24, p = .0045, p = 0001). As mentioned before, a possible reason for this is that the gas-mileage problems were more difficult in the moderate and hard sections.

The largest effect in the entire analysis is the difference between Ca and Cb (F = 418.09, df = 1/24, p = .0001), with an average slowing of 7.04 mi/h (11.3 km/h). Unfortunately, in retrospect it can be seen that the effect of the navigational message is confounded with the effect of subjects slowing for the turn, and these cannot be separated without Cb speed data for the other groups (which cannot be obtained). The best guess is that the slowing was due to preparation for the turn, especially because Ca for the other groups (which includes the 200 ft (60.96 m) closest to the turn) was slower than Ca for the simple groups.

Another large effect occurs in the contrast analyses for loading-by-subzone interactions. Comparing the easy section to the moderate section, note the change from Cb to D. In the easy section the drivers slowed by 1.7 mi/h (2.74 km/h), whereas in the moderate section their speed in the last subzone (D) was faster than in subzone Cb by 2.7 mi/h (4.34 km/h). The hard section was more similar to the moderate section than the easy section, although the increase in speed from Cb to D was only 0.6 mi/h (.97 km/h). It is logical that speeds in subzone D were higher than those in subzone Cb, as D is longer and the drivers had more time to regain their normal speed. The reasons why subzone D in the easy section was slower than expected has been discussed previously.

The age-group-by-subzone interaction was also similar to those discussed previously. The largest age effects occurred in subzone Cb, especially in the moderate and hard sections, where the older subjects drove significantly slower than the middle-aged subjects, who drove significantly slower than the younger subjects.

Channel and Complexity Analysis

An additional analysis was computed for the speed data that deleted the map-control group and separated the other six groups into a channel-by-complexity matrix. The two channels were visual and auditory, and the three complexities were simple, medium, and complex. Thus the design had six factors: channel, complexity, age group, sex, loading and subzone. The analysis did not include the straight zones.

Figure 21 shows the results for the complexity factor, while figure 22 shows the results for the channel factors. As in the original speed analysis, there were significant effects for age group (F = 11.74, df = 2/72, p = .0001), loading (F = 60.05, df = 2/144, p = .0001), subzone (F = 700.71, df = 3/216, p = .0001), and loading -by-subzone (F = 122.41, df = 6/432, p = .0001). The effects here are very similar to the original. Deleting the map control group had little influence on these results.

Both the complexity factor (F = 17.53, df = 2/72, p = .0001) and the channel factor (F = 13.42, df = 1/72, p = .0005) were significant. There was not a channel-by-complexity interaction, except in conjunction with subzone (F = 5.43, df = 6/216, p = .0001). Other interactions not already covered in the original speed analysis include a loading-by-complexity effect (F = 8.43, df = 4/144, p = .0001), a subzone-by-channel effect (f = 12.26, df = 3/216, p = .0001), a subzone-by-complexity effect (f = 16.42, df = 6/216, p = .0001), and a loading-by-subzone-by-complexity effect (F = 2.36, df = 12/432, p = .0059).

It was suspected that many of these interactions were due to the low speeds in subzone D by drivers using the complex visual device. To investigate this possibility, two additional analyses were run, the first without subzone D and the second without the complex groups. First looking at figure 21, the largest differences were between the complex groups versus the simple and medium groups. This is the overall complexity effect. Without the complex groups, the overall complexity effect just misses significance (F = 6.97, df = 1/48, p = .0112). A significant complexity-by-subzone effect (F = 27.49, df = 3/144, p = .0001) is left, due to differences between simple and medium groups in subzone Ca, but this is due to the exclusion of subzone Cb from the simple groups. Without this artificial difference, the speed data is virtually identical for the simple and medium groups.

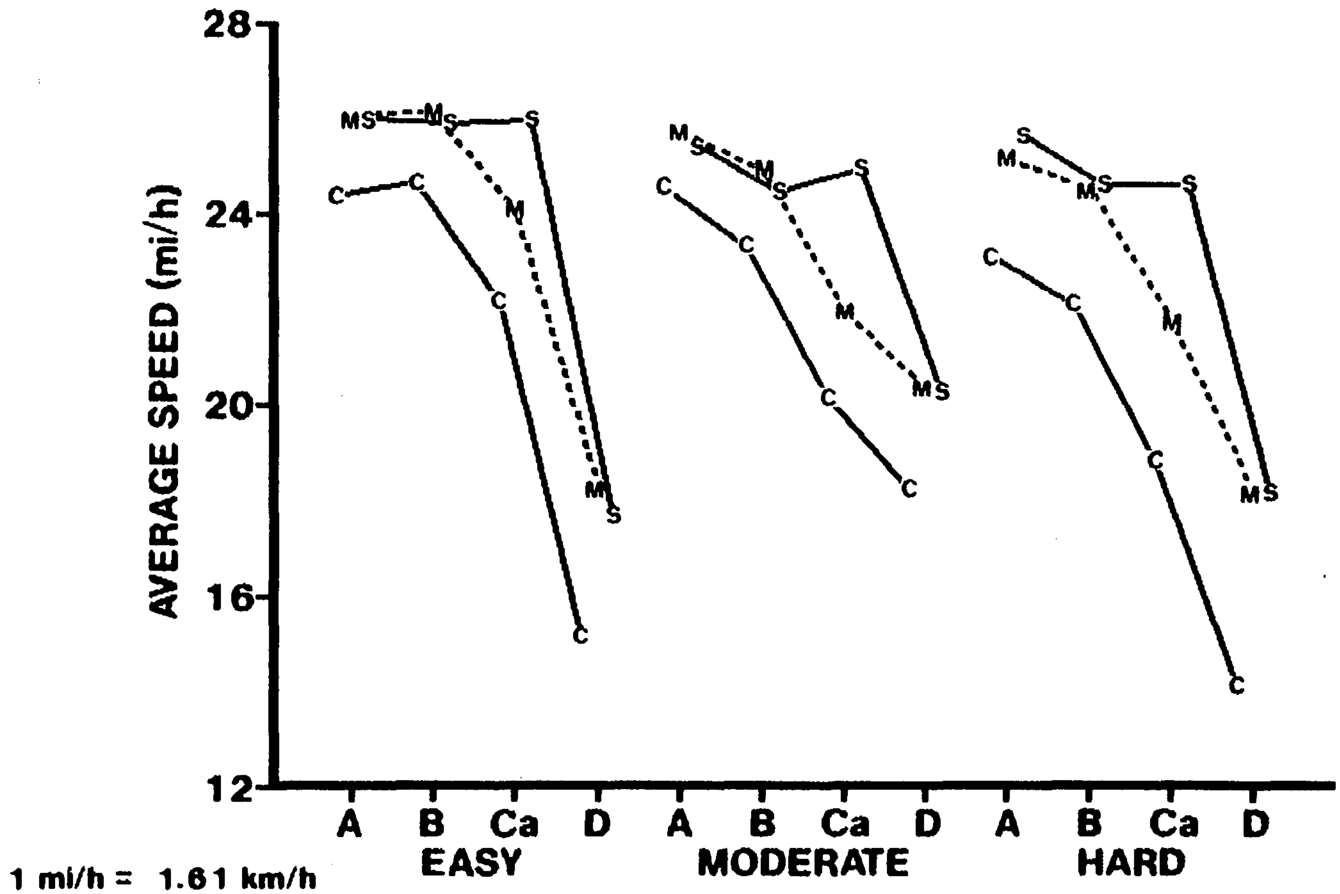


Figure 21. Comparison of simple vs. medium vs. complex devices, by loading and subzone.

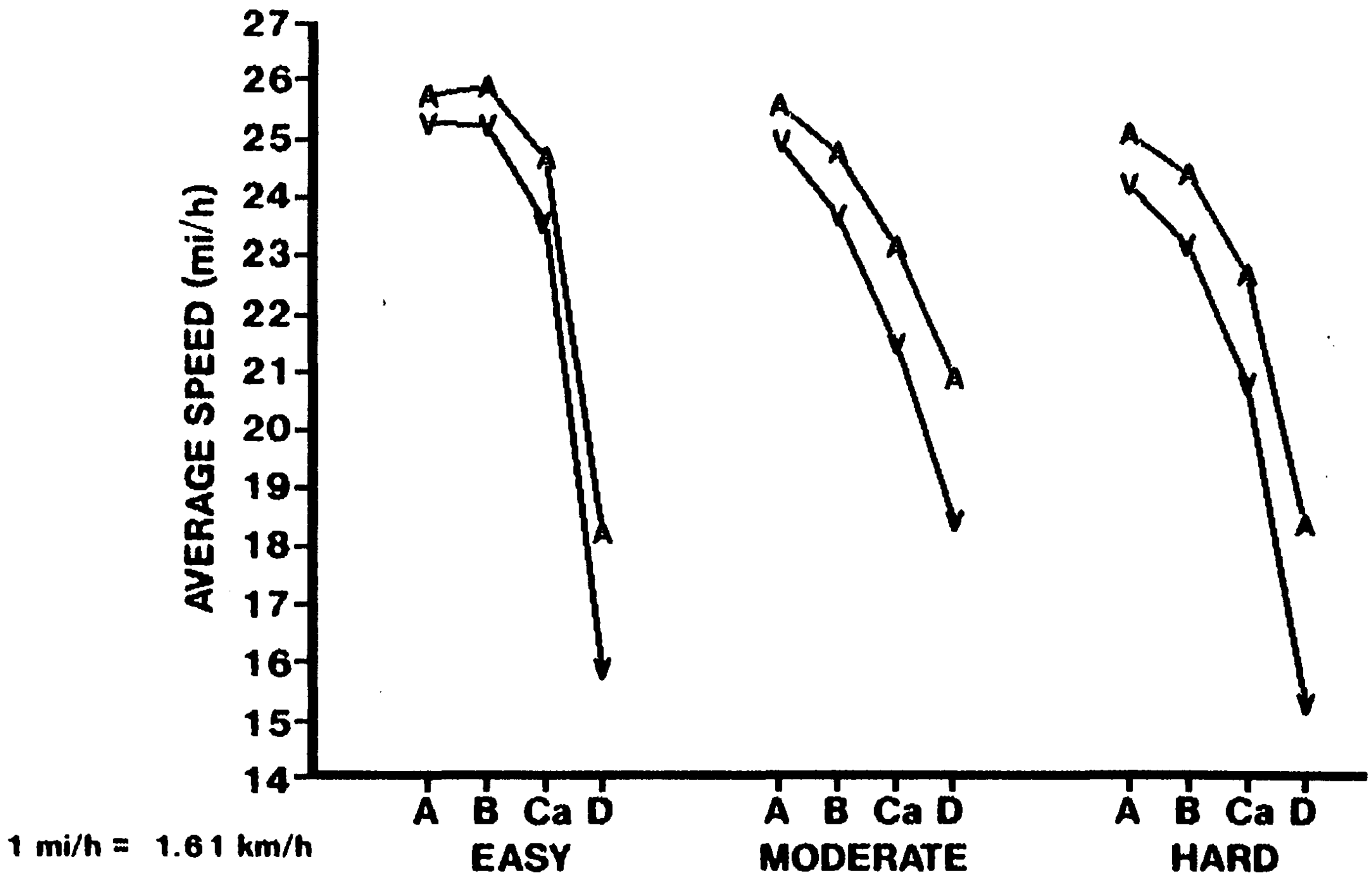


Figure 22. Comparison of visual vs. auditory devices, by loading and subzone.

The loading-by-complexity interaction occurred between the moderate and hard sections. The contrast comparing the two sections shows significant differences between the complex groups and the others. All groups were slower in the hard section, but the complex groups slowed by more than twice as much as the others, showing that increased load had more effect on the complex groups, as was expected. The analysis without subzone D shows the same pattern, and obviously, the analysis without the complex groups shows no loading-by-complexity effect.

Concerning the loading-by-subzone-by-complexity effect, the contrasts indicate it occurs when comparing subzones only between the easy and moderate sections, not the moderate and hard sections. It is still significant when subzone D is removed, but is no longer significant when the complex groups are removed from the analysis. Inspection of the changes involved (from subzone to subzone and from section to section) indicate that the major cause is the increase from B to Ca in the moderate section for the simple groups, when they show no difference in the easy section, and the other groups slow from B to Ca in both sections. No explanation is offered for the effect.

Looking at figure 22, both the overall channel effect and the channel-by-subzone effect can be seen. The auditory groups averaged 1.5 mi/h (2.41 km/h) faster than the visual groups, and the effect is greatest in subzones Ca and D. In fact, removing subzone D removes the overall channel effect, although a channel-by-subzone effect remains. Removing the complex groups removes both effects.

This last point leads to an explanation of the final effect mentioned, the subzone-by-channel-by-complexity effect. Inspection of the means, especially comparing the audio groups to their visual counterparts, shows that the simple and medium groups show consistent audio-visual differences, but the complex visual group shows increasing differences from the complex audio group as the subzones progress. This leads to the conclusion that loading interacts with complexity and channel at the higher levels. Perhaps the complex visual device simply has too much to distract the driver.

LATERAL PLACEMENT

Variance of Lateral Placement

It should be emphasized that the lateral placement variance measure includes the leeway adjustment based on the changing lane width of the drive. In real numbers, the subjects' performance is quite similar in the three workload conditions. However, because the lanes become narrower, similar variability results in more dangerous driving.

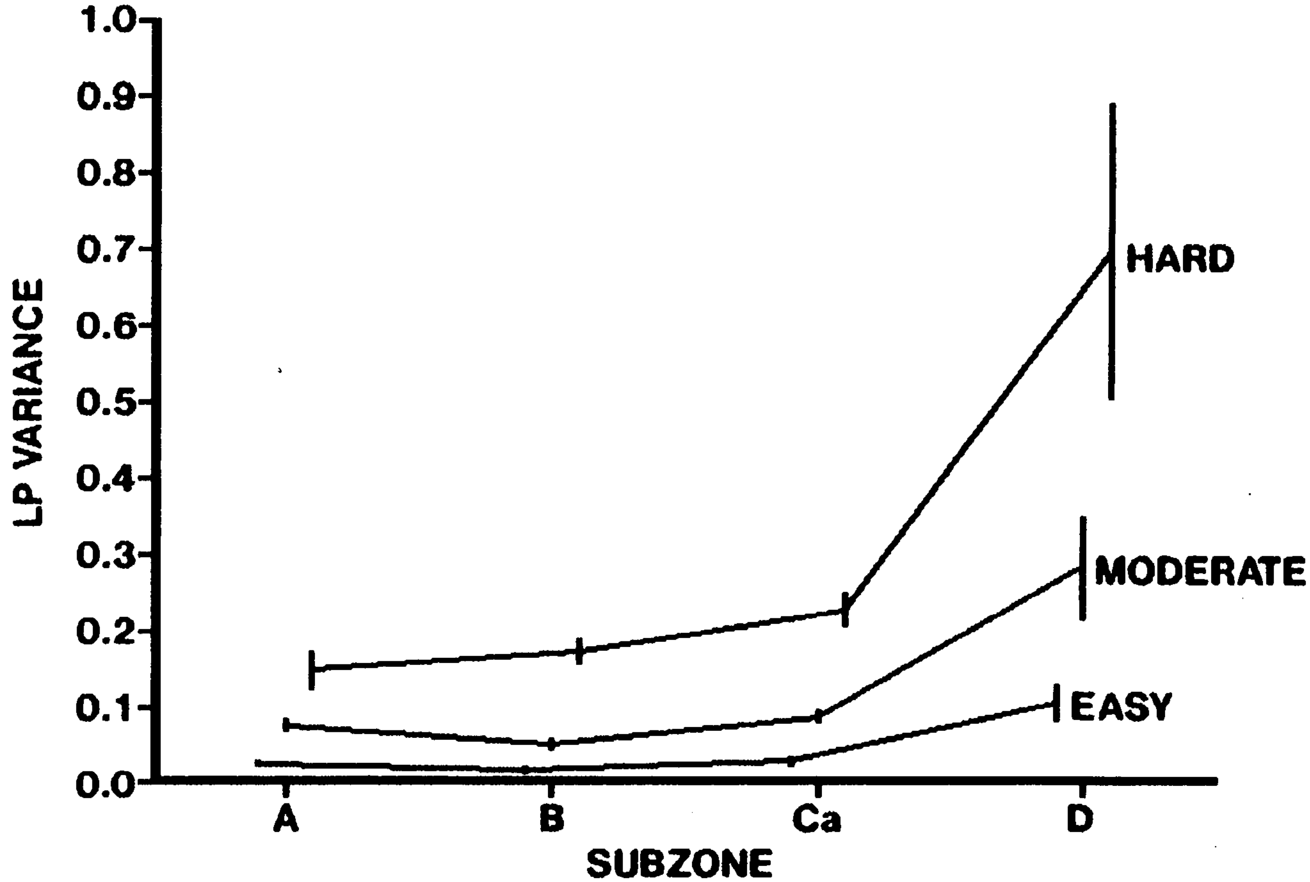
During analysis of the lateral placement data, it was noted that two subzones, 6B in the moderate loading section, and 11A in the hard loading section, seemed inconsistent with the rest. Further investigation indicated that the problem in 6B was due to a sharp change in the heading of the road, which the drivers could not be expected to follow. This increased their variance of lateral placement for one portion of the zone. Because that portion could not be separated from the good data, all lateral placement data for this subzone were dropped. Likewise, in 11A the lateral placement calculations were incorrect for one intersection of the subzone, so the lateral placement data for this subzone were also deleted.

The variability of subjects' lateral placement (relative to leeway) increased as a function of workload in the three sections of the drive. Contrast tests of this variable indicated that variance was higher in the hard section of the drive than in the moderate section ($F = 62.47$, $df = 1/84$, $p = .0001$), and higher in the moderate section than in the easy section ($F = 84.14$, $df = 1/84$, $p = .0001$).

The effect of loading was influenced by subzone ($F = 15.60$, $df = 6/504$, $p = .0001$; see figure 23a). There were several significant differences within this interaction; for simplicity these will be discussed as subzone contrasts by loading section. Figure 23b shows an enlarged view of the loading-subzone interaction for subzones A, B, and Ca. In the easy section, the effect ($F = 63.25$, $df = 3/252$, $p = .0001$), although it appears quite small, is statistically significant in each subzone. Variance decreases from subzone A to subzone B ($F = 10.66$, $df = 1/84$, $p = .0016$).

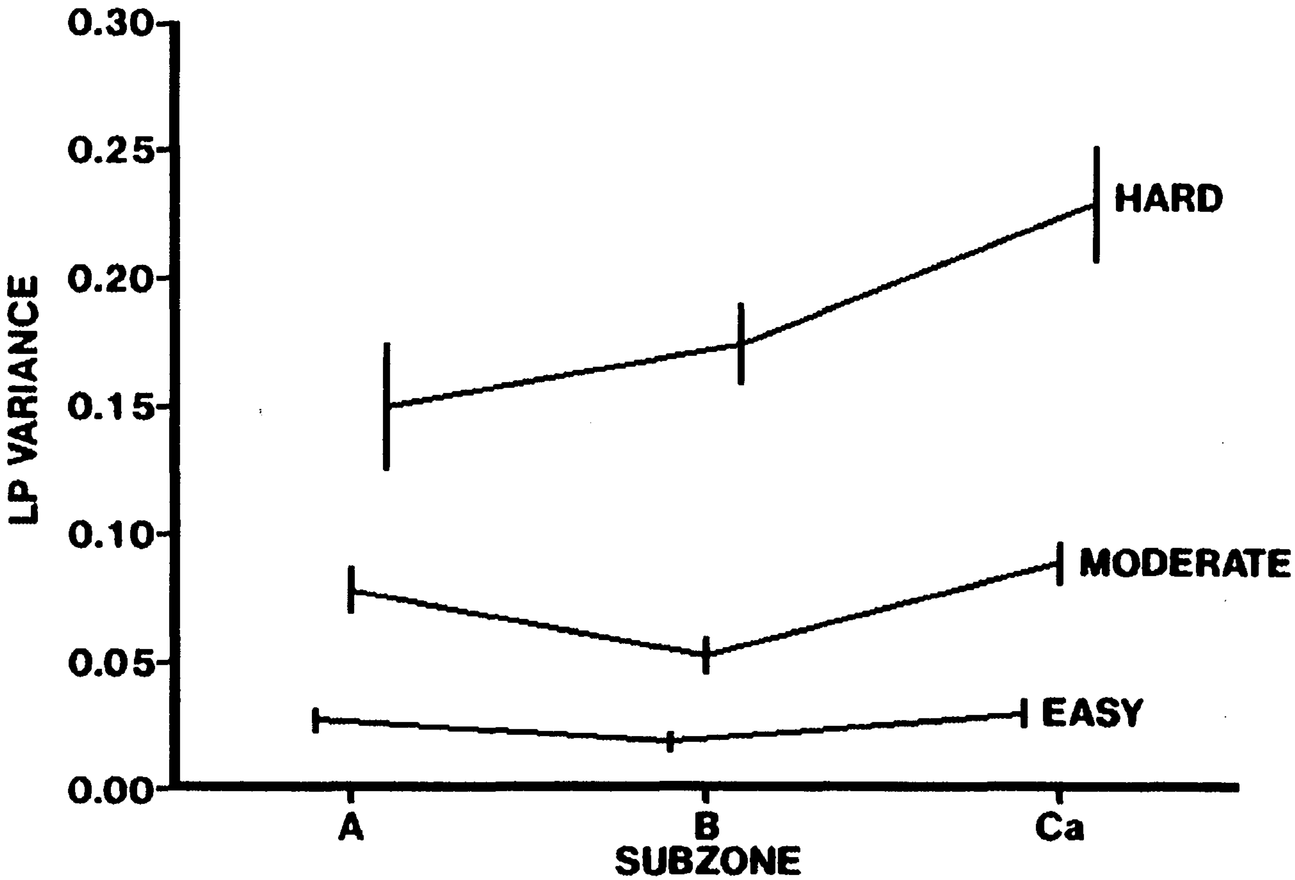
This is possibly the effect of the stimulus presentation following the very low workload levels of those portions of the drive preceding the B subzone. Hearing the gas-mileage problem may have increased subjects' overall attention level. This effect may be similar to the inverted-U performance-anxiety curve in that workload levels which are too low would tend to cause boredom, thus lowering attention to the task. A sudden auditory stimulus demands attention, and may add sufficient short-term workload to improve performance.

Variance continues to increase in subzone Ca ($F = 18.36$, $df = 1/84$, $p = .0001$), and increases again following the turn in subzone D ($F = 61.85$, $df = 1/84$, $p = .0001$). However, the magnitude of the latter result appears to be an artifact related to the HYSIM itself, as discussed previously. Subjects tended to turn wide, and did not begin to make corrections until near the end of the turn. This is referred to as a trajectory effect. In much the same way that the trajectory of any projectile will show a small error if measured near its source,



a. Including subzone D.

Figure 23. Lateral placement (LP) variance scores broken down by loading and subzone. (Error bars indicate +/- 2 standard errors of the mean.)



b. Enlarged, excluding subzone D.

Figure 23. Lateral placement (LP) variance scores broken down by loading and subzone (continued). (Error bars indicate +/- 2 standard errors of the mean.)

but a large error relative to the target, the subjects show small error at the start of the turn (in subzone Ca), but a large error in subzone D.

The moderate section variance pattern is almost identical. The decrease from A to B in the lateral placement variance measure (F = 34.11, df = 1/84, p = .0001), although it appears inconsistent with the workload hypothesis, is interpretable in light of the average lateral placement result for the same subzone. Lane placement tended to "worsen" in the sense that subjects did not stay centered in the lane. However they tended to keep their vehicle positioned away from the other car. Thus at this level of workload, performance in this subzone was reasonably stable. In contrast, in the hard section variance increases from A to B, which may reflect the load of a difficult gas-mileage problem added to an already high workload situation. Though the trend is clear, this result is not significant by the chosen standard (F = 5.68, df = 1/84, p = .0195), due to the greater spread of the subjects' variance scores in the A and B subzones.

Lane placement variance was also affected by an interaction of subzone and age group (F = 4.36, df = 6/252, p = .0001). As is evident in figure 24, this significant effect is due to the larger variance scores of the older group in subzone D.

Sex of subject emerged as a significant factor in interaction with subzone (F = 6.17, df = 3/252, p = .0056; see figure 25), as well as with both subzone and loading (F = 5.73, df = 6/504, p = .0049). Collapsed across loading, female subjects varied more than males in subzone D. This difference is accentuated in the breakdown of means by loading shown in figures 26 (females) and 27 (males). This sex interaction may be due to a phenomenon often found in older groups which have no upper age limit in which the women are older, on average, than the men. This was the case among this group of subjects, though the difference in mean age was not statistically significant. In the younger group, the women averaged 0.29 years older than the men, in the middle group the difference was 0.19 years, but in the older group the difference was 1.52 years. Of the seven subjects aged 70 or over, only one was a male.

To further investigate this possibility, two sets of analyses were run on the hard section only, where the subzone-by-sex effect was the strongest. In the first set, separate analyses were done for each age group. The subzone-by-sex effects were larger for the older group, although the probability did not even reach the .05 level, much less the .01 level used in this study. The second set of analyses was the same except that each person's age was included as a covariate. This reduced the significance level in the older group (from p = .0502 without the covariate to p = .1147 with age as covariate) while

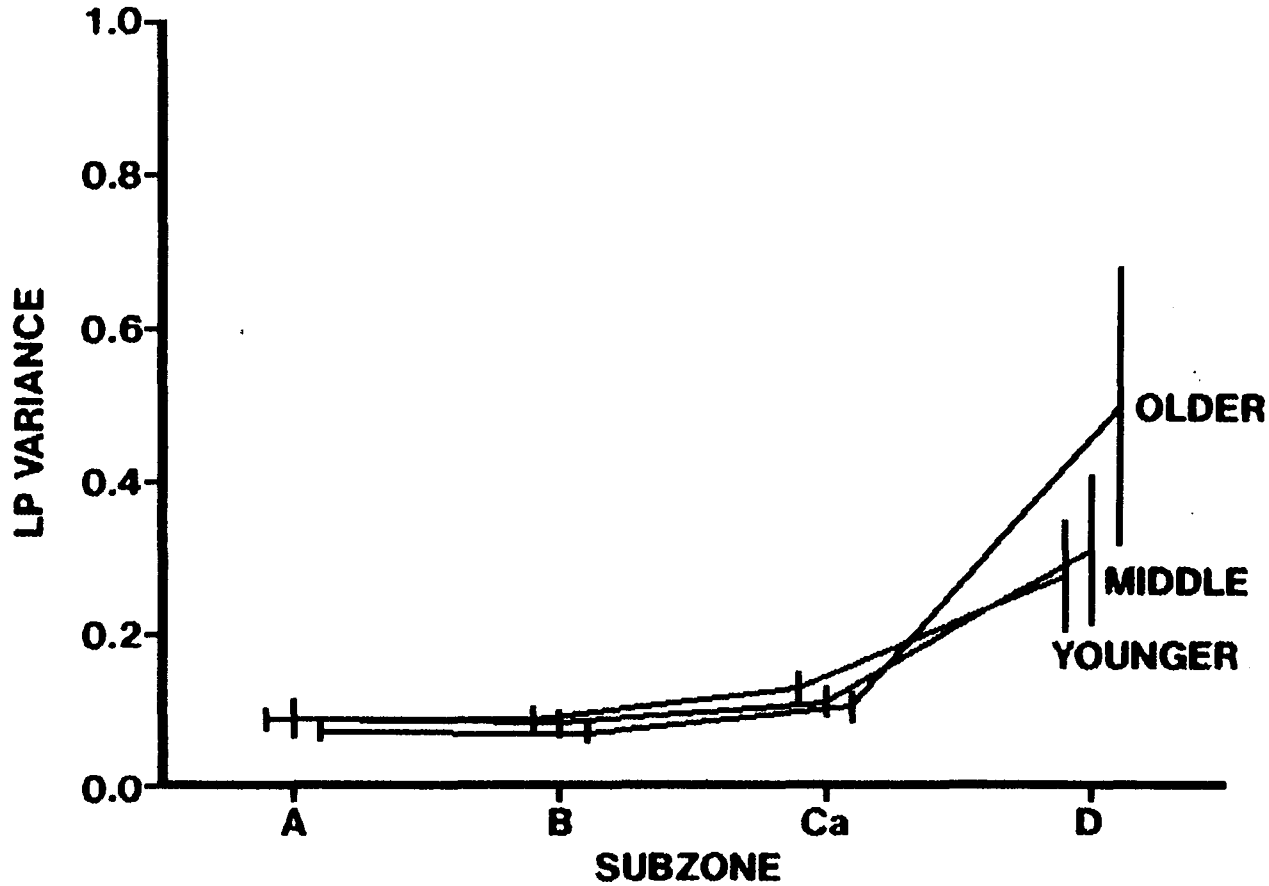


Figure 24. Lateral placement (LP) variance scores broken down age group and subzone. (Error bars indicate +/- 2 standard errors of the mean.)

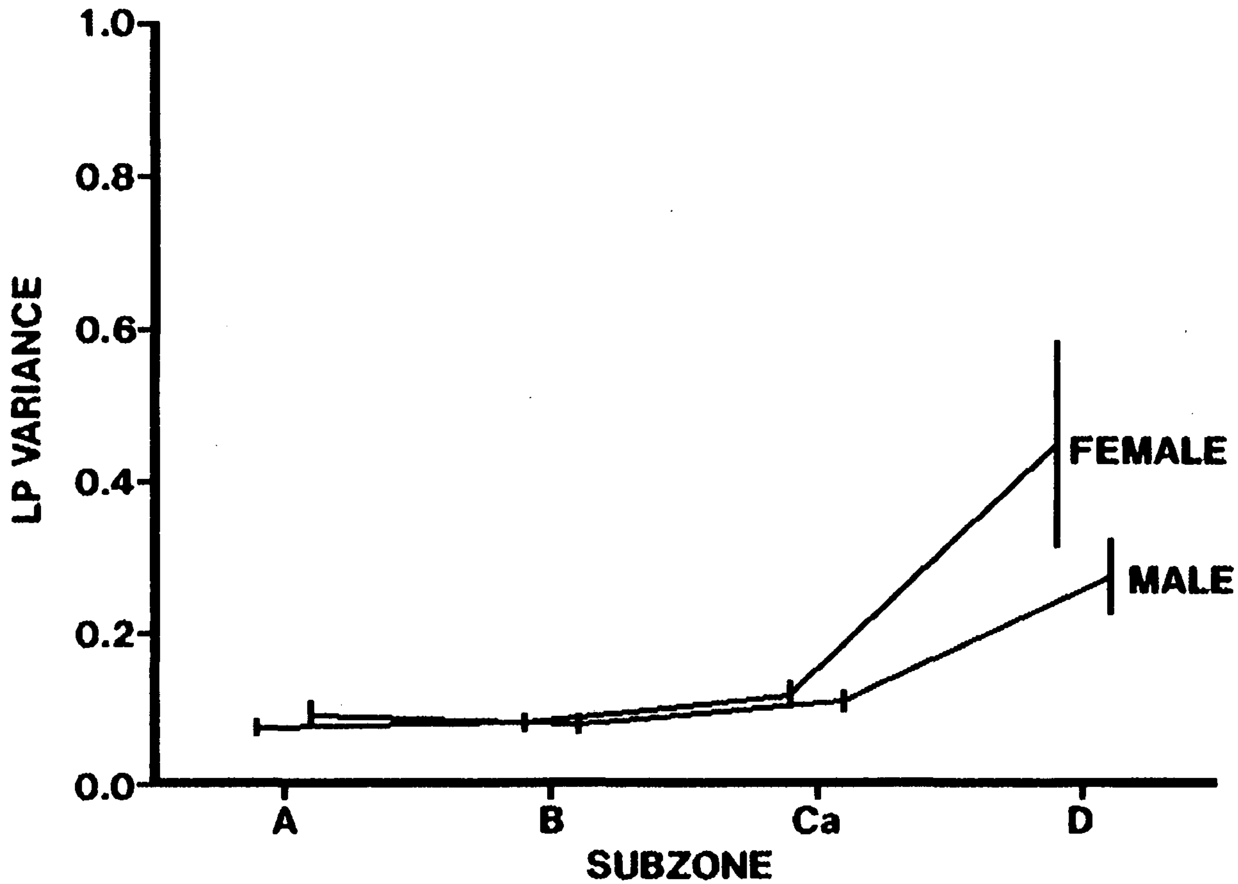


Figure 25. Lateral placement (LP) variance scores broken down by sex and subzone. (Error bars indicate +/- 2 standard errors of the mean.)

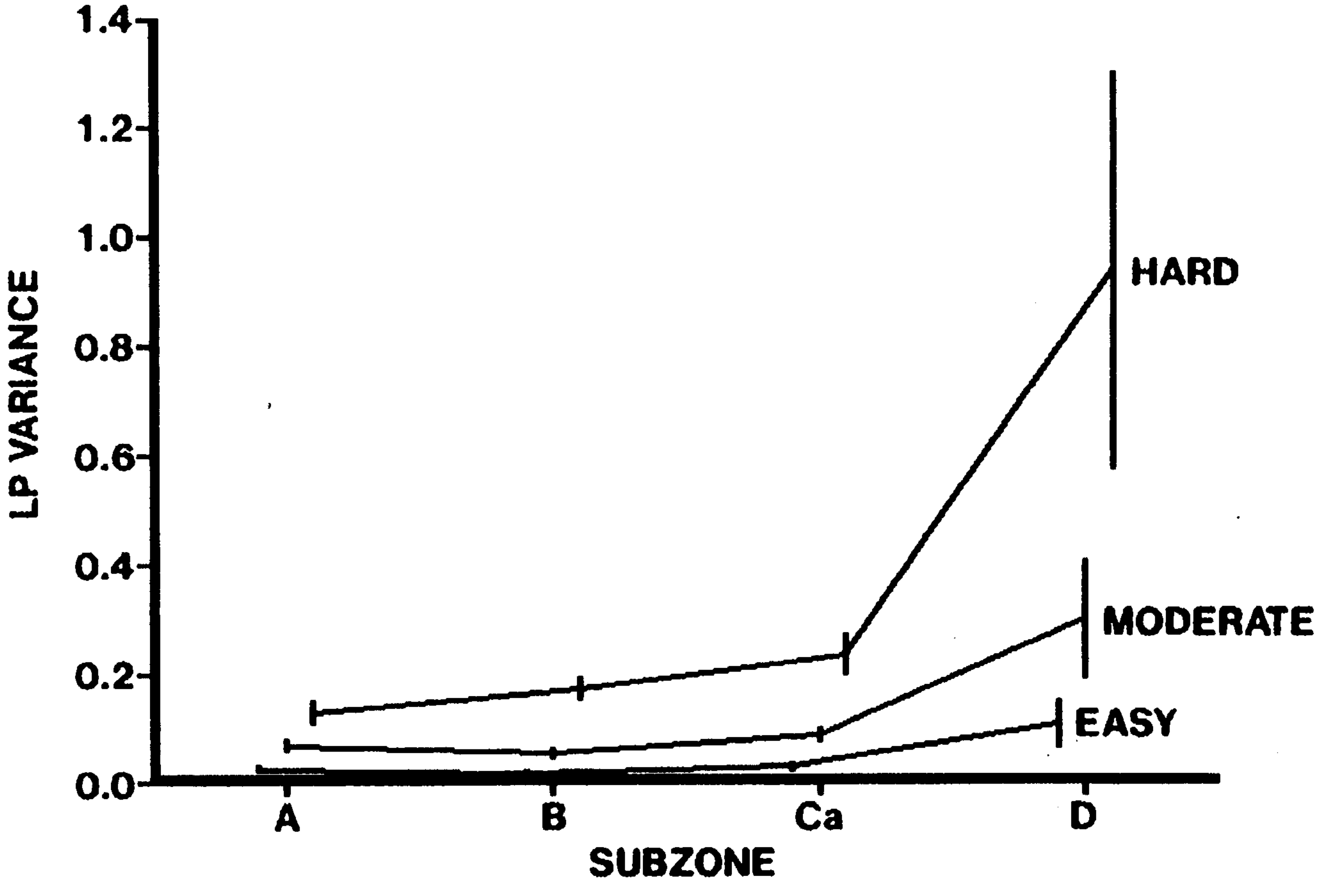


Figure 26. Lateral placement (LP) variance scores broken down by loading and subzone, females only. (Error bars indicate +/- 2 standard errors of the mean.)

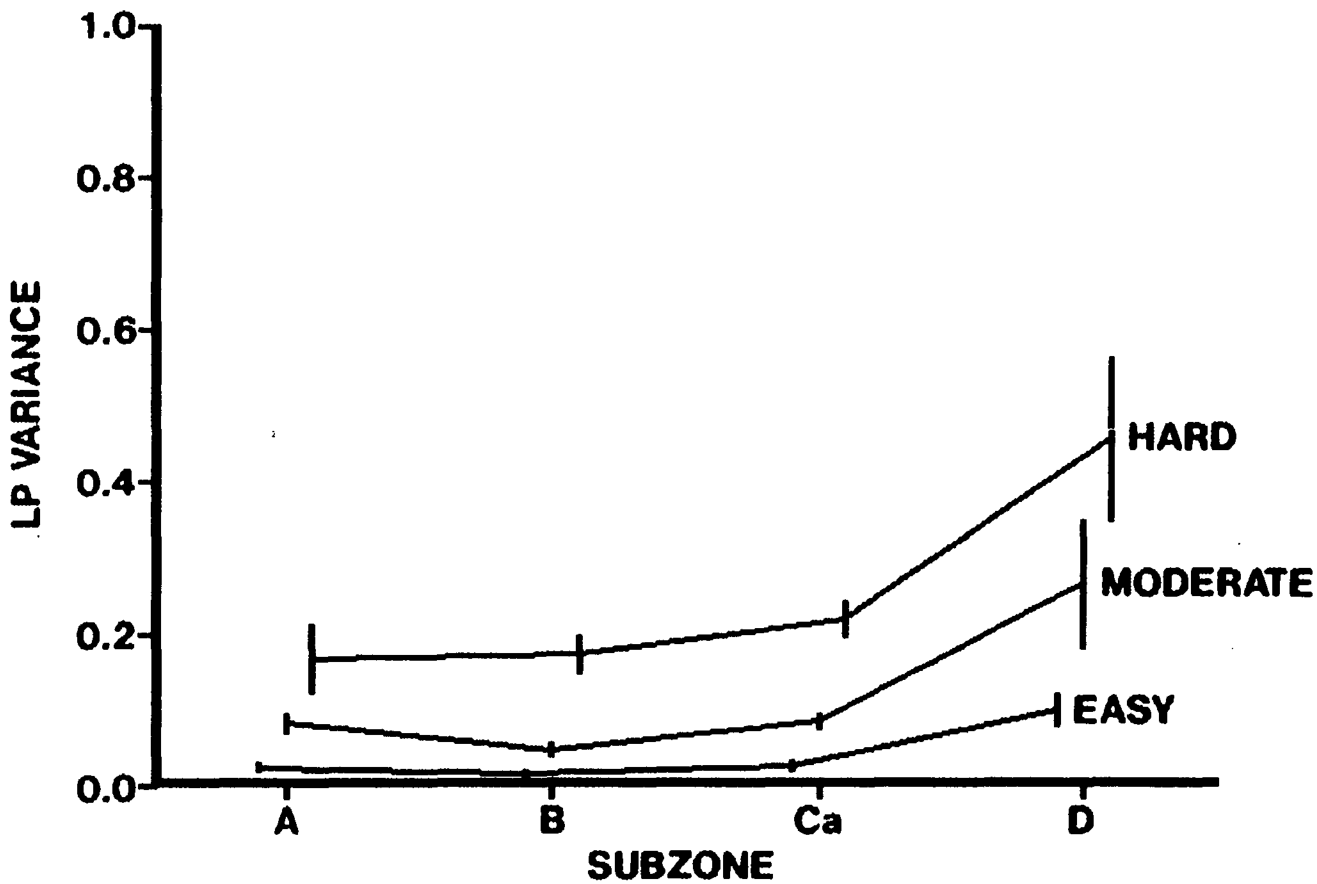


Figure 27. Lateral placement (LP) variance scores broken down by loading and subzone, males only. (Error bars indicate +/- 2 standard errors of the mean.)

the young and middle groups remained the same. This is what would be expected if the female-male differences were related to age differences.

As a result, the significant sex factors in variance of lateral placement should be held in abeyance until a study in which the age range is similar for males and females corroborates these results.

No significant treatment effects were found in the analysis of lateral placement variance. Separate analyses of the simple groups, therefore, showed the same pattern of changes in subzones A, B, Ca, and D. The Ca to Cb changes appear to capture the subjects' preparation for the upcoming turn, as was discussed in regard to the decrease in speed for these subzones (see figure 20). This is particularly suggested in the loading-by-subzone interaction ($F = 29.17$, $df = 2/48$, $p = .0001$), in which there was a greater decrease in lateral placement variance in the hard section than in the easy ($F = 38.83$, $df = 1/24$, $p = .0001$), and moderate ($F = 32.65$, $df = 1/24$, $p = .0001$) sections. Recall that subjects were instructed to "cut off" the center and edge lines while making their turns to compensate for the inaccuracies in the HYSIM's graphic representation of these features. To do this properly requires use of the delineations to judge when to begin the turn. The probable result is closer attention to these cues, and thus to maintenance of lane position following the guidance message. The subzone interaction is due primarily to the larger decrease in variance from Ca to Cb in the hard section. The increased workload level apparently caused a higher level of lateral placement variance in the hard section Ca subzone relative to the easier sections of the drive, thus the decrease from Ca to Cb is greater in that section as subjects anticipate the turn.

Average Lateral Placement

Remember that in addition to the adjustment for leeway mentioned in the methods section and the previous section, the average lateral placement data were also 'corrected' for the direction of the turn and placement of the other vehicle. That is to say, if the turn in the zone was to the left, then lateral placements to the left of centerline of the driver's lane were considered positive, and placements to the right were negative. Because in the moderate and hard sections the other vehicle was always in the lane opposite the turn direction, lateral placements toward the vehicle were also negative.

The average lateral placement data are presented in figures 28, 29, and 30 (easy, moderate, and hard loading sections respectively). The same vertical scale has been used in all three figures to emphasize the differences among the loading sections. At the same time, the point regarding leeway in the variance of lateral placement section should be restated:

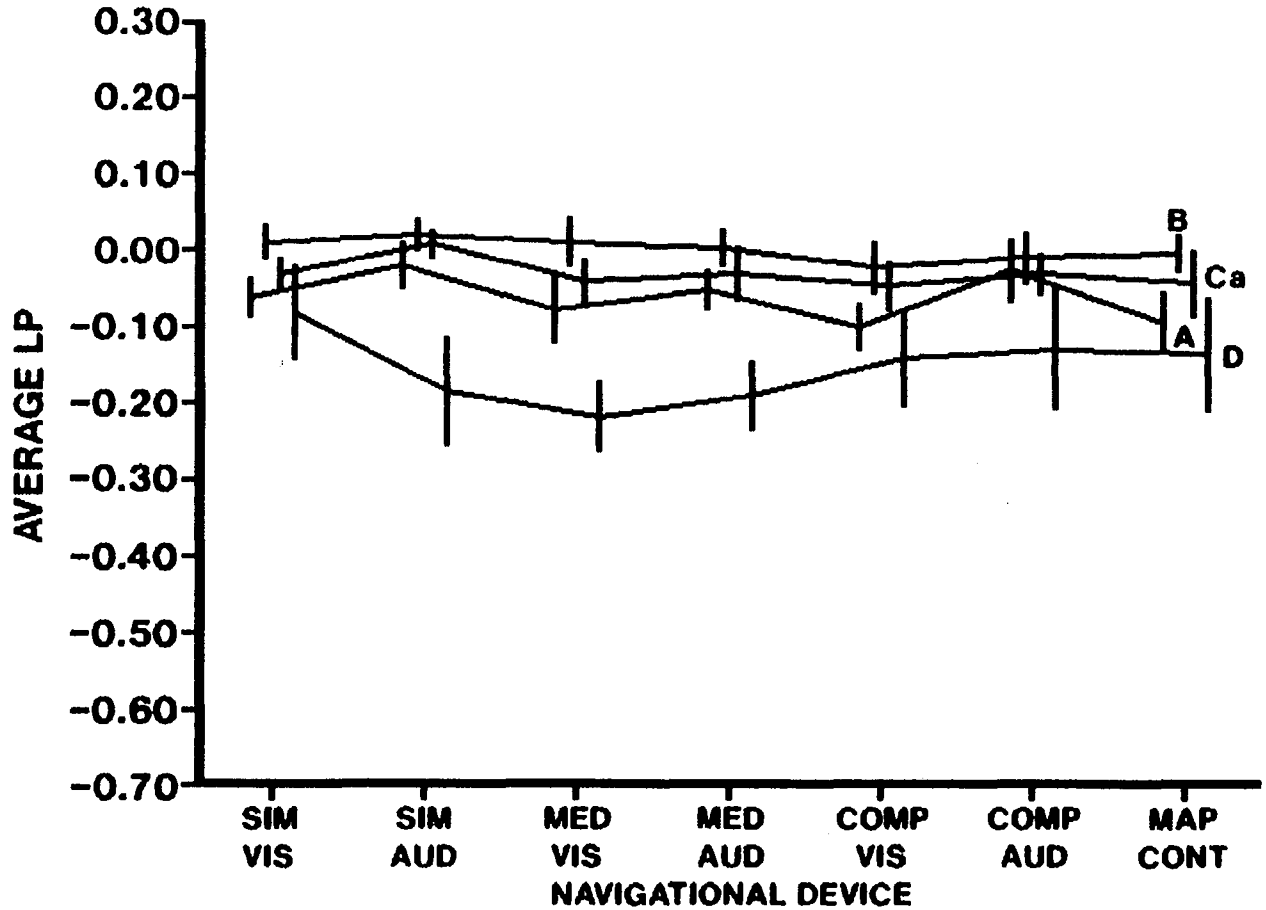


Figure 28. Average lateral placement (LP) broken down by subzone and treatment, easy loading only.
(Error bars indicate +/- 2 standard errors of the mean.)

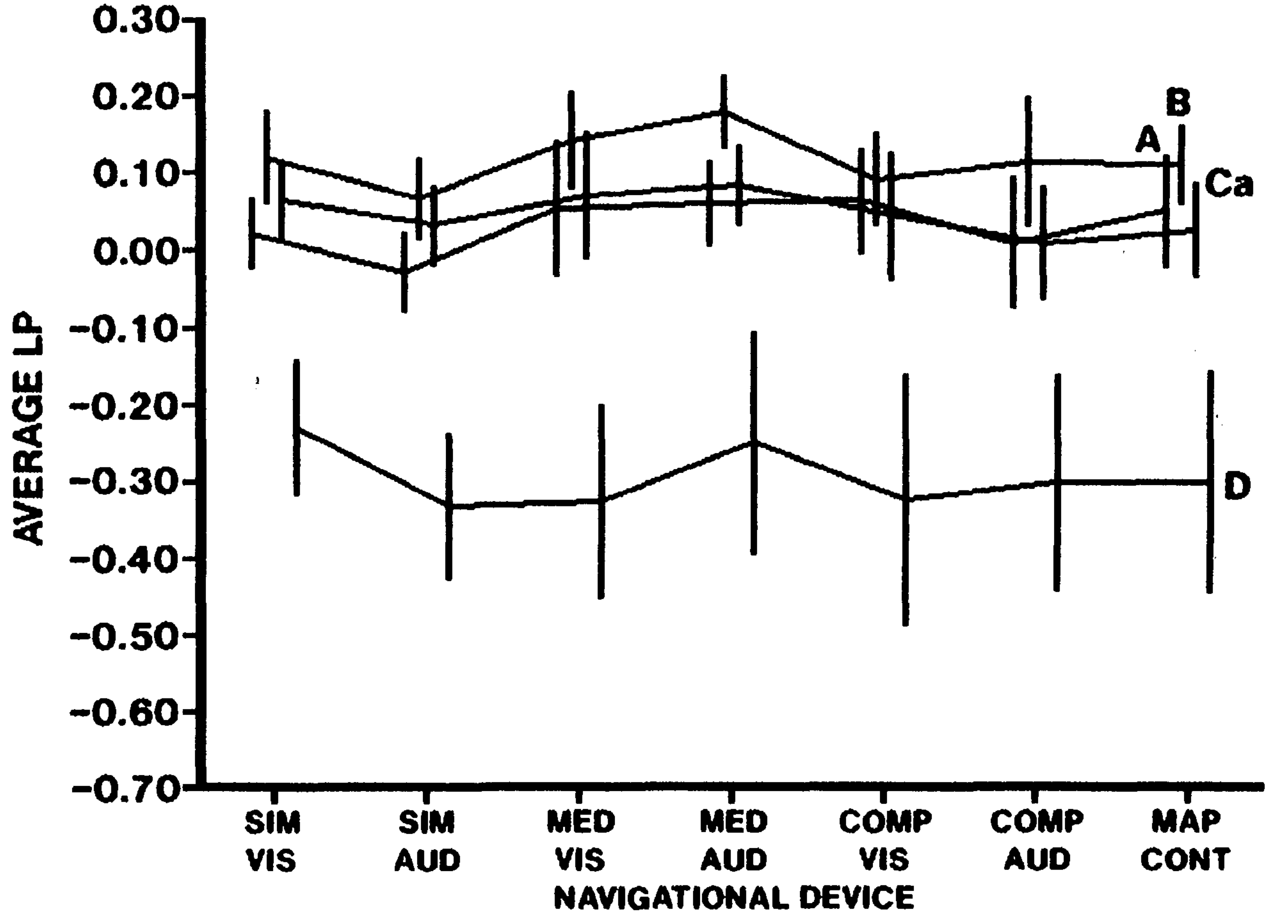


Figure 29. Average lateral placement (LP) broken down by subzone and treatment, moderate loading only.
(Error bars indicate +/- 2 standard errors of the mean.)

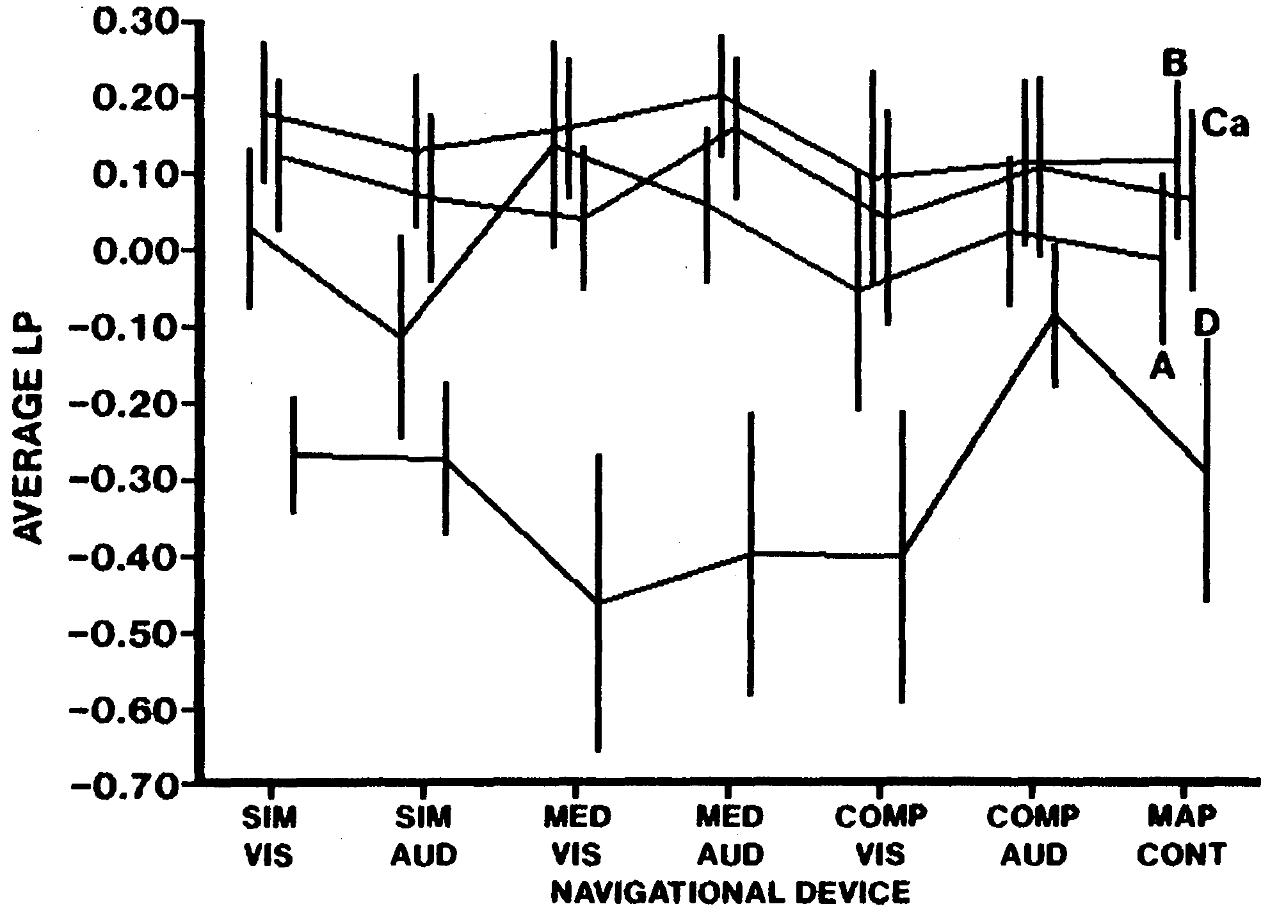


Figure 30. Average lateral placement (LP) broken down by subzone and treatment, hard loading only. (Error bars indicate +/- 2 standard errors of the mean.)

The differences in the unadjusted lane placements (the raw lateral placements) were fairly equal. However, the leeway-adjusted scores, which are pictured, emphasize the increase in danger from loading section to loading section.

The most salient effect in the data was a subzone effect ($F = 363.41$, $df = 3/252$, $p = .0001$). When the data were averaged over treatment, the order of the subzones was quite invariant. Subzone B was always the most positive, then subzone Ca, then subzone A, and subzone D was always the most negative. Even when the data were broken down by loading section this order remained, and the profile analyses (which compared A to B, B to Ca, and Ca to D) were all significantly different at the $p = .0001$ level. Of course, the question remained whether subzone A was different from subzone Ca. To answer this another set of analyses was run using a contrast between subzone A and the other subzones. With one exception (moderate A vs. moderate Ca), these were also significant, usually at the $p = .0001$ level.

As regards subzone Cb, an analysis comparing it to Ca (for the simple groups) found no effects except a loading effect similar to that in the overall analysis. Thus, unlike average speed and lateral placement variance, there were no changes in average of lateral placement as subjects in the simple groups drove from Ca to Cb.

There is a plausible explanation as to why subzone D was always most negative: Drivers tended to cut off too little of the corners at the beginning of a turn, which placed them wide of the mark in subzone D. In the moderate and hard sections drivers sometimes were so far in the other vehicle's lane that when it reappeared, it did so directly in front of them. This was more common for subzone-by-age-group effect ($F = 10.31$, $df = 6/252$, $p = .0001$).

Concerning subzone B, in the easy section it was closest to the middle of the lane, and in the moderate and hard sections it was farthest away from the other vehicle. In this sense it could be considered the safest subzone. Just as in the variance of lateral placement, the gas-mileage question is thought to have improved the driver's attention level, thus improving performance in subzone B.

The subzone effects for A and Ca are not as explicable. In the moderate and hard sections, Ca was closer to the middle of the lane than B, and thus the drivers were better placed for the turn. This does not apply in the easy section where they are slightly wide before the turn, unless they started wide so they would not have to cut off as much of the corner.

Concerning subzone A, in the moderate and hard sections the average is closer to the middle of the lane than any of the other subzones. A possible explanation is that if the drivers are less attentive, centering themselves in the lane is a more automatic driving response than staying away from the other vehicle. However, this does not apply in the easy section, where the drivers were slightly negative in subzone A. It cannot be related to staying to the right or left since the easy section had two left turns and two right turns and any such tendency would have been canceled out.

It is true that one of the two situations where there was a treatment effect was in subzone A of the easy section, and the map-control and complex visual groups, which knew the direction of their turn at subzone A, were significantly more negative than the simple audio group, which did not know the direction of the next turn. In this sense the map-control and complex visual groups could have been 'swinging wide' before the turn as was posited for all groups in subzone Ca of the easy section.

Unfortunately, the complex audio group, the other group which knew the turn direction by subzone A, did not fit this pattern at all.

Moving on to the other treatment effect, in subzone D of the hard section, the complex audio group was closer to the middle of the lane than any other group, and significantly closer than the medium visual group. This effect also defies explanation.

There was also a minor loading effect ($F = 5.51$, $df = 2/168$, $p = .0048$), where the lateral placement (collapsed across subzones) was more negative for the easy section than for the moderate section, but there were no differences between the moderate and hard sections. This is easily explained by the introduction of the other vehicle in the moderate zone. With no oncoming traffic, the drivers set their average lateral placement slightly away from the car or truck that was shadowing them.

NAVIGATIONAL ERRORS

The dependent variables used in this study were chosen to reflect safety-related human factors issues in the use of navigational devices. Thus, the effectiveness of the devices is essentially a digression from the purpose of the research. However, the subjects made a number of errors which appeared to be related to which device was used.

Navigational errors were first screened for those caused by either the experimenters or equipment faults, and for those which resulted from the combined idiosyncrasies of a particular device with some aspect of the experimental apparatus or scenario. The latter type affected three devices. In the first case there was a conflict in the appearance of the road geometry (in one zone) as presented in the HYSIM versus that shown on the complex visual device. Several subjects in the complex visual group missed the turn in that zone, and pointed out the inconsistency. In the other instance, the truck used in the hard section blocked the subjects' view of the street sign at one intersection. This appeared to affect both the complex audio and the map-control groups. Errors for the zones in which these problems occurred were not included in the count for the affected devices.

Responses in a turn zone were counted as errors if the subject drove beyond, turned before, or turned the wrong direction at the correct intersection. This procedure yielded the results shown in table 2.

Table 2. Frequency of navigational errors, by device.

Simple		Medium		Complex		Map
Visual	Audio	Visual	Audio	Visual	Audio	Control
16	0	3	1	12	8	14

The Chi Square analysis performed on these totals, based on the number of correct turns versus errors for each device, was significant (Chi Square = 34.73, df = 6, $p = .0001$). These results should be viewed with caution however, because they are based on repeated measures, rather than independent observations, as required for this test.

Although the Chi Square tests for an overall difference, rather than differences between the groups, the devices appear to fall into three categories: (1) simple audio, medium audio, and medium visual, with the lowest number of errors; (2) map-control, complex visual, and simple visual, with the highest number; and (3) complex audio falling in between. The simple audio group performed much better than the simple visual group, most probably because the spoken message attracted more attention in the quiet environment of the HYSIM. Driving requires constant processing of visual information, and thus the single arrow may be an insufficient cue under routine workload conditions.

Of the two complex systems, subjects made fewer errors with the audio device. Subjects in this condition apparently used street signs for confirmation. Most of their errors were clustered in the hidden sign zone, which was not counted; the rest were scattered through different zones. But hearing the name of the street periodically during the drive, in addition to the pattern of the messages, appeared to be more useful than either a paper map or a dynamic map display. Subjects in the complex visual group seemed less dependent on street signs, as they made no more errors at the hidden sign intersection than at others. It is possible that some subjects simply had difficulty correctly identifying the correspondence between the electronic map and the roads in HYSIM. If so, this problem may be exacerbated on actual roadways, which are naturally much more complex than can be reproduced in HYSIM.

DISCUSSION

Before interpreting the results, several points should be re-emphasized. First, the devices simulated in this study do not presently exist on the commercial market, at least not with automatic routing capabilities. Thus, no comparisons should be inferred regarding devices currently in use.

Second, the simulated nature of this study must be kept in mind. Although the techniques to increase driver workload such as crosswinds and narrow lanes were successful, generalization to real-world driving is limited because only a nighttime scene was used, with only one other vehicle present. In addition, it is a sparse environment both visually and auditorially. However, it does provide a baseline scenario, and it could be argued that differences found in this study would be exaggerated in the real world.

Third, the older group in the study had a wider age range than the younger and middle groups, had more subjects eliminated due to simulator sickness, and the remainder may have been superior to the general older driving population. Many of the subjects entered the study for reasons of curiosity as much as for money, thus these subjects may have been more adventurous and less conservative than the general older population. It is definite that this sample excluded that proportion of older drivers who do not drive at night. It is also recognized that the lower limit of this older group is younger than the usual definition of older drivers. This was necessary due to the difficulty in recruiting a sufficient number of older subjects.

Even though the six subjects who were both sick in the simulator and were retained in the final data did not differ from those who were not sick, it cannot be said with certainty that those who were dropped from the study due to sickness do not differ in driving from those who had no problems. The attrition rate was much higher than anticipated, and no plans had been made to compare the two groups. The older group was seriously affected (greater than 50 percent sickness) while the middle-aged groups suffered less (about 25 percent) and the young group hardly at all (about 2 percent).

Problems of this magnitude had not occurred in previous HYSIM studies. Possible factors include a large number of sharp turns, starts and stops, and the duration of the scenario. Previous studies were usually on Interstate or primary highways with gentle curves, few stopping points, and were of durations shorter than 20 minutes without a break.

AGE EFFECTS

In general, the older drivers performed less safely. They drove more slowly, had larger variability in lateral placement, had longer reaction times to the gauges, were more likely to be in the other vehicle's lane after the turn, and were more likely to make navigational errors compared to the other two age groups.

It cannot be overemphasized that the age factor interacted with the loading factor. This was true in reaction time to gauge changes, in speed, and in both average and variance of lateral placement. Future studies must include both factors to adequately determine the response of older drivers in extreme situations in the real world.

The age data in this study are slightly inconsistent with those generally reported. Usually, older groups have larger within-group variance. That is, they usually have a wider range of abilities. The only variable for which this occurred in this study was variance of lateral placement. For the other variables there was no consistent pattern.

TREATMENT EFFECTS

The most salient treatment effects occurred with the complex visual device. These effects are closely linked to the safety of driving performance. Subjects in this condition missed more gauge changes, had longer reaction times, and drove more slowly than subjects using any other devices except the strip map. At some points even subjects using the strip maps performed more safely than the complex visual group.

Note that measures of lateral placement are not included in the above list, possibly because subjects gave lateral placement their highest priority. To maintain lane position, which is so critical to safety, perhaps drivers will sacrifice speed, navigation and other peripheral tasks. This is consistent with the theory of risk homeostasis (behavioral adaptation).

Comparing the three auditory devices to the three visual devices, subjects using the former did not reduce their speeds as much during high load situations. Also, they made fewer navigational errors than those using visual devices.

In terms of complexity, the subjects using the complex devices drove more slowly than those using the other devices. It should be noted that the navigational tasks given to the subjects were minimal. It is expected that navigation in the real world would exaggerate the differences found here. Even though the only difference between the simple devices and the medium devices was the large number of navigational errors made by those using the simple visual device, it is suspected that the redundancy offered by the medium devices would result in safer driving overall in the real world. The medium devices take advantage of human factors principles established in positive guidance in highway signing by providing the optimal amount of information at the proper time.[35] Anecdotally, several subjects, especially older ones, commented that the complex devices gave too much information. This was true for both the complex visual and complex audio devices.

Future studies should add medium complexity devices which combine both auditory and visual channels, such as ERGS and AUTOGUIDE.

APPENDIX A: DEPARTMENT OF TRANSPORTATION/FEDERAL HIGHWAY ADMINISTRATION HIGHWAY DRIVING SIMULATOR (HYSIM)

I. OVERVIEW

The central feature of HYSIM is the car cab. Except for engine, drive train, and wheels, the car is complete and subjects participating in an experiment "drive" the car. All controls for velocity and heading--steering wheel, accelerator and brake-- are functional and the "feel" of the controls has been carefully maintained. Other ancillary controls--lights, shift selector, fan switches, etc.--are also functional.

As the car is operated, the driver views a roadway scene projected on a curved screen located at the front of the car. The displayed scene elements come from two sources: (1) roadway lines, another vehicle in the scene, and guidance markers (cones, delineations, etc.) are projected by a wide-screen television projection system, and (2) overhead and shoulder mounted signs and traffic signals are projected by one of four 35-mm slide projectors. Together these systems form the nighttime roadway environment. All projection equipment and associated electronics are mounted in a gantry which spans the car near its midsection. Figure 31 shows a floorplan of the HYSIM laboratory.

All of the modules are under computer control. The displayed scene responds appropriately to the driver's manipulations of the car controls. As the driver speeds up, elements in the roadway scene appear to move by more quickly and in registry with the roadway; as the steering wheel is turned, the scene shifts in azimuth to simulate a heading change.

There is a central control console where the experimenter monitors simulator operations. The experimenter can also verify that the experiment is progressing according to plan, observe the driver or the roadway scene, and check to assure data are being properly collected and recorded. Typical data available are: (1) speed, (2) elapsed time, (3) steering wheel position, (4) number or pressure of brake applications, (5) accelerator position, (6) lateral placement, (7) discrete event occurrences (experimenter defined responses to stimuli), and (8) various psychophysiological measures (heart rate, GSR, respiration rate, etc.).

HYSIM capabilities include simulation of (1) head and/or cross-winds, (2) slippery road surfaces, (3) various sets of vehicle dynamics, (4) fog, (5) wind and road noises, (6) a siren sound activated when the driver exceeds a certain preset speed, and (7) HYSIM Highway Advisory Radio messages.

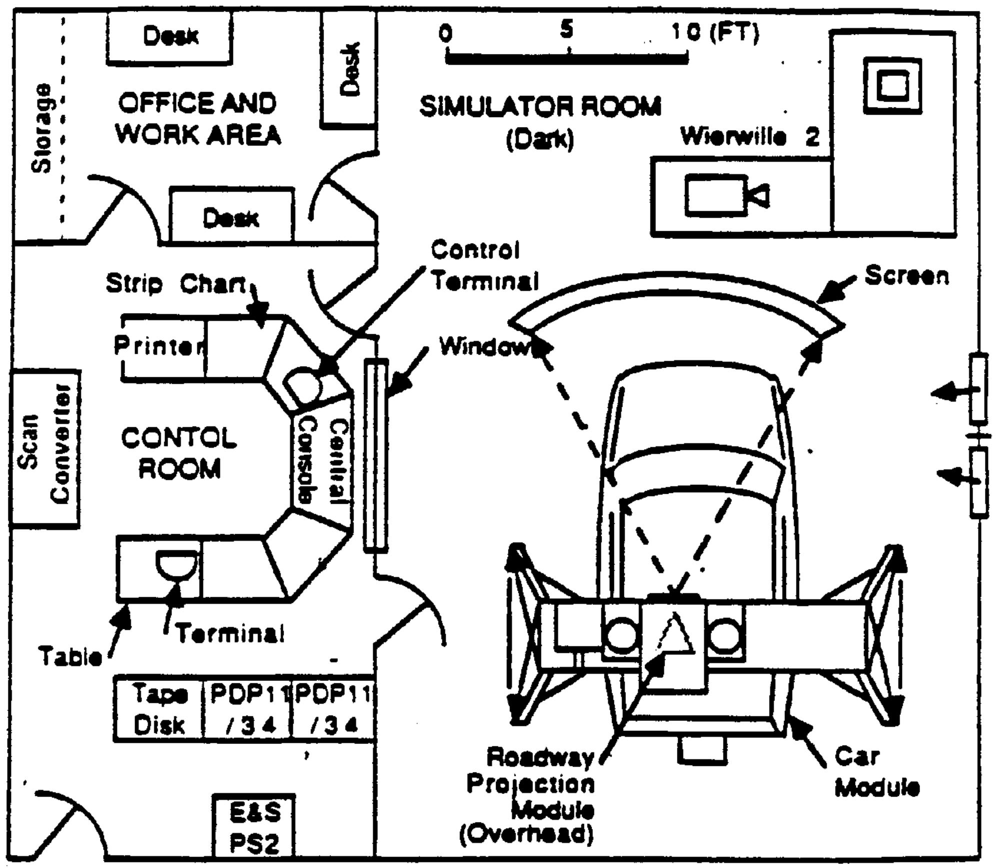


Figure 31. Sketch of floorplan of HYSIM laboratory.

II. MODULE DESCRIPTIONS

The subsystems, or modules, of HYSIM operate in various combinations to meet simulation requirements to study a range of Human Factors highway research problems. The simulator was designed on a modular basis to (1) allow maximum system flexibility, (2) retain partial operational capability in the event of failure of a subsystem and (3) facilitate modification and augmentation of the system as the state of the art changes with regard to individual subsystems.

A modular representation of HYSIM is shown in figure 32. A brief discussion of the purpose and function of major subsystems follows.

A. Scenario Computer:

The Scenario Computer is a DEC PDP 11/34 with a NISSHO N1100 CPU/memory board and 2-megabytes of memory. Its secondary storage consists of one 5-megabyte disk and is ported to two 160-megabyte disk drives. It has an associated 300 lpm line printer, an 8-track IBM compatible tape drive, and up to four CRT terminals. As the operating system for the Scenario Computer is a multiuser system, all four terminals may be used simultaneously. During a simulation, real-time software is run at high priority, yielding degraded response for the terminal user in this mode.

The Scenario Computer provides primary control of the experimental scenario during real-time HYSIM operations. It performs navigational calculations to keep track of the car position relative to the visually displayed network. The Scenario Computer controls most peripheral simulator devices, and handles the data collection for the experiment. It is also used for software development.

B. Graphics Computer:

The Graphics Computer is also a DEC PDP 11/34. It has 124K words of memory and secondary storage of one 5-megabyte disk and is ported to two 160-megabyte disk drives.

The Graphics Computer has two primary functions: (1) perform simulation of vehicle dynamics, and (2) act as a host for the Computer Graphics Unit. The key features of the vehicle dynamics are:

- Two degrees-of-freedom lateral equations, side velocity and yaw rate.
- Simplified model of a three-speed automatic transmission.
- Tire skid limits on side force and braking force.

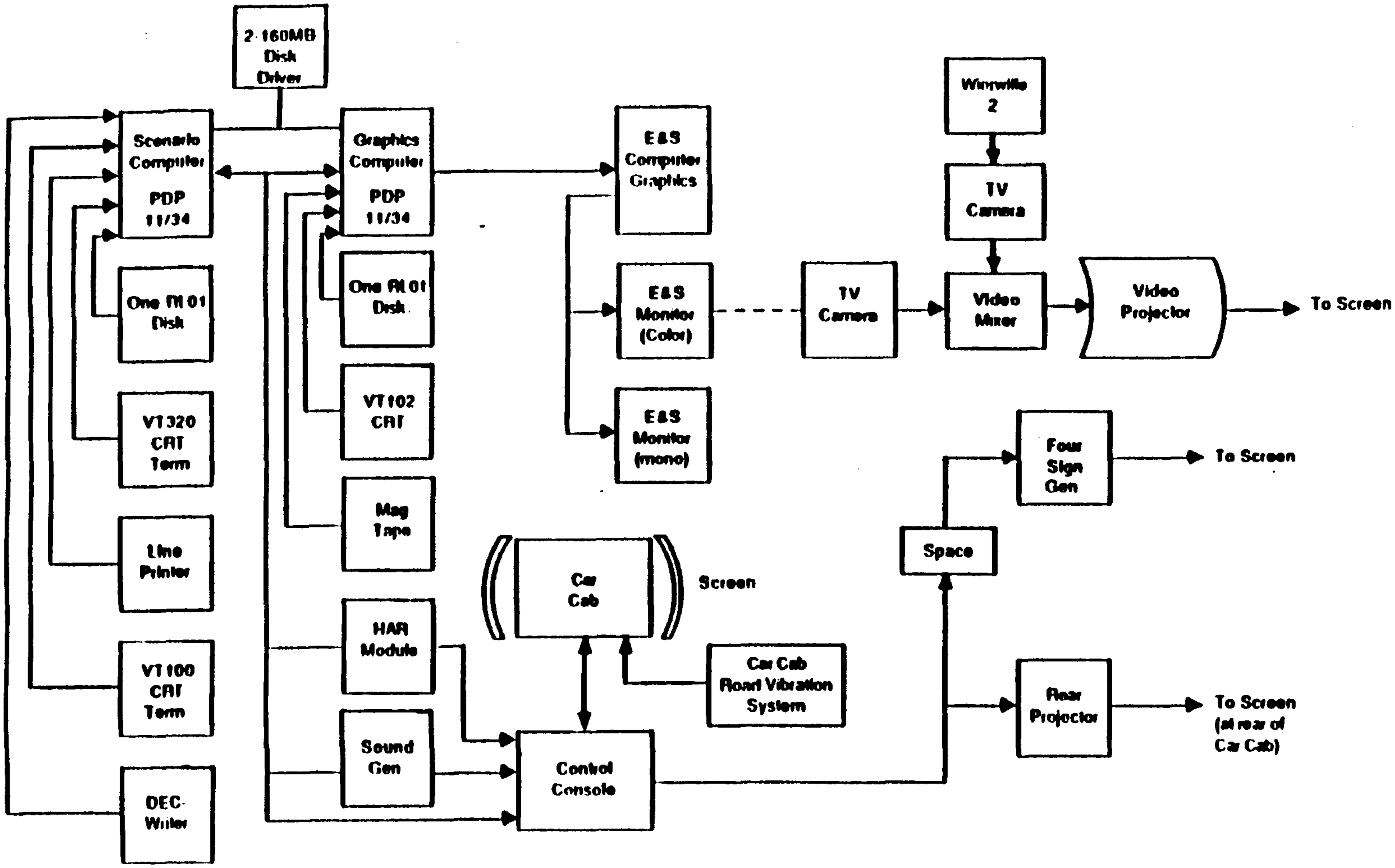


Figure 32. Modular representation of HYSIM.

- Inclusion of steering wheel disturbances (sum of sine waves generated by the Scenario Computer) which approximate effects of lateral or longitudinal wind gusts on steering control.

The various parameters which define the characteristics of the vehicle can be changed to simulate different vehicles or different road conditions, such as a wet road, or icy patches on a road.

The output of the vehicle dynamics portion of the software is updated car position and velocity. This data is transmitted to the Scenario Computer for use in navigational calculations and data collection.

Updated car position and velocity are also used to update visual display data used by the Computer Graphics Unit hosted by the Graphics Computer. The updated display data contain a complete description of the roadway that is to be drawn and any fixed objects which exist in a portion of a scenario. A new data base is brought in from disk when the driver nears the physical limits of the current data base.

C. Computer Graphics Unit and TV Link:

The Computer Graphics Unit is an Evans and Sutherland Picture System 2 (PS2). In combination with the TV Link, it is a primary source of visual information in the HYSIM. The PS2 takes the aerial view data base from the Graphics Computer and transforms it into an appropriate two-dimensional perspective view of the roadway. This transformed presentation is displayed on a color Evans and Sutherland monitor which is viewed by a Panasonic color TV camera. The output of the camera is projected onto a curved screen in front of the car by an Aquastar wide-screen TV projection system. The image projected to the driver has a field of view which is 50 degrees (87 r) horizontally and 40 degrees (.70 r) vertically.

The Computer Graphics Unit is used primarily to produce line drawings of roadway delineations. This unit, while capable of diminished brightness as a function of distance (fade) cannot produce solid surfaces or perform hidden line removal. Available delineation features include solid and dashed lines, posts and cones, and raised reflectors. the color of each feature is user selected. In addition to the delineations, the user can specify arbitrary two- or three-dimensional line drawn fixed objects (buildings etc.).

D. Sign Generators:

Another important source of visual information is provided by the four Sign Generators mounted in the gantry on either side of the Aquastar. These are controlled by the Scenario Computer. Each Sign Generator consists of a:

- Mast 35-mm random access slide projector with 80 slide capacity.
- Zoom lens with computer-controlled servos on the zoom and aperture, and manual control of focus.
- Yaw mirror which is servo-controlled to move the projected image laterally across the screen.

The zoom lens makes a sign image appear to grow as the driver approaches it. The usable zoom ratio is 9:1 on two of the Sign Generators and 13.5:1 on the other two Sign Generators. Thus, the sign's distance from the driver could range, for example, from 450 ft (137.16 m) to 50 ft (15.24 m) in the 9:1 generators, or 675 ft (205.74 m) to 50 ft (15.24 m) in the 13.5:1 generators. Where longer sight distances are required two sign generators can work in combination.

The yaw mirror keeps the sign in the proper relationship to the road as the driver maneuvers the car and also keeps the sign image moving in registry with the roadway. Brightness of the projected image is controlled by the computer via control of the aperture of the zoom lens and the voltage to the lamp in the projector. Both are controlled in a continuous manner to provide compensation for a variety of factors including zoom ratio, simulated visibility conditions, and individual slide differences. The images from the Sign Generators are projected directly onto the 44 by 112 in (111.76 by 284.48 cm) screen mounted on the front of the car.

E. SPACE Unit:

The SPACE unit is designed to work in conjunction with the Sign Generators. By rapidly alternating between two slides, this system allows for the addition of changing signal lights and signs with flashing lights to the scenario.

F. Wierwille 2:

The Wierwille 2 module allows driver interaction with another vehicle on the simulated roadway. A scale model of a vehicle is placed on a platform and the image is captured by a Sharp TV camera. The rotation of the platform, the position of the camera's 15:1 zoom lens and affiliated azimuth mirror are all under computer control. By changing these computer controlled variables, apparent relative motion of the scale model vehicle is achieved. The image from the Sharp camera is video mixed (via Chroma-Keying) with the roadway image and displayed by the Aquastar projection system.

G. Rear Projector:

The last item of the visual display equipment is the Rear Projector. It projects onto a screen at the rear of the car to provide a rearview mirror image for the driver. This projector is a random access system, but does not have the affiliated zoom lens or yaw mirror found with the Sign Generators. Consequently, displayed images are static. The Scenario Computer controls lamp brightness on the Rear Projector, and can call up any one of 80 slides.

H. Highway Advisory Radio Module:

HYSIM can simulate Highway Advisory Radio (HAR) messages by way of Scenario Computer control of a Sony stereo cassette tape recorder. A series of messages are prerecorded on a stereo cassette, and the computer then sequentially accesses an appropriate message at a preprogrammed point in the scenario. The message is played to the driver as if through the car radio. The Sony tape recorder is mounted in the operator's console, along with an identical unit used to record intercom communications between the driver and the experimenter or to play prerecorded instructions to drivers.

I. Sound Generators:

Other sound effects in the car cab come from a series of specially built Sound Generators. Those controlled by the Scenario Computer include a crash sound, a siren sound used to signal speed violation, and the sound of crossing raised lane or pavement markers (thumps). Those controlled by the Graphics Computer include wind noise, engine sounds, and tire squeal.

J. Car Cab

The Car Cab is a nearly intact 1980 Ford Fairmont. The major missing parts are the engine, drive train, and wheels. Analog signals from the cab to the Graphics Computer include steering wheel position, accelerator position, and brake pedal application and force. One analog signal is sent from the Graphics Computer to the Car Cab to drive the speedometer. Ten discrete signals are sent from the cab to the Scenario Computer covering such items as the turn signals, headlights, horn, and high beam switch. Drivers are often informed by an experimenter to utilize one of these signals as a response to a particular event in the scenario. If psychophysiological measures are collected, the signals are preamplified and conditioned by a Gould unit located in the Car Cab. The conditioned signals are sent to the Graphics Computer.

The feel of the brake pedal has been maintained by leaving the brake system intact, and adding a vacuum pump to replace the vacuum boost from the engine. The feel of the steering wheel is simulated by a high-torque servo-motor system. The force level can be changed by adjusting servo-motor parameters.

K. Operator's Control Console

The last major HYSIM module is the Operator's Console. All wiring between the computers and the other peripheral equipment (excluding the PS2) is routed through the Operator's Console. This provides for a central location for running and monitoring an experiment. All analog signals in and out of both computers are available, and voltages can be checked with a built-in digital voltmeter. By the installation of jumpers in a patch panel, any of these signals can also be displayed on any channel of a built-in strip chart recorder. The real-time software can also start and stop the strip chart recorder (or any other data collection device) at any selected scenario location. A light panel, allowing the experimenter to continuously monitor any of the psychophysiological measures is located here.

The operator's computer terminal is located at the Operator's Console, along with a monochrome television monitor. The monitor can be connected to the Panasonic TV camera, so that it displays the picture being produced by the PS2, or it can be switched to a separate closed circuit TV camera mounted in the vicinity of the car for viewing the subject's movements. The remote controls for this monochrome camera are located at the Operator's Console, and include control of azimuth, elevation, zoom ratio, focus and aperture.

APPENDIX B: TEXT OF TEST DRIVE GUIDANCE MESSAGES USED IN THE COMPLEX AUDIO CONDITION

1. OAKLAND & CANDLER + 133 ft (40.54 m):

   You are heading Southeast on Oakland
   You are crossing Ferris.
   The next four streets are LaBelle, Manchester, Victor, and Gerald.
   Your next turn is a left (Northeast) onto Caniff in approximately 1.8 miles.

2. OAKLAND & FARRAND + 184 ft (56.08 m)

   You are heading Southeast on Oakland.
   You are passing McLean on your right.
   The next four streets are Colorado, Rhode Island, Massachusetts, and California.
   Your next turn is a left (Northeast) onto Caniff in approximately .7 miles

3. OAKLAND & ENGLEWOOD + 82 ft (24.99 m)

   You are heading Southeast on Oakland.
   You are crossing Rosedale.
   The next street is Harmon on your right, and then Caniff.
   You should turn left (Northeast) onto Caniff.

4. CANIFF & DELMAR +74 ft (22.56 m)

   You are heading Northeast on Caniff.
   You are crossing Cardoni.
   The next four streets are Hindle, Russell, Greeley, and Grand Haven.
   Your next turn is a left (North) onto Mound in approximately 1.7 miles.

5. CANIFF & JOSEPH CAMPAU + 71 ft (21.64 m)

   You are heading Northeast on Caniff.
   You are passing Mitchell on your left.
   The next four streets are Mcdougall, Charest, Gallagher, and Sobieski.
   Your next turn is a left (North) onto Mound in approximately .9 miles.

6. CANIFF & FENELON + 444 ft (135.33 m)

You are heading Northeast on Caniff.
You are crossing Buffalo.
The next street is Alpena, and then Mound.
You should turn left (North) onto Mound.

7. MOUND & CASMERE + 285 ft (86.87 m)

You are heading North on Mound.
You are passing Talbot on your left.
The next four streets are Sobieski, Charles, Emeline, and Rowley.
Your next turn is a right (East) onto 7 Mile in approximately 1.7 miles.

8. MOUND & DESNER + 456 ft (138.99 m)

You are heading North on Mound.
You are crossing McNichols.
The next four streets are Brimson, Davison, Iowa, and Nevada.
Your next turn is a right (East) onto 7 Mile in approximately 1 mile.

9. MOUND & STOCKTON 2 + 467 ft (142.34 m)

You are heading North on Mound.
You are crossing Hildale.
The next street is Robinwood and then 7 Mile.
You should turn right (East) onto 7 Mile.

10. 7 MILE & DWYER + 186 ft (56.69 m)

You are heading East on 7 Mile.
You are crossing St. Louis.
The next four streets are Mt. Elliott, Filer, Girardin, and Sherwood.
Your next turn is a right (South) onto Chalmers in approximately 3.3 miles.

11. 7 MILE & ANTWERP 2 + 640 ft (195.07 m)

You are heading East on 7 Mile.
You are crossing Outer.
The next four streets are Blackmoor, Gruebner, Langholm, and Algonac.
Your next turn is a right (South) onto Chalmers in approximately 1.9 miles.

12. 7 MILE & DRESDEN + 145 ft (44.20 m)

You are heading East on 7 Mile.
You are crossing Strasburg.
The next four streets are Hamburg, Barlow, Waltham, and Gouldburn.
Your next turn is a right (South) onto Chalmers in approximately 1 mile.

13. 7 MILE & VERONA + 257 ft (78.33 m)

You are heading East on 7 Mile.
You are passing Rondo on your right.
The next street is Gratiot, and then Chalmers.
You should turn right (South) onto Chalmers.

14. CHALMERS & EASTWOOD + 74 ft (22.56 m)

You are heading South on Chalmers.
You are crossing Saratoga.
The next four streets are Faircrest, Linnhurst, Glenwood, and Park Grove.
Your next turn is a right (West) onto Harper in approximately 2.1 miles.

15. CHALMERS & SPRING GARDEN + 128 ft (39.01 m)

You are heading South on Chalmers.
You are crossing Seymour.
The next four streets are Troester, Cedar Grove, Hazel Ridge, and Young.
Your next turn is a right (West) onto Harper in approximately 1.4 miles.

16. CHALMERS & CAMDEN + 252 ft (76.81 m)

You are heading South on Chalmers.
You are crossing Hampshire.
The next street is Evanston, and then Harper.
You should turn right (West) onto Harper.

17. HARPER & PARK + 607 ft (185.01 m)

You are heading West on Harper.
you are passing Annsbury on your right.
The next four streets are Norcross, Harrell, Barrett, & Gunstone.
Your next turn is a left (Southwest) onto Gratiot in approximately 1.5 miles.

18. HARPER & ST. JEAN + 149 ft. (45.42 m)

You are heading West on Harper.
You are passing Beniteau on your left.
The next four streets are Athens, Venice, Anstell & Lemay.
Your next turn is a left (Southwest) onto Gratiot in approximately .7 miles.

19. HARPER & BEWICK + 151 ft. (46.02 m)

You are heading West on Harper.
You are crossing Hurlbut.
The next street is Cadillac, and then Gratiot.
You should turn left (Southwest) onto Gratiot.

20. GRATIOT & MC CLELLEN + 93 ft (28.35 m)

You are heading Southwest on Gratiot.
You are crossing Belvidere.
The next four streets are Lambert, Holcomb, Rohns, and Crane.
Your next turn is a left (Southeast) onto Mt. Elliott in approximately 2 miles.

21. GRATIOT & MAXWELL + 127 ft (38.71 m)

You are heading Southwest on Gratiot.
You are crossing Parker.
The next four streets are Van Dyke, Seyburn, Baldwin, and Townsend.
Your next turn is a left (Southeast) onto Mt. Elliott in approximately 1.2 miles.

22. GRATIOT & BELLEVUE + 316 ft (96.32 m)

You are heading Southwest on Gratiot.
You are crossing Beaufait.
The next street is Meldrum, and then Mt. Elliot.
You should turn left (Southeast) onto Mt. Elliot.

23. MT. ELLIOT & PULFORD 2 + 97 ft (29.57 m)

You are heading Southeast on Mt. Elliot.
You are crossing Mack.
The next four streets are Ludden, Preston, Elba, and Heidelberg.
Your next turn is a left (Northeast) onto Jefferson in approximately 1.4 miles.

24. MT. ELLIOTT & FORT + 155 ft (47.24 m)

You are heading Southeast on Mt. Elliott.
You are passing Congress on your left.
The next street is Larned on your right, and then Jefferson.
You should turn left (Northeast) onto Jefferson.

25. JEFFERSON & BEAUFAIT + 196 ft (59.74 m)

You are heading Northeast on Jefferson.
You are passing Bellevue on your left.
The next four streets are Concord, Canton, Helen, & Grand.
Your next turn is a left (Northwest) onto Cadillac in approximately 1.7 miles.

26. JEFFERSON & VAN DYKE + 126 ft (38.40 m)

You are heading NOrtheast on Jefferson.
You are passing Parker on your left.
The next four streets are Seminole, Iroquois, Burns, and Fischer.
Your next turn is a left (Northwest) onto Cadillac in approximately .9 miles.

27. JEFFERSON & PARKVIEW 1 + 232 ft (70.71 m)

You are heading Northeast on Jefferson.
You are passing Motorboat on your right.
The next street is Pennsylvania, and then Cadillac.
You should turn left (Northwest) onto Cadillac.

28. CADILLAC & ST PAUL + 666 ft (202.99 m)

You are heading Northwest on Cadillac.
You are crossing Kercheval.
The next four streets are Vernor, Charlevoix, Goethe, and Mack
Your next turn is a right (Northeast) onto Warren in approximately 1.4 miles.

29. CADILLAC & CANFIELD + 476 ft (145.08 m)

You are heading Northwest on Cadillac.
You are crossing Forest.
The next street is Gordon, and then Warren.
You should turn right (Northeast) onto Warren.

30. WARREN & BEWICK + 125 ft (38.10 m)

You are heading Northeast on Warren.
You are crossing Garland.
The next four streets are St. Clair, Harding, French, and Montclair.
Your next turn is a right (Southeast) onto Alter in approximately 2.3 miles.

31. WARREN & ST. JEAN + 79 ft (24.08 m)

You are heading Northeast on Warren.
You are passing Gladwin on your right.
The next four streets are Conner, Eugene, Maynard, and Cope.
Your next turn is a right (Southeast) onto Alter in approximately 1.6 miles.

32. WARREN & PHILIP = 68 ft (20.72 m)

You are heading Northeast on Warren.
You are crossing Manistique.
The next street is Ashland, and then Alter.
You should turn right (Southeast) onto Alter.

33. ALTER & VOIGHT + 163 ft (49.68 m)

You are heading Southeast on Alter
You are passing Canfield on your right.
The next four streets are Waveney, Lozier, Mack, and Goethe.
Your next turn is a left (Northeast) onto Kercheval in approximately 1.2 miles.

34. ALTER & GOETHE + 252 ft (76.81 m)

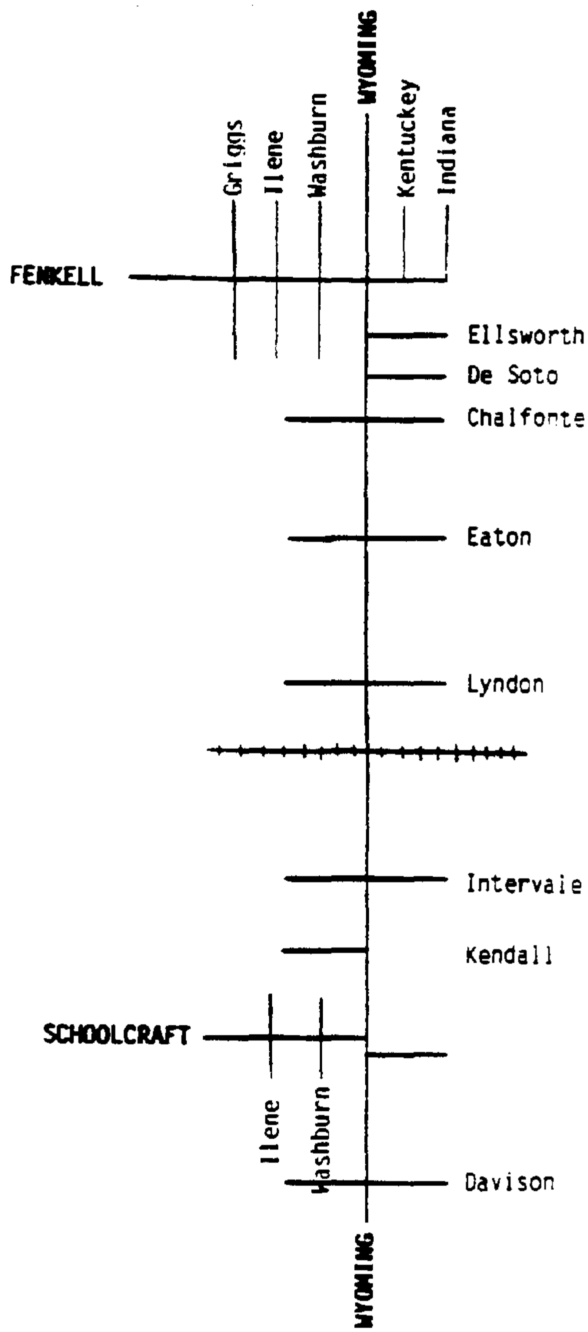
You are heading Southeast on Alter.
You are crossing Charlevoix.
The next street is Vernor, and then Kercheval.
You should turn left (Northeast) onto Kercheval.

APPENDIX C: SAMPLE PAGE OF STRIP MAPS USED BY MAP CONTROL GROUP SUBJECTS

#4

WYOMING from **SCHOOLCRAFT** to **FENKELL.**

After turning **LEFT** from **SCHOOLCRAFT**, drive **NORTH** for approximately **1** mile, then turn **LEFT** onto **FENKELL.**



APPENDIX D: TEXT OF GAS MILEAGE PROBLEMS USED AS COGNITIVE LOADING DURING TEST DRIVE

"Easy" Section

Question: "How far will you have to walk if the next gas station is X miles, and you have enough gas to go Y?"

Problems Used:

	X	Y	A
1.	60	50	10
2.	95	75	20
3.	65	35	30
4.	50	20	30
5.	20	10	10

"Medium" Section

Question: "How far will you have to walk if the next gas station is X miles, and you have enough gas to go Y?"

Problems Used:

	X	Y	A
1.	46	22	24
2.	66	32	34
3.	38	26	12
4.	98	54	44
5.	42	28	14

"Hard" Section

Question: "How far will you have to walk if the next gas station is X miles, your car gets Y miles per gallon, and you have Z gallons?"

Problems Used:

	X	Y	Z	A
1.	67	7	8	11
2.	58	5	6	28
3.	47	9	4	11
4.	49	8	3	25
5.	57	4	6	33

APPENDIX E: COPY OF INFORMED CONSENT RECORD

Part 46, subtitle A to Title 45 of the Code of Federal Regulations relating to the Protection of Human Subjects in Research requires your informed consent for participation in Federal Highway Administration driving studies. Section 46.103(c) gives the following definition:

> "Informed consent means the knowing consent of an individual or his legal authorized representative, so situated as to be able to exercise free power of choice, without undue inducement or any element of force, fraud, deceit, duress, or other form of constraint."

We are asking you to be a subject in a study evaluating the effect of various navigational aids on driver performance under varying conditions. Please consider the following elements of information in reaching your decision whether or not to consent.

1. You will be asked for biographical information necessary to the study. All information provided is confidential and the source of information will not be disclosed to the public.

2. Prior to beginning the study, you will be given a visual acuity test. Minimum acceptable corrected vision for this study is 20/40 (binocular, far vision).

3. A photocell will be clipped to your ear lobe while you drive. This is a commonly used, non-invasive technique to obtain heart rate data.

4. You will drive a car in the HYSIM Laboratory through simulated streets of Detroit, Michigan. You should not be familiar with Detroit as we are testing situations in which a person would be using either simulated roadway signs or on-board navigational devices. You will drive a practice route to familiarize yourself with the situation, and then drive the experimental route. The driving task should take 2 to 2 1/2 hours. Including preliminaries listed in paragraphs 1--2, the entire session should take no more than three hours.

5. In the past, a small percentage of drivers in HYSIM have experienced motion sickness. If, during the study, you experience any discomfort, notify the experimenter immediately and the experiment will be stopped. Aside from this, you will not be subjected to risks exceeding those ordinarily encountered in working in an office building.

6. You are free to decline consent, or withdraw consent and discontinue participation in the session at any time.

7. Upon completion of the session, you will be paid $40.00 for your participation. You must complete the entire session to receive full remuneration.

The basic elements of information have been presented and understood by me, and I consent to participate as a subject.

NAME: (Please print) ______________________________

SIGNATURE: ______________________________

DATE: ______________________________

ADDRESS: ______________________________
PHONES: HOME: ______________ WORK: ______________
DATE OF BIRTH: ______________
(FHWA USE: DO NOT FILL IN) ACUITY: _____ HYSIM NUMBER: ____

APPENDIX F: INSTRUCTIONS

Instructions to be read verbatim to subject before practice drive:

(Have subject sit on passenger side. Explain seat and steering wheel adjustments, etc. Explain that after reading the instructions you will drive for a short distance to demonstrate the operation of the vehicle before the subject begins the practice drive).

You are about to start the practice drive, which is a 14 mile loop through Detroit. Here is a map of it. (Hand map to subject). We are starting here at Joy Road and Minock Street, heading east.

IF COMPLEX VISUAL: The stars indicate different destinations during the drive. The number refers to a list of destinations stored in this navigational device. I'll tell you more about it later.

We'll go east on Joy and make a left onto Greenfield Road, go north on Greenfield and make a right onto Schoolcraft Avenue, go east on Schoolcraft and make a left onto Wyoming Avenue, go north on Wyoming and make a left onto Fenkell Avenue, go west on Fenkell and make a left onto Evergreen Road, go south on Evergreen and make a final left back onto Joy Road. You must drive the entire loop at least once. After that you may stop if you feel comfortable, or continue if you need to.

You will be starting out on a four-lane street, although you will also drive on two-lane streets. All streets are two-way, so stay to the right of the double yellow line. On four-lane streets, please drive in the left lane, at least during this practice drive. Before turning, always use your directional signals. This is a simulated nighttime drive, and the only features you will be able to see will be the street lane markings, traffic lights and signs, and sometimes another vehicle. The speed limit for all roads you'll drive on is 25 miles per hour. If at any point in the drive you feel you don't want to continue for any reason, inform me and the drive will be stopped.

The reason for the practice drive is to get you used to driving in HYSIM and used to the feel of the car. I also want to give you some practice with the navigational device you'll be using.

IF COMPLEX VISUAL:
(NOTE: Be sure device location is at Joy and Minock, east is up, and destination is at Greenfield and Ellis.)

This device, as you can see, gives a map-like display which follows you as you drive. The arrowhead (point to Joy & Minock) in the center is your car, and the star (point to Greenfield and Ellis) is your first destination. The numbers on the right are map scales. The 20-mile scale means the map represents 20 miles from top to bottom. Likewise with the other scales. We have set the destination so all you have to do is drive straight down the road and make only one turn. All the destinations are set up like this. Never try to take a route that requires more than one turn. To show your present location and your destination on the same screen, the device is currently set on a map scale of 5 miles (point to indicator on screen). However, we want you to always drive on the 1/4 mile scale so we can have consistency among subjects.

(Press the 1/4 mile button and wait until display has filled.)

This is the scale we want you to work with all the time. This arrow with the number beside it (point) points to your destination, and the number is your mileage to it. The arrow to its right shows which direction is north. Note that 'up' on the map is the direction you are travelling, unlike printed maps. On the left-hand side of the map are some other symbols, but you won't have to use them.

One thing you will have to do is change destinations several times during the drive. All you have to do is stop at a stop sign and push a few buttons. I'll show you how when we get to your first destination.

IF MEDIUM VISUAL:

This device gives you word messages about when to turn. For example, your first turn is a left turn onto Greenfield Road. Three blocks before there, this box will display the message, "Take 3rd left". In the next block it will display, "Take 2nd left." And, in the next block it will display, "Take 2nd left." And, in the last block before Greenfield Road, it will display, "Take 1st left." All you have to do is pay attention to the box to know where to turn.

IF SIMPLE VISUAL:

This device shows arrows to tell you where to turn. For example, your first turn is a left turn onto Greenfield Road. In the last block before Greenfield Road, it will display a left arrow. All you have to do is pay attention to the box to know where to turn.

IF COMPLEX AUDIO:

This is how your navigation device works: You will hear messages over your radio that will tell you what street you are on, what streets are coming up, and in the case of turns, which way to turn. All you have to do is pay attention to the woman's voice to know where to go.

IF MEDIUM AUDIO:

This is how your navigational device works: You will hear a woman's voice give you instructions over the radio. For example, your first turn is a left turn onto Greenfield Road. Three blocks before there, you will hear, "Take 3rd left". In the next block it will say, "Take 2nd left." And, in the last block before Greenfield Road, it will say, "Take 1st left." All you have to do is pay attention to the voice to know where to turn.

IF SIMPLE AUDIO:

This is how your navigational device works: You will hear, "Left, left, left," or "Right, right, right," in the block before your turn. For example, your first turn a left turn onto Greenfield Road. In the last block before Greenfield Road, you will hear a woman's voice say, "Left, left, left." All you have to do is pay attention to the voice to know where to turn.

IF MAP CONTROL:

I also want to give you some practice with the strip-maps you will be using to find your way. Each page shows one street, starting from where you turn onto it, and ending at where you turn off it. (Hand maps to subject.) Look at the first page. On the left is a label showing the limits of the map: "Joy, from Evergreen to Greenfield." Below that are instructions for that street: "Start at Minock, drive east for approximately 2 miles, then turn left onto Greenfield." The maps are set up so that you will always be going UP the page, no matter whether you're going north, south, east, or west. The intersection where you have to turn is always at the top of the page, and the turn direction is highlighted with a green pen. Of course you will keep the maps with you during the drive so you can refer to them. You don't have to memorize the route. Right now, take a few minutes to familiarize yourself with them. Feel free to write notes on them if you want to.

There are two other things I want you to do during the drive. The first is to watch these two gauges, the water-temperature gauge (point) and the oil-pressure gauge (point) for changes during the drive. We have simulated water-temperature and oil-pressure problems with your car. All you have to do is press the button above each gauge if one of the needles jumps outside the normal limits as marked on the gauges (point). These changes will occur suddenly. If the needle only goes near to the line but stays within the bracket, don't do anything. These changes will occur quite a few times during the drive, so you'll have to check the gauges often.

The other thing you need to do during the drive is solve some gas mileage problems that will come over the radio. They will sound something like this: "How far will you have to walk if the next gas station is 54 miles away and you have enough gas to go 41?" You would subtract 41 from 54 and say, "13." Some of the problems will be easier, some will be harder, involving both multiplication and subtraction. In any case, don't try to write down anything, do all the figuring in your head, and give an answer as quickly as possible, even if you're not positive it's right.

Any questions? (If not, begin the demonstration drive. Describe and demonstrate characteristics related to steering, turns, brake response etc. After completing the demonstration have the subject take the driver's seat. Assist the subject in making any adjustments necessary, and attach the earclip, before telling the subject to begin).

During practice drive:

A. After Piedmont St.: "During the practice drive we want you to purposely make two wrong turns. This is so you can practice turning around in the cul-de-sac that is at the end of every wrong turn. You'll do one a few blocks from here, at Faust St., and another one later."

1. At the first school sign, say, "Turn left at Faust, the next street with a street sign."
2. After turn, say, "When you get to the cul-de-sac, bear to your right and go around the circle counter-clockwise. Always go around the cul-de-sacs this way."
3. At end of circle, say, "Turn right here to get back on the side street, then turn left at the intersection to get back onto your route, which is Joy Rd. Should you ever make a wrong turn, remember to make the SAME turn when you get back to the main road. Here you turned LEFT off Joy, so turn LEFT when you get back to it."

A. Just before St Marys (2nd street after Asbury Park), direct attention to oil gauge so subject can see it change. Prompt pressing the button if necessary.

B. If subject makes a wrong turn: "You just made a wrong turn, but that's OK. At the end of this street is a cul-de-sac where you can turn around."

1. Help subject through U-turn in cul-de-sac.
2. Tell subject which way to turn to get back on route.
3. Reassure subject.

C. If subject doesn't turn: "You should have turned there, but that's OK. At the end of this street is a cul-de-sac where you can turn around."

1. Help subject through U-turn in cul-de-sac.
2. Tell subject which way to turn to get back on route.
3. Reassure subject.

IF COMPLEX VISUAL:

D. At Greenfield and Ellis, help subject through selection of next destination:

"All of your destination points will be similar to this one, that is, a street with a stop sign shortly after a turn. Now that we've stopped, let me show you how to set the next destination. First you press the MENU button which is in the upper left-hand corner. (When menu appears:) Now press the button next to 'SELECT DESTINATION'. Wait a second for the menu to change, then press the button next to 'STORED LOCATIONS'. (When list appears:) We've put the destinations for the main drive in locations 1 through 11, to make the main drive as easy as possible, so we need to find location number 12. Press the 'down' arrow on the bottom left to move to locations 5-8, then press it again to move to locations 9-12, then press the button next to 12, "Schoolcraft and Sussex". Now the map will reappear at a scale that will include your destination on the screen. Notice that we have set the destination so all you have to do is drive straight down the road and make only one turn. All the destinations are set up like this. Never try to take a route that requires more than one turn.

"Change the scale to 1/4 mile so you'll be ready to start driving." (Note: Coach subject through this procedure at subsequent stopping points until subject can do it alone.)

E. After Greenfield & Orangelawn: "You may have noticed there's only one right turn in the practice drive. To give you more experience with them, I'd like you to take an extra right turn at Plymouth St., which is the street after next. It'll also show you what a cul-de-sac looks like on a four-lane street."

1. At Plymouth Street (second after Orangelawn), say, "Turn right here. Turn into the right lane and stay there, even though I told you to drive in the left lane during the practice drive."

2. After turn, say, "Bear to your right at the cul-de-sac."

3. At end of circle, say, "Turn right here to get back on the side street, then turn right at the intersection to get back onto your route, which is Greenfield Road."

F. When ready to turn onto Fenkell: "Please drive in the left lane along this street because a car will come up from behind you and travel next to you. It will always stay in the right lane, so you don't have to worry about it unless you swerve out of your lane."

G. At Joy and Minock: "This completes one loop on the practice drive. If you feel you've had enough practice, you may put the car in park and take a break while we set up the experimental drive. If you want some more practice, wait until we reset some equipment, then go ahead. After that, you can stop at any point, whenever you feel ready."

Before & during experimental drive:

A. Get subject and seat him/her in car. "OK, the navigational device will guide you through this drive just as in the practice drive. Aside from driving according to the route, the oil and temperature gauges may still change, and you will still have the gasoline problems to do every once in a while. Remember that some of the problems will be harder. In all cases, give us an answer as soon as possible. Concerning the gauges, remember that we only want you to reset them when the needles go outside the lines, but not if they only go near them. Any questions?" If so, answer as best as possible. When subject is ready, say, "I'll be in the control room during the drive, and we can talk back and forth over the intercom. When I turn down the lights you may start." When settled in control room: "OK, go ahead."

B. If subject takes a wrong turn or misses a turn, use same instructions as in practice drive.

C. If subject fails to reset gauge, say, "You just missed one of the gauges. It reset itself so don't press the buttons now, but try to watch them a little more closely."

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