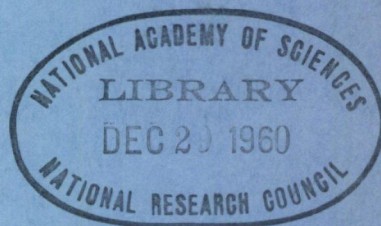


HIGHWAY RESEARCH BOARD

Bulletin 261

Driving Simulators and Application Of Electronics to Highways



TE7
128
o.261

National Academy of Sciences—

National Research Council

publication 770

HIGHWAY RESEARCH BOARD

Officers and Members of the Executive Committee

1960

OFFICERS

PYKE JOHNSON, *Chairman* W. A. BUGGE, *First Vice Chairman*
R. R. BARTELSMEYER, *Second Vice Chairman*
FRED BURGGRAF, *Director* ELMER M. WARD, *Assistant Director*

Executive Committee

BERTRAM D. TALLAMY, *Federal Highway Administrator, Bureau of Public Roads (ex officio)*
A. E. JOHNSON, *Executive Secretary, American Association of State Highway Officials (ex officio)*
LOUIS JORDAN, *Executive Secretary, Division of Engineering and Industrial Research, National Research Council (ex officio)*
C. H. SCHOLER, *Applied Mechanics Department, Kansas State College (ex officio, Past Chairman 1958)*
HARMER E. DAVIS, *Director, Institute of Transportation and Traffic Engineering, University of California (ex officio, Past Chairman 1959)*
R. R. BARTELSMEYER, *Chief Highway Engineer, Illinois Division of Highways*
J. E. BUCHANAN, *President, The Asphalt Institute*
W. A. BUGGE, *Director of Highways, Washington State Highway Commission*
MASON A. BUTCHER, *Director of Public Works, Montgomery County, Md.*
A. B. CORNTHWAITE, *Testing Engineer, Virginia Department of Highways*
C. D. CURTISS, *Special Assistant to the Executive Vice President, American Road Builders' Association*
DUKE W. DUNBAR, *Attorney General of Colorado*
FRANCIS V. DU PONT, *Consulting Engineer, Cambridge, Md.*
H. S. FAIRBANK, *Consultant, Baltimore, Md.*
PYKE JOHNSON, *Consultant, Automotive Safety Foundation*
G. DONALD KENNEDY, *President, Portland Cement Association*
BURTON W. MARSH, *Director, Traffic Engineering and Safety Department, American Automobile Association*
GLENN C. RICHARDS, *Commissioner, Detroit Department of Public Works*
WILBUR S. SMITH, *Wilbur Smith and Associates, New Haven, Conn.*
REX M. WHITTON, *Chief Engineer, Missouri State Highway Department*
K. B. WOODS, *Head, School of Civil Engineering, and Director, Joint Highway Research Project, Purdue University*

Editorial Staff

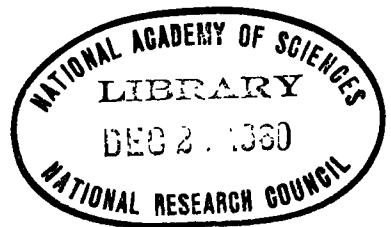
FRED BURGGRAF ELMER M. WARD HERBERT P. ORLAND
2101 Constitution Avenue Washington 25, D. C.

The opinions and conclusions expressed in this publication are those of the authors
and not necessarily those of the Highway Research Board.

^{NRC.}**HIGHWAY RESEARCH BOARD**
Bulletin 261

***Driving Simulators and Application
Of Electronics to Highways***

**Presented at the
39th ANNUAL MEETING
January 11-15, 1960**



**1960
Washington, D. C.**

\$1.40

TE7

N28

no. 261-270

Department of Traffic and Operations

Fred W. Hurd, Chairman
Director, Bureau of Highway Traffic
Yale University
New Haven, Connecticut

COMMITTEE ON ROAD USER CHARACTERISTICS

T. W. Forbes, Chairman
Highway Traffic Safety Center
Michigan State University
East Lansing

- Terrence M. Allen**, Department of Psychology and Highway Traffic Safety Center, Michigan State University, East Lansing
Earl Allgaier, Research Engineer, Traffic Engineering and Safety Department, American Automobile Association, Washington, D.C.
Joseph E. Barmack, Assistant Vice President, Dunlap and Associates, Inc., Stamford, Connecticut
Siegfried M. Breuning, Civil Engineering Department, Michigan State University, East Lansing
Leon Brody, Director of Research, Center for Safety Education, New York University, New York
Harry W. Case, Department of Engineering, University of California, Los Angeles
John J. Conger, Professor of Clinical Psychology, University of Colorado Medical School, Denver
William G. Eliot, Highway Engineer, Bureau of Public Roads, Washington, D.C.
Bernard H. Fox, Accident Prevention Program, U.S. Public Health Service, Washington, D.C.
Gordon K. Gravelle, Deputy Commissioner, Department of Traffic, New York
William Haddon, Jr., Director, Driver Research Center, New York State Department of Health, Bureau of Motor Vehicles, Albany
Slade Hulbert, Assistant Research Psychologist, Institute of Transportation and Traffic Engineering, University of California, Los Angeles
Joseph Intorre, Administrative Assistant, Institute of Public Safety, Pennsylvania State University, University Park
Merwyn A. Kraft, Research Coordinator, Flight Safety Foundation, Inc., New York
A. R. Lauer, San Luis Obispo, California
David B. Learner, Human Factors Research Group, Research Laboratories, General Motors Corporation, Detroit, Michigan
James L. Malfetti, Executive Officer, Safety Education Project, Teachers College, Columbia University, New York
Richard Michaels, Bureau of Public Roads, Washington, D.C.
Alfred L. Moseley, Moseley and Associates, Boston, Massachusetts
Charles W. Prisk, Director, Highway Safety Study, Bureau of Public Roads, Washington, D.C.
Robert V. Rainey, Department of Psychology, San Fernando Valley State College, Northridge, California
David W. Schoppert, Automotive Safety Foundation, Washington, D.C.
Virtus W. Suhr, Accident Research Analyst, Illinois Division of Highways, Bureau of Traffic, Springfield
Clifford O. Swanson, Chief, Research and Statistics, Iowa Department of Public Safety, Des Moines
Julius E. Uhlauer, Research Manager, Personnel Research Branch, TAGO, Department of the Army, Washington, D.C.
George M. Webb, California Division of Highways, Sacramento

***Special Committee on
Electronic Research in the Highway Field***

**O.K. Normann, Chairman
Deputy Assistant Commissioner for Research
Bureau of Public Roads**

John L. Barker, Development Engineer, Automatic Signal Division, Eastern Industries, Inc., East Norwalk, Connecticut
Henry A. Barnes, Department of Traffic Engineering, Baltimore, Maryland
Joseph B. Bidwell, Head, Engineering Mechanics Department, Research Staff, General Motors Research Laboratories, Warren, Michigan
William N. Carey, Jr., Chief Engineer for Research, AASHO Road Test, Ottawa, Illinois
J. Douglas Carroll, Jr., Director, Chicago Area Transportation Study,
Leslie E. Flory, David Sarnoff Research Center, R.C.A. Laboratories, Princeton, New Jersey
Bernard H. Fox, Psychologist, Accident Prevention Program, Division of Special Health Services, Department of Health, Education and Welfare, Washington, D.C.
William L. Garrison, Department of Geography, University of Washington, Seattle
Daniel L. Gerlough, Senior Staff Engineer, Thompson Ramo Wooldridge, Inc., Canoga Park, California
Richard C. Hopkins, Chief, Instrumentation Branch, Traffic Operations, Bureau of Public Roads, Washington, D.C.
Fred W. Hurd, Director, Bureau of Highway Traffic, Yale University, New Haven, Connecticut
E.A. Landry, Assistant Chief Engineer, Louisiana Department of Highways, Baton Rouge
James L. Malfetti, Safety Education Project, Teachers College, Columbia University, New York
Alger F. Malo, Department of Streets and Traffic, Detroit, Michigan
Burton W. Marsh, Director, Traffic Engineering and Safety Department, American Automobile Association, Washington, D.C.
Richard M. Michaels, Bureau of Public Roads, Washington, D.C.
C.L. Miller, Director, Photogrammetry Laboratory, Massachusetts Institute of Technology, Cambridge
Theodore F. Morf, Engineer of Research and Planning, Illinois Division of Highways, Springfield
LeRoy T. Oehler, Highway Research Laboratory, Michigan State University, East Lansing
Eldon J. Yoder, Joint Highway Research Project, Purdue University, Lafayette, Indiana

Contents

DRIVING SIMULATOR RESEARCH

Slade Hulbert and Charles Wojcik	1
--	---

ENGINEERING AND PSYCHOLOGICAL USES OF A DRIVING SIMULATOR

Bernard H. Fox	14
----------------------	----

Discussion:

C. H. Hutchinson	25
T. W. Forbes	26
J. L. Malfetti	26
J. E. Uhlaner	26
H. W. Case and S. Hulbert	26
S. M. Breuning	27
L. Brody	27
J. E. Barmack	27
R. Michaels	28
D. B. Learner	29

Closure: Bernard H. Fox	31
-------------------------------	----

SOME TECHNICAL CONSIDERATIONS IN DRIVING SIMULATION

Bernard H. Fox	38
----------------------	----

STANDARD ELECTRONIC UNITS INTERCONNECT TO PROVIDE FLEXIBLE DIGITAL RECORDING

Richard C. Hopkins	44
--------------------------	----

ELECTRONIC HIGHWAYS

Joseph B. Bidwell, Albert F. Welch and Eugene A. Hanysz	50
---	----

Driving Simulator Research

SLADE HULBERT and CHARLES WOJCIK, Institute of Transportation and Traffic Engineering, University of California, Los Angeles

● INCREASING AND SPREADING interest in simulators and simulation in general as well as in the specific topic of automobile driving simulation has fostered the writing of this paper about the Institute's research and development program for a driving simulation facility. Two separate devices will be described along with results of testing a number of driver subjects.

As stated in an internal report (1) several members of the Institute staff have become,

convinced that driving simulation holds tremendous potential for really getting at the highway safety problem. We are also convinced that investment in driving simulation research will pay off hundreds of thousands of times over, merely through its one aspect of permitting effective pretesting of highway designs — such pretesting being normal in most engineering work but not now possible with highway design insofar as how the driver will react to it is concerned. And finally, we are convinced that by promising to really tell us something about how drivers behave on the road, research with a driving simulator will provide key information, the lack of which is now stymying other lines of investigation.

We feel that the need for very extensive and expedited development in this simulation field is extremely urgent. The tremendous loss of life on our highways should have told us in any recent year that the time had arrived for getting at the basic causes of accidents. Now the urgency is multiplied, because we are embarking on a vast highway construction program, building-in danger features that can lay on us an appalling, accumulating toll of deaths and suffering and wasted dollars for years and years to come.

An ultimate facility as currently envisioned by the Institute has been described in an earlier publication (2). Certain logical and necessary steps leading to the design of this ultimate facility are being followed and have resulted at this time in two devices wherein drivers can be measured and observed as they "drive" in the research laboratory. In one device the subject drives in a mock-up of a vehicle and in the other device an actual automobile is used.

DYNAMOMETER FACILITY

In a 30- x 20- x 10-ft room, an automobile with its rear wheels on the steel rollers of a chassis dynamometer can be operated in response to two motion pictures. One picture presents the forward view and the other the rearward scene which is seen in the rear-view mirror. On a curved screen 8 ft from the driver the forward picture is shown by a projector located 1 ft above the car in line with the driver's position. The rear picture is projected from inside the car onto a screen which just covers the rear window. Stray light from the projectors is supplemented by two goose-neck lamps containing 5-watt bulbs thus providing fairly uniform illumination inside and outside the vehicle at between 5 and 10 foot-candles. The adjustable dash light is set to balance the illumination and make the speedometer clearly visible. Steering wheel movements displace the forward picture from side to side which gives the driver a strong impression

of controllability of his lateral position on the highway. A "highway feel" of steering is accomplished by having the front wheels rest on turntables to increase ease of movement. The steering system is spring loaded to simulate the self-aligning tendency of a rolling vehicle so that the steering wheel tends to return to center. Engine noise is real, but indicated speed has been made twice that of the actual speed of the wheels on the rollers. This doubling of the indicated speed has the effect of equating it with vehicle noise (engine noise and tire-on-roller noise). A flywheel attached to the rollers simulates vehicle momentum and contributes to realism of engine performance and speed changes.

Engine temperature is controlled directly by an auxiliary radiator and indirectly by a refrigeration air-conditioning unit which controls room air temperature. Tire overheating is prevented by a cooled-air system blowing on the tires. Exhaust fumes are ducted outside the building and there is a constant change of room air.

The vehicle undergoes some low-amplitude vibration at approximately 50 cps produced by the action of the tires on rollers. This action is similar to that experienced and recorded while driving on newly surfaced road.

Driver responses are recorded on four channels of a Brush six-channel, ink-writing recorder. Vehicle speed, steering movements, brake and accelerator pedal action, and the driver's galvanic skin response are recorded along with written notations about the motion picture events being shown to him.

TILTING CHAIR FACILITY

To provide simulation of the physical forces experienced while driving, a driver's compartment is mounted so that it can be tilted fore and aft (pitch) and from side to side (roll) as well as rotated (yaw). The driver's outside view is restricted to a motion picture projected on a cylindrical screen 6 ft from him. This picture, from an extremely wide-angle 160-deg lens, completely fills the driver's field of vision through the windshield aperture. Because this picture is of low brightness the entire room is made dark during projection with all stray light being trapped by a ventilated box that houses the projector.

The essence of this device lies in the fact that both the projection screen and projector are attached to the driver's compartment and, therefore, move with that cockpit when it is tilted. Thus, even when he is tilted the driver's visual world including his horizon reference does not move and the changing physical forces exerted on his body by gravity are then perceived as acceleration forces or centrifugal forces depending on the direction of tilt (pitch or roll, respectively).

At the present time this device is tilted manually in response to the driver's actions and the motion picture scene. When, for example, the driver removes his foot from the accelerator pedal or applies the brake, a signal light informs the operator and he tilts (pitch) the device an appropriate amount and rate depending on the traffic situation.

MOTION PICTURE TECHNIQUES

Electrically driven cameras are mounted fore and aft on a 1957 Chevrolet station wagon. Positioning the cameras so that they are at driver's eye level is crucial if perspective distortion is to be avoided. When highway curves (vertical or horizontal) are to be photographed, it becomes necessary to construct a view finder on the vehicle in order to plan the content of the movie. Each section of highway must be selected carefully for certain characteristics that will appear in the completed movie. The view finder is absolutely necessary for selection of a road with acceptable alignment and sight distances. Road smoothness is desirable but a ride that is too level results in a motion picture that gives the driver a floating or detached experience that is unrealistic and, therefore, undesirable for simulation use.

RESULTS TO DATE

Results can be described in two categories: first, what has been learned about driving simulation techniques, possibilities and feasibilities; and second, what has been learned about driver reactions, responses and opinions.

When presented in these devices, color motion pictures even with a narrow field (approximately 50 deg actual and 38 deg apparent) were far more realistic than was expected. Provided that care is taken in selecting the highway and traffic situations, films such as these can be extremely useful in research. This conclusion is based on the recorded driving behavior of subjects and the personal observations of the Institute staff, other research persons and the naive drivers who volunteered to be subjects. Nearly all these persons have reported without being solicited, that they felt as though they were "on the road" and "in the picture." They also "drove" as though they were truly involved; for example, slowing when sight distance was restricted, increasing speed on straight sections and steering constantly and alertly. To reach this stage of simulation fidelity, it was necessary to:

1. Make the projected front image fill at least 50 deg of the driver's view.
2. Adjust the speed of film projection to suit individual preferences.
3. Double the indicated speed to offset noise generated by the engine and dynamometer.
4. Mechanically link the steering mechanism to the transverse rotation movement of the front projector.
5. Simultaneously project a rearward scene to be viewed in the rear mirror.
6. Spring load the steering mechanism to return the steering wheel to center.
7. Provide approximate highway conditions of resistance to steering movements.
8. Select highway sections and traffic events so that critical information was not expected by the driver to occur outside of his field of view.
9. Instruct the driver that only normally encountered situations would occur on this trip and that he was to assume himself to be on a cross-country trip where he would continue on this road at least the next one-half hour and not have to look for turn-offs or directions.

Approximately 50 deg of visual field was judged to be the "balance point" in terms of realism of effect, in the compromise between clarity of picture and size of picture. This balance point would vary with the characteristics of the camera lens and projection lens that would be used. Apparently size distortion of objects in the picture is of minor importance providing the movie does not contain scenes showing an approach too close (approximately 20 ft) to vehicles or other objects that are directly in the path. Objects to the side (passed or passing) can undergo size distortion within wide limits and still be acceptable. Motion pictures such as these can be used successfully to simulate driving providing a two-lane highway with no stops for crossroads is used and no slower moving vehicles are encountered. Faster moving vehicles which pass are accepted but may be responded to. Horizontal curves are accepted when sight distance is not restricted by the edge of the picture. Vertical curves are accepted up to a difference in grade of approx. 10 percent. At this amount of curvature, sight distance was drastically reduced for a brief period of time (less than $\frac{1}{2}$ sec). This could conceivably be corrected by panning the camera down then up at just the correct time. Dips in the road are accepted and in fact seem to enhance the realism at least up to $\frac{1}{2}$ ft in 10 ft when driven over at 50 mph. There is an interaction between the length of the dips and the speed of the camera car (or apparent speed, when projector speed differs from camera speed) such that the longer the dips the faster the car must go in order for the duration of picture disorientation to remain within acceptable limits.

To date, in addition to trial work, 47 subjects have been tested at least once on the dynamometer driving simulator device; 12 of these subjects have been tested more than once. Seventeen of these drivers were recruited from the UCLA Medical Center outpatient population. Twenty-one of the subjects are volunteers from the student body population. Nine staff member volunteers have been tested twice and two of them three times.

Each driver on each test session experienced two simulated trips, each of approximately 15-min duration. One drive is over a straight road and the other is over a winding road. Traffic is light on both trips and no stops are required. Records of their speed, steering, brake and accelerator pedal movements and their GSR, have been analyzed for a series of traffic events during each trip and for the trip as a whole.

TABLE 1

	Students		Staff		Outpatients	
	Range	Median	Range	Median	Range	Median
(a) Speed (mph)						
Winding Road:						
Max.	33-66	55	35-57	44	29-66	46
Avg.	0-51	35	18-42	33	0-62	31
Min.	0-40	13	0-33	13	0-53	11
Straight Road:						
Max.	37-73	57.2	40-70	53	37-84	59
Avg.	31-66	48	35-62	42	29-64	44
Min.	0-59	31	0-51	35	0-57	24
(b) Steering Wheel Movement (deg)						
Winding Road:						
Max. left turn	36-360	132	72-168	120	24-288	132
Max. right turn	60-384	144	60-288	120	24-300	156
Straight Road:						
Max. left turn	0-120	72	12-84	24	24-240	60
Max. right turn	12-300	84	12-120	36	24-180	84
(c) Speed Reduction Behavior						
Winding Road:						
Times brakes used	0-21	10	0-24	1	0-30	8
Times car slowed	4-32	20	3-33	13	0-29	20
Straight Road:						
Times brakes used	0-3	0	0-3	0	0-9	0
Times car slowed	1-18	7	0-12	2	0-17	6

Table 1 (a) shows that speeds were slower on the curved road for all three groups. There is considerable overlap among the speeds and among the groups. Because there was no direct speed feedback the ranges are no doubt much larger than would be found on the actual road.

Table 1 (b) reveals greater amounts of maximum steering wheel movement on the winding road for all three groups. Some tests were conducted without steering feedback (linkage between wheel and projector). Under these conditions, steering wheel movements were grossly oversize. Differences between the winding road and straight road are clearly evident in Table 1 (c) which shows consistently smaller numbers of speed reduction actions on the straight road.

All of the previously mentioned conclusions are in accordance with what one would expect drivers to do on these two roads. The extent of the ranges for the recorded values is perhaps surprising when one considers that all drivers were exposed to identical driving environments.

In order to assess the extent of practice effects, 12 drivers (7 students and 5 staff) were tested more than once. At least three weeks elapsed between first and second drivers. Subjects were instructed to look on these trips as repeat journeys over the same routes they had driven during the initial test session.

TABLE 2
GROUP COMPARISONS OF FIRST WITH SECOND DRIVE

	First Drive		Second Drive	
	Range	Median	Range	Median
	(a) Speeds (mph)			
Winding Road:				
Max.	37-61	46	37-59	35
Min.	0-17	7	0-31	17
Straight Road:				
Max.	42-73	59	37-59	48
Min.	0-22	33	15-44	35
(b) Steering Wheel Movement (deg)				
Winding Road:				
Max. left turn	36-240	120	36-252	120
Max. right turn	72-384	96	60-288	120
Straight Road:				
Max. left turn	12-240	60	0-204	24
Max. right turn	12-300	60	0-216	24
(c) Speed Reduction Behavior				
Winding Road:				
Times brakes used	0-22	11	0-10	4
Times car slowed	5-33	21	4-32	17
Straight Road:				
Times brakes used	0-3	0	0-3	0
Times car slowed	0-18	9	0-13	4

Group comparisons are given in Table 2 (a), 2 (b), and 2 (c). There is no clear evidence of differences between the group of first drives and the group of second drives.

Collections of individual comparisons between first and second drives are given in Table 3 (a), 3 (b), and 3 (c). No consistent, statistically significant differences appear. The greater number of braking actions during the first drives over the winding road is statistically significant but there is no evidence of a similar difference for the straight road drives. Conversely the difference in number of times car slowed that occurred during the straight road trip did not occur during the winding road trip. Thus, there is little or no evidence in these data for any practice effect. Verbal reports from the subjects suggest that they found the second drive to be more "natural" in that they "felt more confident" and "had time to look around a little at the scenery."

The behavior of these 47 drivers as they negotiated the winding road made quite clear the fact that many of these drivers had difficulty steering around curves. A recent study by Stewart (3) provides field data that also show drivers have trouble with curves. A possible rating system for sections of highway is suggested by Chandler, Herman and Montroll, et al. (4) in their concept "acceleration-noise" which resembles the "number of times braked" and "number of times slowed" scores reported in this paper. These scores are apparently more sensitive than some of the others that were used and are not difficult to record.

With the tilting chair device it has been possible to produce accelerometer records quite similar to those taken in a vehicle making normal and panic stops.

Ten naive experimental subjects and 12 research persons report experiencing a greater degree of realism when the cab was tilted than when it remained stationary.

TABLE 3

	Number of Drives		
	1st > 2nd	2nd > 1st	1st = 2nd
(a) Speed Comparisons Between 1st Drive and 2nd Drives			
Winding Road:			
Max.	5	5	1
Min.	2	8	1
Straight Road:			
Max.	9	3	0
Min.	4	6	2
(b) Steering Wheel Movement Comparisons Between 1st and 2nd Drives			
Winding Road:			
Max. left turn	4	6	3
Max. right turn	7	5	1
Straight Road:			
Max. left turn	8	4	0
Max. right turn	7	3	1
(c) Speed Reduction Comparisons Between 1st and 2nd Drives			
Winding Road:			
Times brakes used	11	0	1
Times car slowed	6	5	0
Straight Road:			
Times brakes used	4	3	6
Times car slowed	10	1	1

Realistic simulation of centrifugal forces and positive acceleration has been easier to accomplish than simulation of negative accelerations. This is due to the fact that negative accelerations are usually of greater amplitude with shorter onset times and, therefore, require more skill and strenuous action on the part of the human operator and often result in a less appropriate motion of the device. This empirical evidence has been supplemented by conclusions reached by analytical methods, as follows:

During an automobile ride, the human body is subjected to a number of forces which can be classified into three groups: disturbance forces due to car action or road deficiencies, gravity, and inertia forces. In the first group are included such forces as those caused by vibration of the car, rough surface of the road, etc. Gravitational force remains constant but the reactions (that is, the reaction of the car seat on the human body) change with different orientations of the car with respect to the earth; thus any road incline changes these reactions. Inertia forces are due to changes in velocity and direction. Simulation of the first two types of forces does not represent a serious problem. However, simulation of inertia forces is a more complicated matter. Before discussing the methods of simulating inertia forces it is appropriate to analyze these forces as they appear during a ride.

Kinematics of a Human Body Considered as a Point in Motion on a Plane Curve

The path of a point P along the plane curve is shown in Figure 1. V_1 and V_2 are the velocity vectors, they are tangent to the path. The values of the tangential and normal accelerations are:

$$a^T = \frac{V_1 - V_2}{dt} = \frac{dV}{dt} = s \frac{d\theta}{dt} \quad (1)$$

$$a^N = \frac{V d\theta}{dt} = \frac{d\theta}{ds} V^2 = \frac{V^2}{s} = w^2 s = \left(\frac{d\theta}{dt} \right)^2 s \quad (2)$$

It is clear that in order to evaluate a^T and a^N the values of s and θ have to be known.

Consider a point P representing a human body in a car proceeding a long flat curve (Fig. 2). It is known that for any flat curve the curvature can be expressed as follows:

$$\frac{1}{s} = \frac{d\phi}{ds} \quad (3)$$

Inasmuch as the dimensions "a" and "b" are much smaller than s ,

$$ds \approx b \quad d\phi \approx \phi$$

thus

$$\frac{1}{s} = \frac{\phi}{b}$$

Further, from the geometrical relationship in Figure 2

$$\begin{aligned} \frac{b}{\phi} &= \frac{a}{\alpha - \phi} & \phi &= \frac{b}{a} (\alpha - \phi) \\ \phi + \frac{b}{a} \phi &= \frac{b}{a} \alpha & \phi &= \frac{b/a \alpha}{1 + b/a} = \frac{\alpha b}{a + b} \\ s &= \frac{a + b}{\alpha} = \frac{L}{\alpha} \end{aligned} \quad (4)$$

in which $L = a + b =$ wheel base in feet

$\alpha =$ average turn angle, in radians.

For Figure 1 Eq. 3 can be written

$$d\theta = \frac{ds}{s} \quad (5)$$

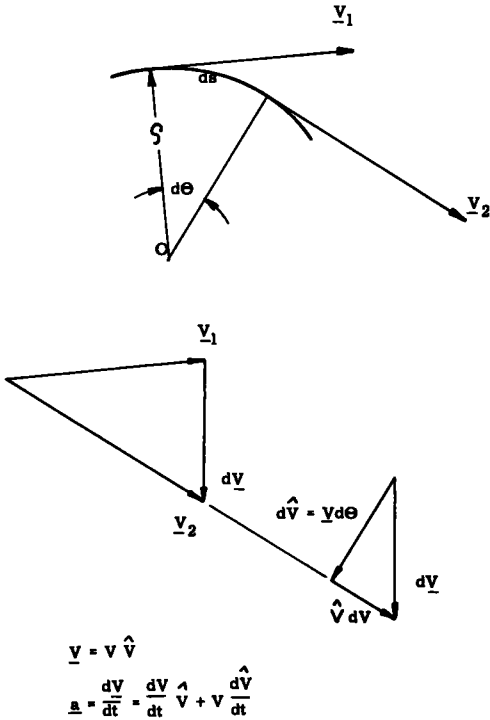


Figure 1.

but

$$ds = R d\psi \quad (6)$$

in which $R =$ radius of the wheel in feet
 $\psi =$ angle of rotation of the wheel in radians.

Substituting the values for s and ds in Eq. 5

$$d\theta = \frac{R \alpha d\psi}{L} \quad (7)$$

thus

$$w = \frac{d\theta}{dt} = \frac{R \alpha}{L} \frac{d\psi}{dt} \quad (8)$$

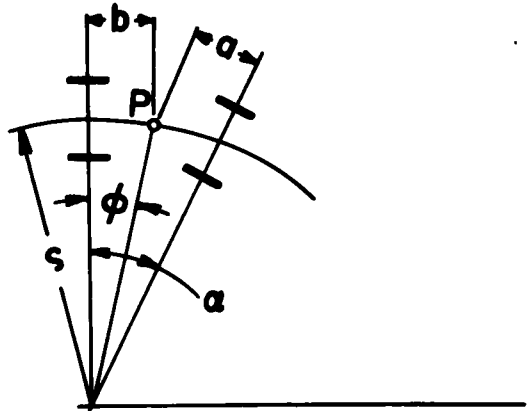


Figure 2.

and

$$\ddot{w} = \frac{d^2 \theta}{dt^2} = \frac{R}{L} \left[a \frac{d^2 \psi}{dt^2} + \frac{da}{dt} \frac{d\psi}{dt} \right] \quad (9)$$

Now the tangential and normal accelerations can be written

$$a^T = s \ddot{w} = \frac{R}{a} \left[a \frac{d^2 \psi}{dt^2} + \frac{d\psi}{dt} \frac{da}{dt} \right] \quad (10)$$

$$a^N = w^2 s = \frac{R^2 a}{L} \left(\frac{d\psi}{dt} \right)^2 \quad (11)$$

These are the general equations for a^T and a^N .

In case when $a = \text{const.}$

$$\frac{da}{dt} = 0$$

$$a^T = R \frac{d^2 \psi}{dt^2} \quad (12)$$

and

$$a^N = \frac{R^2 a}{L} \left(\frac{d\psi}{dt} \right)^2 \quad (13)$$

in case when

$$\frac{d\psi}{dt} = \text{const.} = n$$

$$a^T = 0 \text{ and } a^N = \frac{R^2 a}{L} n^2 \quad (14)$$

For the motion on a straight line

$$a = 0 \quad a^N = 0$$

$$a^T = R \frac{d^2 \psi}{dt^2} \quad (15)$$

SIMULATION OF INERTIA FORCES

Let a be the value of simulated acceleration. The simplest way to simulate an acceleration is to rotate the subject and in this manner obtain the tangential component of g equal to the desired value a . Analyze the process of deceleration in the case of a sudden stop. The simplified deceleration graph is shown in Figure 3.

To simulate acceleration (or deceleration) by means of an orientation of vector g it will be useful to determine the value of a_1 and the angle of tilt θ_1 that is associated with it.

Consider now the forces acting on a point (body of mass m) moving along an arc of radius r in a vertical plane, when simulating the deceleration (Fig. 4).

NORMAL FORCE

$$F_N = mg \cos \theta + m (\ddot{\theta})^2 r \quad (16)$$

Tangential force

$$F_T = m \theta \dot{v} + mg \sin \theta \quad (17)$$

Because

$$F_T = ma^T \text{ and } F_N = ma^N,$$

$$a^N = g \cos \theta + (\ddot{\theta})^2 r \quad (18)$$

$$a^T = r \ddot{\theta} + g \sin \theta \quad (19)$$

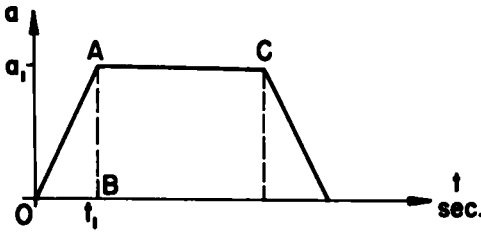


Figure 3.

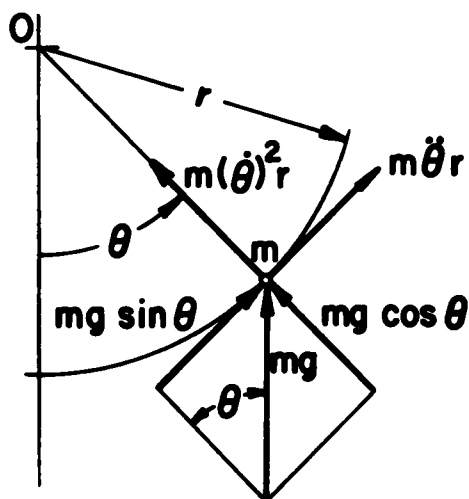


Figure 4.

Inasmuch as a human body cannot be considered as a point, it is quite clear that different parts of the body will have different values of $\theta \dot{r}$ (due to difference in r). This component will only appear in the intervals $0 < t < t_1$ and $t_2 < t < t_3$ and because it is an undesired term it may be called a disturbance.

During the transition from 0 to θ_1 , $\theta \ddot{r}$ changes its value from 0 to $+\theta_{\max}$ to 0 to $-\theta_{\max}$ and to 0 .

Assuming a sinusoidal character for these changes (Fig. 5), the amplitude of θ is inversely proportional to the square of time t_1 (time at which θ_1 is reached) and proportional to θ_1 itself. Thus for great t_1 (that is, for a moderate rate of deceleration) one has disturbances of low amplitude which may not be detected by human senses. On the other hand for small values of time t_1 the amplitude of the disturbance is high but of short duration. This is shown in Figure 6 where for const. θ_1 two values of t_1 are considered; a'_T , a''_T are the sums of the disturbances $\theta \dot{r}$ (r taken as unity) and $g \sin \theta$ which for small angles (up to 30 deg) can be written with sufficiently good approximation $g \theta$. It is a goal of this research to investigate whether these disturbances are within the limits of human perception and if so to find the way to minimize them.

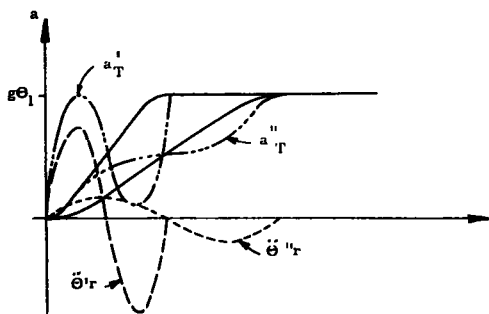


Figure 6.

The acceleration simulating the deceleration is a^T , given by Eq. 19. It consists of two terms $\theta \dot{r}$ and $g \sin \theta$. Component $g \sin \theta$ is a tangential component of vector g and component $\theta \dot{r}$ which is the result of motion of point m from the state of rest to some position defined by the angle of tilt θ_1 . There are two possible situations when the component $\theta \dot{r}$ is equal to zero:

1. When the point m is at rest (ruling out motion with constant angular velocity).
2. When $r = 0$ (point m lies on the axis of rotation).

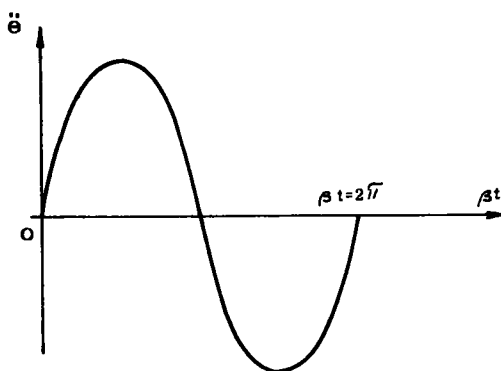


Figure 5. Angular acceleration.

It is fair to assume that a great part of these disturbances is damped out before they reach the sensing organs. An important part of this research is to find if there is an optimum point in a human body which should be taken as a center of rotation (a point for which $r = 0$ and therefore $\theta \dot{r} = 0$).

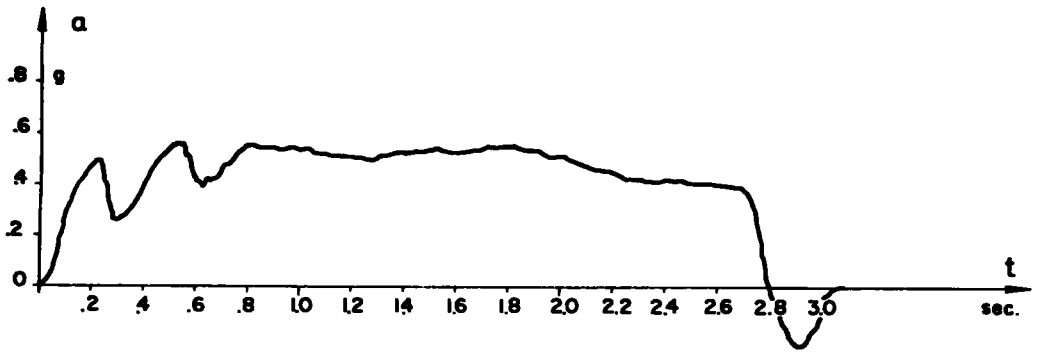


Figure 7. Sudden stop from 35 mph.

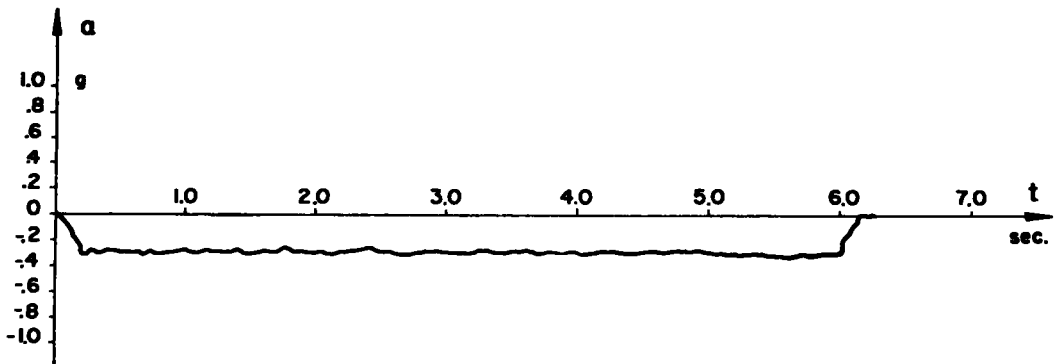


Figure 8. Acceleration up to 35 mph.

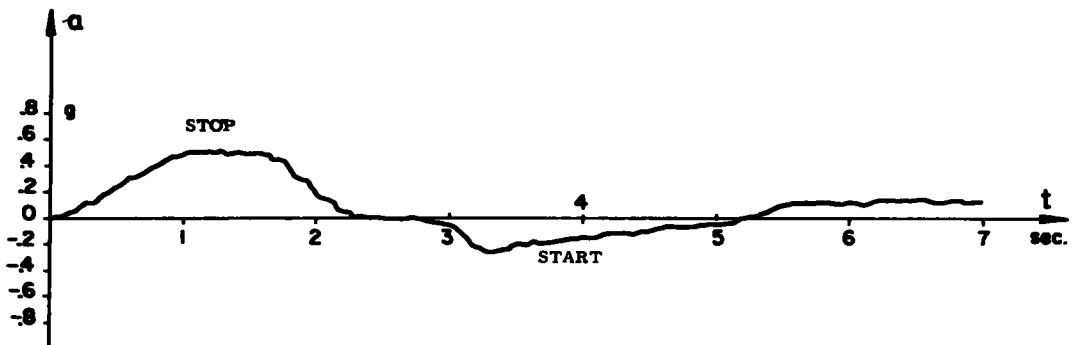


Figure 9. Stop and start.

Accelerations Experienced in Driving

Because knowledge of actual accelerations is of great importance in simulation of inertia forces, the Institute conducted numerous road tests. Deceleration values were of primary interest and they were taken in several traffic situations. In addition to these road tests, the accelerations experienced in the tilting chair were measured. Positive values are shown for deceleration and negative for acceleration in Figures 7-12.

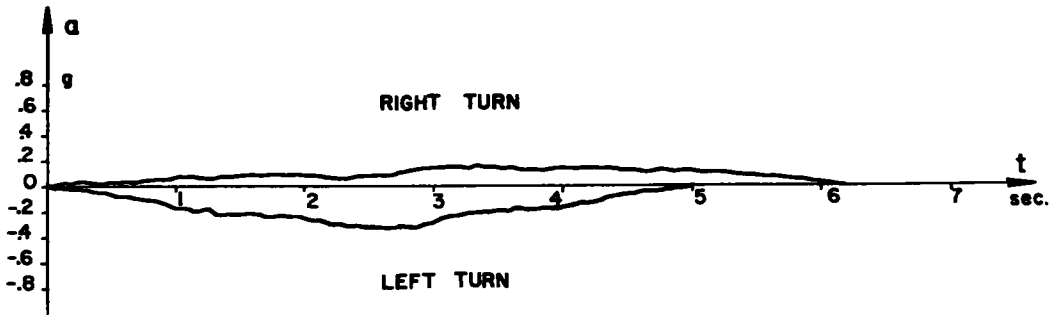


Figure 10. Left and right turn.

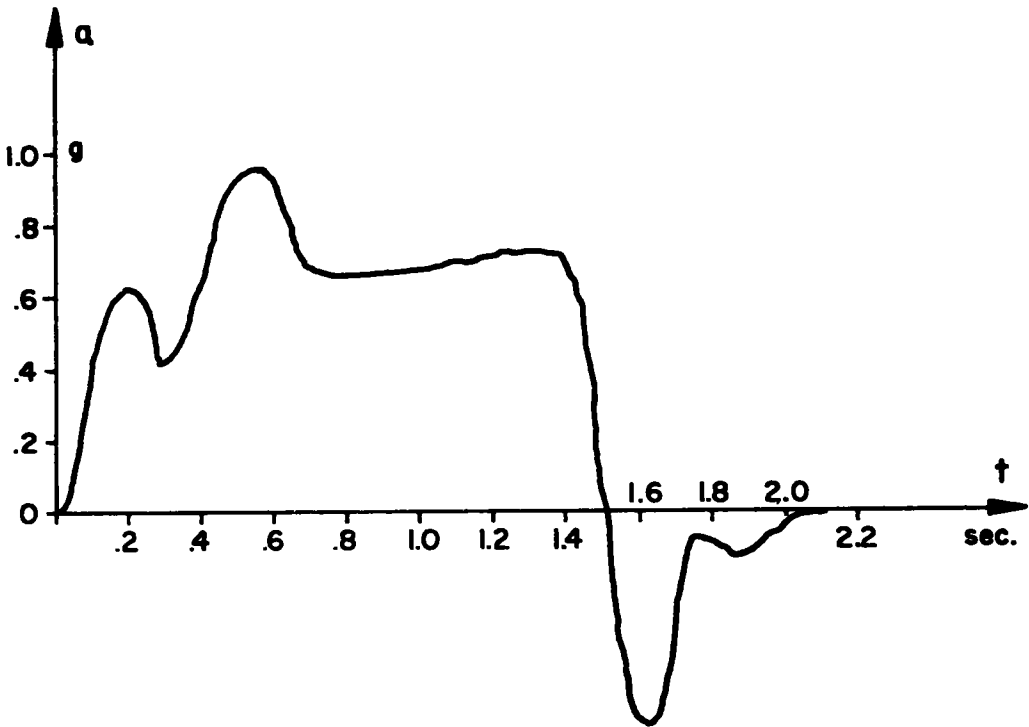


Figure 11. Sudden stop from 20 mph (in actual car).

It is important to observe a resemblance of curves in Figures 11 and 12, where Figure 12 represents the deceleration in a simulated drive in the tilting chair. The only difference is a "wrong direction" (negative) disturbance caused by the fact that the axis of rotation was placed about $1\frac{1}{2}$ ft below the seat. Were this axis taken above the center of gravity of the body this disturbance would have a positive sign.

The fact that there is an intimate relation between types of research problem and varieties of simulation techniques has been made increasingly clear as experience has been gained with drivers on the Institute's simulation devices. There is no doubt a positive relation between fidelity of simulation and realism of the resulting driver behavior. It is helpful, however, to consider the types of simulatable traffic situations separately from the fidelity with which those situations can be simulated. The visual

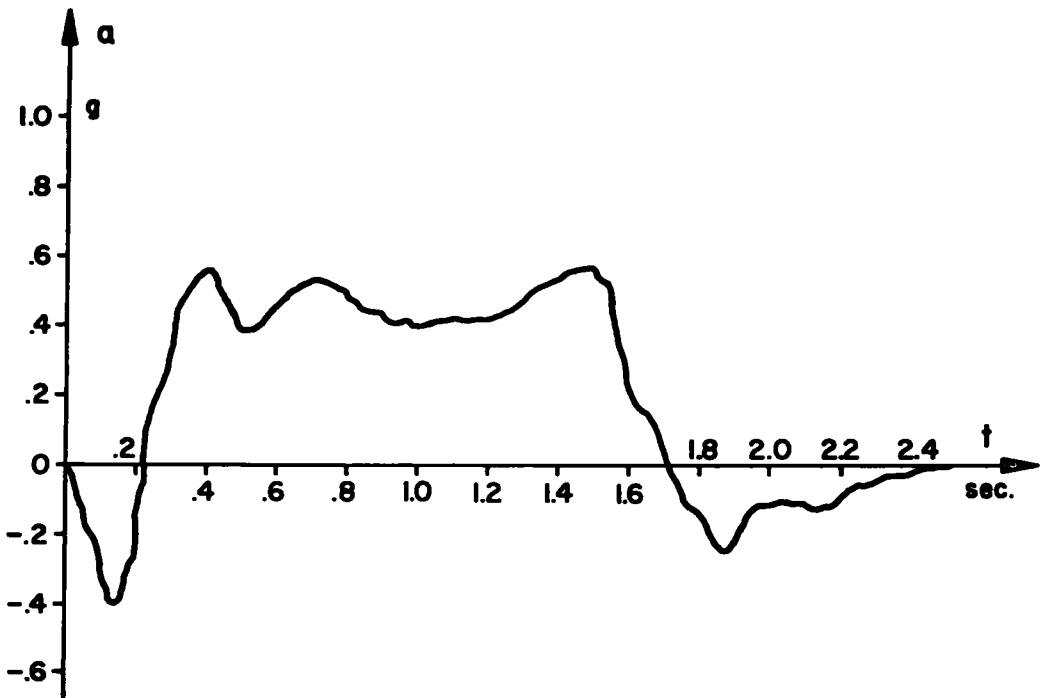


Figure 12. Simulated sudden stop from 20 mph in tilting chair.

TABLE 4

Traffic Situation	Examples of Research Problems	Type of Simulation Visual Display
Cross-country or freeway driving where no cross traffic is encountered and no vehicles overtake or are passed, and either there is only one lane or no reason for changing lanes or making unusual speed changes.	Steering systems, some highway signing and pavement markings, physical and mental conditions of drivers, temperature and noise effects on driving, highway design features not involving actions of other vehicles or drastic speed changes.	Motion picture, forward view, steering feedback (moving projector) projection speed variable but not linked, camera car attempts to follow normal patterns of speed and lateral placement, camera speed normal (24 frames/sec).
Add overtaking vehicles.	Tendencies to speed up when being overtaken, reactions to being followed at various distances.	Same, plus motion picture rearward view.
Add events that will cause large speed changes for some drivers and small or none for others (for example, object on or near road, dips). Subtract other moving objects at locations where slowdowns might occur.	Reactions to more unusual events, classification of driver's, highway signing and pavement markings where speed changes are intimately involved, highway design features involving speed changes.	Projection speed linked to vehicle speed, camera car attempts uniform speed and lateral placement, camera speed high (35 frames per sec).
Add two lanes available or freeway situation where changes between two lanes may be desirable.	Greater range of steering system use, highway signs and pavement markings involving lane changes, highway design features and conditions requiring lane change.	Two projectors forward, two projectors rearward (only one set exposed at a time). Two camera cars running alongside each other or two passes of single car over deserted road.

display system is the limiting factor in determining the types of traffic situations that can be presented. Aspects other than visual (for example, sound and physical forces) are important as they bring about the fidelity of simulation. Thus, fidelity is in this sense a different dimension which can be considered separately for each type of visual display system. In Table 4 traffic situations are given along with the corresponding type of visual display system and examples of the types of problems that may be investigated. Only those systems currently under trial at the Institute are included in this table.

REFERENCES

1. "Progress in Driving Simulation for Research in Street and Highway Safety." Tech. Memo. L-13, Inst. Trans. Traf. Eng., University of California, Los Angeles, 6 pp. (October 22, 1958).
2. Hulbert, S. F., and Mathewson, J. H., "The Driving Simulator." *Police*, 3:2, 44-47 (Nov-Dec. 1958).
3. Stewart, R. G., Hill, V. L., and Warmoth, E. J., "Non-Collision Fatal Accidents: How Many Can be Prevented?" *Traffic Safety, Research Review*, National Safety Council, 3:4, 26-28 (Dec. 1959).
4. Chandler, R. E., Herman, R., and Montroll, E. W., "Traffic Dynamics: Studies in Car Following." *Operations Research* 6:2, 165-184 (March-April 1958).

Engineering and Psychological Uses of A Driving Simulator

BERNARD H. FOX, Accident Prevention Program, U.S. Public Health Service

● THE CONCEPT of a driving simulator has a long history (5, 7, 31). A number of approaches have been made to the problem, some with intent to simulate more accurately and others less accurately, depending on the different uses to which the simulator was to be put. Indeed, some of these devices were not even considered by the maker or user to be a simulator, but rather a tool to create specific responses which happened to have some resemblance to a driving situation. A recent instrument which was intended to simulate motor behavior in driving, and in some respects, perceptual behavior, was the apparatus used to examine the effect of drugs on a skill resembling driving (19). Yet the similarity of the task to driving behavior was not particularly close, even though it may have seemed so superficially. A recent investigation (3) at Ohio State University used an instrument whose purpose was to establish some visual responses to road signs and billboards, and which had controlled motion as input and output elements. This machine, however, was not intended as a simulator of the driving task. Yet it concerned itself with perceptual and motor responses which were in a sense similar to those of driving.

In view of the foregoing contrast, it is important to define the kinds of instruments under consideration. The degree to which an instrument can be viewed as a driving simulator is dependent at least on two things: (1) the intent of the experimenter, which will be reflected to some extent in the perception and behavior of the subject at the controls of the instrument, according to the experimenter's instructions; and (2) the objective similarity of the inputs and outputs of the instrument to the driving situation. If there is any doubt, the intent of the experimenter defines the machine as a driving simulator. Thus a continuum of identity must be postulated, with a decision dependent on intent and construction of the apparatus. To establish a framework, the term "simulator" will be used to mean an instrument in which the subject's action bears a resemblance physically to that in real driving, where the intent of the experimenter is that the subject's action bears this resemblance, and where the subject perceives it as having this resemblance.

Objectives in the traffic field can generally be defined along two dimensions: efficiency and safety.

One of the necessary ways of reaching greater efficiency and safety is to learn as much as possible about driving and traffic behavior. Thus the objectives, at least in this part of the schema, become the acquisition of facts. Now it becomes possible to extend the objectives to details. What kinds of facts? How many? With what limitations? Are they available by other means? How will they lead to greater safety and efficiency? Etc.

The attempt to acquire such facts is called research. A driving simulator should be able to search out facts which would tend to improve within both dimensions the relationship among the objects involved in traffic activities. It should do so by allowing the experimenter to examine in fairly great detail certain existing or planned relationships in this field.

Some of the answers to the question, "Why build a simulator?" were given previously (11, 16), but are worth repeating and amplifying. However, in addition, other related questions can be asked which are at least as important. First, what research cannot be done or will not be done if a simulator is not available? Second, how much will the total strategic program of accident prevention research be hindered by lack of information which could be made available by use of a simulator? The reasons for building a simulator are as follows:

1. A simulator will permit research which is unsafe to do otherwise.
2. It will permit certain research which cannot be done full scale without unthinkable cost, where equivalently useful information takes excessive amounts of time to accumulate, and where great expenditure of effort, time, money, lives, and injury has already occurred because this research was not done. This is research on full-scale high-way configurations in advance of use.
3. It will permit research which is physically impractical to do at present by other techniques.
4. It will permit research with a degree of experimental control which is quite impossible to achieve by other techniques.
5. Because of the organized quality of a simulator research program, it can lead to research, if priorities permit, which would ordinarily not be done at all, even though such research could be done by other means.
6. It will permit a whole new experimental milieu for certain inquiries into human behavior which have not until the present been particularly concerned with behavior while driving. These are mostly psychological topics, but can also be medical and physiological.

Some examples of these kinds of research will be given, followed by the answers to the additional questions posed. But because the additional questions involve some fundamental problems, it becomes necessary to digress at this point with a short discussion of theory of values as it relates to accident prevention research.

Values in the Strategy of Planning Traffic Research

Omitting for the moment the uses of a simulator for training, for public health information, advertising purposes, direct selection purposes, etc., consider only the case where a driving simulator is to be used for research.

The range of need for a driving simulator lies on a continuum from low to high, and is dependent on several dimensions of cost and gain. Items of cost may include such things as economic investment, time investment, effort investment, physical risk investment, public opinion effects, etc. There are different realms of dividends, and each of these can be used as a partial measure of the worthwhileness of each of the areas of investment. Some examples of gains are saving of money, information about driver reaction, earlier acquisition of such information, greater amount of information acquired, greater access to information than available otherwise, and greater confidence in the derived information.

For each research task the costs are associated with the gains, and a decision must be made as to the worthwhileness of carrying out the research in the manner in question. The values are again associated when a different method of attack is considered, until a decision is reached to conduct the research in a given fashion or not. Whenever the cost of some items is too great, such as risk of injury or death beyond a certain amount, it does not matter how much gain might result from the research: it is not worth that cost. Certain gains have never been evaluated — perhaps, in this case, one might even say most gains. And when they have been evaluated, the balancing against certain research costs has never been made. In addition, the likelihood of a particular gain being achieved is itself a matter of probability in the research, and in many cases even the very nature of the gain is not known in advance, let alone its magnitude. This follows from the nature of research itself, which implies investigating the unknown.

Thus, decisions as to use of one method or another are based on complex interplay of values and uncertainties. It becomes difficult to say how important any particular research is a priori, and therefore to say how desirable any particular method of conducting that research is.

Limiting Costs for Research Priorities

An attempt will be made to assign some values to certain research which can be done on a simulator before going into the question of the other kinds of research for which a simulator is feasible. Of course, any such assignment is personal judgment. There is every likelihood that someone else would recast the values which are described here.

For purposes of limitation, one can say that there is a black area of no limit of value on certain occurrences to the subject: death, loss of limb, maiming, and most kinds of disabling events. (Excluded are temporary disabling events like induced epileptic seizure, induced sleep due to fatigue, etc.) In most live car experimentation on the highway, an agency is not in a secure enough situation to promise that the subject will not have an accident, let alone incur or produce an injury. The most it can do is promise that all other things being equal, he will have as small a chance as if he were driving under normal conditions for his own purposes.

However, the moment a set of conditions is imposed on the subject or the public which will or might increase hazard to any important degree, either to him or the public, a responsible agency ordinarily does not even make this promise, unless it provides foolproof safeguards both to the public and to the subject. Because one is generally not sure of the range of probabilities in many cases, most public agencies will lean over backwards, and undertake research only when the risk of increased hazard is vanishingly small.

Classes of Research Which Would Be Done on a Simulator

Now, returning to the major question, there are several reasons for building a simulator. Consider them in turn.

1. A simulator will permit research which is unsafe to do otherwise. This is the most important reason. What kinds of inquiry fall into this category, defined as research with ponderable risk of injury? A few have already been mentioned (11). Some examples follow:

- a. Changing (usually reducing) physical capacity deliberately in order to test the limits of adequate performance.
 - (1) Decreasing visual efficiency. Some examples would be putting on the driver glasses which would decrease acuity; reducing the peripheral field; deadening pupillary response; and imposing glare or inadequate or excessive lighting.
 - (2) Removing or reducing the function of a limb or of motor faculties, including lowered control capacity.
 - (3) Deafening a person artificially; for example, with a masking noise. This should really not be excluded from live car experimentation, because at least the self-trained deaf person can compensate very well.
 - (4) Inducing slight drug overdosage to a person under real drug treatment; for example, slight hyperinsulinism in diabetics, or slightly excess antihistamine or tranquillizer.¹
 - (5) Think seriously of testing a person with one of the psychotomimetic drugs to see what his behavior would be; for example, with lysergic acid derivatives. It must be pointed out emphatically, however, that one should not draw the inference in any sense that such drugged states resemble physiologically or functionally those which are called truly psychotic states.
 - (6) Treating the healthy subject with standard therapeutic doses of many drugs such as amphetamines, antihistamines, tranquillizers, etc.¹
 - (7) Dosing with various amounts of alcohol under various kinds of social conditions.¹
 - (8) Fatiguing a driver excessively.¹
 - (9) Causing a driver to become sleepy.¹
- b. Causing a change in the person's outlook on risk-taking behavior or

¹In all these cases the experiment would be done under the supervision of a physician who has experience and competence in toxicology, anesthesia, or other areas which the experiments may require.

his assumptions as to the driving situation.

- (1) Rewarding a driver for excessive speed, that is, inducing a state of "hurry" (8).
 - (2) Stimulating with slight alcohol doses in a normal social situation and requiring driving thereafter.
- c. Changing the driving environment by inserting unexpected signs, etc. This is obviously not so dangerous as the previously cited research. However, indications are that it can still be more hazardous than normal driving.
- d. Inducing sudden emergencies.
- (1) Another car or a pedestrian does something unexpected.
 - (2) A sudden curve or construction lane, or other environmental surprise.
 - (3) Induced skids.
 - (4) Failure of car component, such as brakes, or blowouts.
 - (5) Sudden distractions, like a child acting up, or obstructing vision.

Some work of these kinds has already been done. Only a few will be reported. In certain studies care was taken to try to prevent an accident, but in others the subjects and experimenters deliberately exposed themselves to increased danger. In one study (10) a back-seat observer noted the behavior of a sleep-deprived driver, but the former also began to get sleepy during the runs, and a third observer with dual controls next to the driver functioned as a safety man. This need for cross-safety measures illustrates the dangers of such research. In another case, attempts were made to force an emergency reaction in a simulated emergency in a live car by means of a dummy of a child suddenly propelled in front of the driver so unexpectedly that he could not avoid an "accident." On one occasion, however, the driver swerved so sharply that he deliberately struck one of the cars set on the street as an obstruction, rather than strike what he thought was a child. In another case (2) it was reported that a small group of experts, in a very uncontrolled situation, tried to see what effect reduction of acuity would have on their driving. They put on plus lenses with respect to their optimum vision, and drove several blocks in the environs of Chicago, including intersections with traffic lights, stop signs, and various directional signs. A study was done in England with two expert police drivers under the influence of high doses of alcohol (28). The drivers rode over a test track, but both of them came close to having a bad accident, with no insight into their danger. Work in the general area of skill decrement is still going on (13, 26, 30).

A second kind of inquiry, but in the same large category, must be examined. It is the case where, during the course of natural events on the road, the investigator observes detailed, within-the-car driving behavior. To be sure, this research is included here because it may involve reduced physical efficiency or altered attitudes toward driving, but more interestingly, it involves driving behavior which would have taken place even without the presence of the observer. Experimentation of this kind is still dangerous, however. Good work has been done (9, 25). But observing such behavior from outside the car is not possible, and where both scene and behavior are to be synchronized, has not been attempted inside the car without an observer. Nothing would prevent development of such techniques, of course, except perhaps expense.

2. A second reason for building a simulator relates to simulation of various highway configurations.

To build highway configurations full scale in advance of use for purposes of research in behavior of traffic or in safety design would involve unthinkable financial cost. It is true that configurations of bridges, ramps, interchanges, approaches, etc., have been examined in the past and are still being investigated. For the configurations constructed and for the traffic circumstances in which they operate, research on these full-scale structures could accomplish the same results as would be achieved by using a simulator with these same configurations and circumstances — and moreover, does so in terms of the ultimate criterion, live driving behavior. Nevertheless, a real limitation is imposed by the fact that as things stand now, such investigations cannot

be carried out adequately without long-term observation of accidents (although traffic behavior takes little time to observe), because of the inherently low frequency and unreliable occurrence of accidents.

A far more fundamental point can be raised. Because a simulator with adequate characteristics has not been available until now, many constructions have been carried out which have inadequate characteristics as far as traffic flow efficiency and safety design are concerned. For every design, the civil engineer probably has consulted with the traffic engineer, who described the characteristics he wanted. But because the latter had no empirical evidence for optimal properties, but only theoretical expectation, whenever a new design was to be considered, he had to estimate in terms of experience, the inadequate literature, and personal judgment. Many times these were not enough. As a result, who knows how many hours of traffic delay, with attendant cost to the community government and individuals, have arisen; how many accidents have occurred; how many injuries have resulted; and how many people have died because of inefficient or unsafe configuration?

These matters are well understood by the professionals in the field. That is why they are carrying out studies on existent structures. But they cannot do so full scale on designs which have never been built. If a simulator could be built to pretest road configurations, it would cost nowhere near the amount required to examine a full-scale structure in advance. Probably, if a cost analysis were made, over a period of time the reduction in cost to the community of traffic delay, inefficiency, hospitalization of injured indigents, etc., would exceed the cost of simulator research needed to bring about this reduction. Costs to the individual, of course, are to be counted over and above community costs.

3. There are some kinds of research for which the tools are not available for use right now in a live car, due to certain technical difficulties, although such research is highly desirable. Such research could be done on a simulator. An example of this might be testing brain waves during driving, much in the way that they have been tested in aircraft (27). Small episodes of unconsciousness a few seconds long show up in some people under the influence of alcohol which would not do so normally (23). They can be detected in this way. Behavior by epileptics during induced petit-mal seizures could be observed. None of this is at present possible in real driving research.

4. A simulator will permit research with a degree of experimental control which is quite impossible to achieve by other techniques.

The problem of experimental control has always troubled those working in traffic safety. It becomes especially important because laboratory duplicability such as is found in the ideal case of behavior examination is not possible in the car. The pedestrian situation changes, the opposing cars change, the behavior of the interacting traffic changes. It is now possible only to describe in statistical terms what happens to gross car behavior at certain places and it is difficult to duplicate the exact approach, intersectional behavior, speed, etc., of other traffic. In the simulator it will be possible to pinpoint behavior for particular traffic events, and estimate population characteristics with respect to these traffic events based on actual behavior in the car, which has not been possible up to this time.

For example, just how do various people behave at a circle with multiple entrances and exits. What are the visual lapses, the visual needs that enter into a complex interaction of this type? Problems like these can be pursued in great detail and with great confidence in the generalizability of the results.

5. Because of the organized quality of a simulator research program, it can permit research, if priorities are so arranged, which would ordinarily not be done at all, even though such research could be done by other means.

A large number of research projects which have not received support as individual proposals, but are considered to be desirable nevertheless, might be undertaken if a fine opportunity of this nature were available. These projects, except for the factor of experimental control mentioned previously, could also be done outside the simulator. But they have not been done in the past because of the slow progress of support for research in traffic safety.

Some variables which might be examined in this kind of research are:

- a. Physical variables; for example, fog, rain, road vibrations, temperature, humidity.
 - b. Personal characteristics of the driver — for example, driver training, attitude, experience, personality.
 - c. Sensory and motor characteristics of the driver.
6. A simulator will permit a whole new experimental milieu for certain human research which has not been concerned with driving, but where the driving situation offers an excellent opportunity to exploit a good research environment.

Such research topics might be mentioned as isolation, monotony, vigilance, social interaction, artificial stress, emotional involvement, complex perceptual acts, drug effects, etc.

Alternative Techniques of Research

It has been shown that a simulator is needed to carry out certain research impossible to perform adequately in any other way. Does this now imply either (1) that other research would not be done on the simulator, or contrariwise, (2) that the simulator would take the place of other research techniques? To both questions, the answer is yes and no. Again the cost-gain criterion must be applied in each case. Where research not now being carried out could be done outside the simulator only at extreme cost and with only moderate gain, the use of this instrument is justified if it reduces cost, and affords adequate gain. It could then take the place of other techniques. For example, research into the effect of highway configurations on traffic behavior has too great a cost, with full-scale units, for an unknown gain. On the other hand, research on vehicle design characteristics, particularly human engineering of static characteristics, is far cheaper and more efficient with a live vehicle (21, 29). But human engineering research on vehicle characteristics involving the dynamics of traffic is perhaps more safely done on a fixed simulator of the type discussed here. If a test track is used, a dynamic simulator of vehicle behavior, not driver behavior, can be used (18). But behavior of the driver with varying car dynamics has yet to be measured for purposes of safe driving research. (This instrument has been available not much longer than the time necessary to test it thoroughly and determine some of its characteristics. Hopefully, behavioral research can also be done in the future.)

PLANNING FOR SIMULATOR RESEARCH

Preliminary Simulator Configuration

The steps necessary to achieve a faithful simulator with high feedback potential are essentially almost forced. For designs spoken of in the various reviews of related topics such as feasibility statements about systems (6, 16, 17) visual environment reviews (20, 24), and training device literature (4, 12), development from a simpler to a more complex instrument is most often recommended.

Therefore, it is conceived here that development of a complex simulator would take place in such a way as to allow research to be done at each of the various stages of improvement of the simulator. Just such a program is now under way at UCLA. The purposes are many — for validation, for evaluation of cost-gain quantities, for breaking-in and training purposes, for developing maintenance techniques efficiently, for quick payoff, and for other obvious reasons.

Later the skeleton of one example of a research program will be outlined which might be undertaken if a simulator were to be developed. In this outline it will be assumed that a gradual approach to the construction of a simulator has been taken. That is to say that at an early stage only simplified representation of traffic behavior will be possible, and the subject will have a limited amount of feedback from the scene as a result of what he has imposed on it as input. A program outline will reflect the assumption of graduated development.

For example, a first approximation to an initial developmental stage would have a live, running car which the subject controls, resting on a dynamometer whose design will permit suitable input of vibration, sway, pitch, and road resistance; a 120- to

160-deg forward projection and simultaneous rear projection of a traffic environment picked up from a car in real traffic fitted with color camera equipment; limited lateral translation of the experimental scene coordinated with steering behavior; the running engine and other sounds of the experimental apparatus fairly well matched in intensity and spectrum with apparent speed of the vehicle in traffic; and similar straightforwardly simulated characteristics.

Programming

1. Limitations on experimentation.

With an instrument of the type just described, experimentation would be restricted to observing behavior and internal response in situations which permit only a limited variety of response by the driver, because in this form the simulator has poor potential for exhibiting highly variable feedback to the environment. This means that the circumstances of traffic must be one of two things: they should override individual behavioral variations, for example, constraint of speed is forced into a narrow range, say along a speedway; or they must be such as to prevent scenic input from informing the driver of a discrepancy between his behavior and the camera's behavior. One situation which satisfies the latter condition is that the driver be the only one on the road in the given experiment. In other appropriate situations the interaction between drivers must be low. Such maneuvers as passing are avoided.

2. Measurement.

A first concern must be to describe properly the behavior of drivers, with all that this implies as to frequency and distributive characteristics in a single person and between people. To accomplish this, descriptive measures must be developed which are meaningful, reliable, valid, and statistically or mathematically manipulable, to describe not only what happened, but what ought to happen.

Terms would be used such as real error, tracking behavior, variability, perception of error, probing behavior, feedback, backlash, back action, noise (in the sense of communication theory), system, individual differences, perceptual response, threshold, estimate, etc. To illustrate, consider a single function: where a driver is looking at any given time. One might photograph his eyes, using properly oriented axes to determine on a computer the precise spot on the scene which he is looking at; one might use a TV technique (22) which can give an accurate picture of the same thing; one might use a device which would project infrared from below, reflecting from the eye, and landing on a screen which is subject to rapid scanning, where coincidence of beam (s) and scanning element (s) reads directly into a computer the information which can determine position with no degrees of freedom.

Other measures which would have to be developed have been listed (11), but might be mentioned again briefly; detailed driver action, such as behavior related to the accelerator, brake pedal, gear shifting (if used), steering, turn signals, lights, lighter; gross car action such as turning, stopping, starting, parking, avoiding; physiological responses such as head movement, psychogalvanic response, muscle potentials, blood pressure, breathing, force applied, pulse, brain waves.

A standard driving task would be used, with standard situational events which sometimes lead to accidents — intersection, traffic light, curved road, obscured road, etc. Testing would be repeated to determine variability, and then further repeated often enough to establish fairly accurately a description of how a variety of people act in a given situation. The stimulus is always known, the time of stimulus is known, and the reaction can be observed and described, both statistically and in terms of dynamics.

Programming Priority

Ideally it is best to start with permissible cost and maximum gain. But in this case it is assumed that the cost is permissible because the particular stage of simulator development is assumed to have been achieved. Running cost on a simulator of simple design is not much greater than live research. The only restriction, then, is what research can be done with the given simulator configuration. The range of possible research is unlimited, subject to that restriction, but it needs to be arranged according

to priority. As part of the cost, at least on a theoretical level, must be included steps to determine how confident the researcher might be in his research results. These steps, to be discussed later, are research procedures establishing validity of the simulator research.

To establish priority of research, the results of statistical and experimental research on accidents are used, where available. What are the greatest known contributors to accidents, injuries, and deaths? Setting aside for a moment the consistency of proper classification, and permitting overlapping classes, the list might include such things as driving and drinking, the single car accident, the intersectional accident, the high speed accident, the bad weather accident, the accident at or after dark, the accident with very young or very old driver, and accidents due to poor driving habits, to name a few.

It is important to know just why, or just how, these accidents came about. They were all due to some improper behavior, either commission or omission. It is not known what that behavior is, under what conditions it occurred, who performed it, how often, how correctible it is, how habitual it is, whether it appears in normal driving, what changes must take place to avoid it, its interaction with other driving behavior, how it can be described and measured, etc.

Research Possibilities

Some other questions should be mentioned which might be investigated in a simulator at an intermediate developmental stage, after validation and normal driving are examined.

Certainly these questions should include an evaluation of the effect of various characteristics of signs — design, placement, frequency of appearance, their relationship to destination, individual variability in response to wording, color, and other physical properties, etc. A program of considerable detail and complexity can be devised to study the effects or effectiveness of signs. Initial experiments along this line have been made at UCLA (15).

With the aid of cooperating assistants and cars, emergency situations could be introduced into a filmed sequence and behavior observed. (The objection that an unsuccessful maneuver on the part of the driver must terminate the sequence is not valid because the important part of the experiment is the observation of behavior during the emergency sequence. Even though the subject must be discharged following the experience, his responses are available for analysis individually and in combination with other persons' responses.) Something like a walkie-talkie system in the two or three cars, with adequate warning to the camera car just in advance of an unexpected maneuver by a car or pedestrian to be photographed, would permit an experience to be safe in the live situation which would otherwise be quite dangerous. This kind of experiment is obviously not feasible when the unknowing test subject drives a live car in live traffic, but would be extremely useful and immediately feasible if he drove in a simulator. It is clear, however, that such devices do not make up for the unfortunate limitations of the programmed character of filmed input.

There are many ways of using film effectively. For example, one could take a person on long rides through the country on highways where he is the only one on the road, and study the effects of various factors. These might include fatigue, sleepiness, alcohol, both depressing and stimulating, carbon monoxide, smoking, and the like.

To study any one of these factors properly would entail a whole research program. What would a skeleton program look like?

1. Assume that all research and pretesting, both instrumental and personal, has been done, and the simulator is operational.
2. Set up behavior measures.
3. Validate most of them in a live car, on behavior which does not increase hazard.
4. Examine behaviors involving use of
 - a. Alcohol
 - (1) Treat and do not treat with various doses of alcohol.
 - (2) Set up different driving environments, such as intersec-

sections, quick stops, poorly visible objects, various signs, and various emergencies.

- (3) Select measures from (2) which are applicable. Tentatively, measures might be brain waves, breathing behavior, circulatory responses, psychogalvanic response, muscle action potentials, car control behavior, points of visual regard, points of visual notice, oral questions, questionnaires, and other measures deemed necessary.
- (4) Pay particular attention to measures relating to peripheral vision, threshold of movement detection, speed on different occasions, individual differences, frequency of failure to attend, reaction time, field of attentiveness, control behavior, tendency to anticipate, tendency to make assumptions, tendency to take risks, confidence of driving demeanor, compensation for behavior degradation, social reaction, seizures, disinhibition, etc.
- (5) Re-examine the findings, relate to an operations analysis of the individual driving situations, and make predictions of accident probabilities of the noncompensator and compensator.
- (6) Attempt screening analysis.
- (7) Follow up.

b. Drugs, etc. Follow same concept of research attack.

To fill in the details of a program outline such as the foregoing in any one field is not extremely difficult technically, nor is it hard to decide on priorities within a program. But it needs generalship of a proper order of sophistication to deal with the cost-gain problem and to decide on priorities for different programs. But even planning a single program, however feasible technically, is a sizeable research study in itself (1).

In addition, it must be noted that the choice of priorities depends on the organization conducting the research. Differences will surely be found among those whose orientation is strongest toward training, toward medical, drug, and personal factors, toward highway design, toward traffic engineering, and toward license screening.

In a research program such as the Public Health Service might develop, stress would be placed on effects of alcohol, drugs, medical factors, personal attributes, and emergency situations, but over-all the emphasis in each of these would be their safety aspects.

The differences in the programs for a simulator imply that it might be advantageous to have several units, in order for each interested group to be able to do as much research as is necessary in the various areas emphasized by the group.

OTHER CONSIDERATIONS

Validity

A serious objection has been raised to the use of simulators because their validity has not been ascertained. Validating procedures would of course be necessary during and after the construction of any simulating device. It has been said, however, that the expenditure of a large amount of money is not warranted for "pie in the sky," and that more concrete assurance of payoff should be forthcoming before such an outlay is made. No new piece of training equipment used in practice ever has such assurance, or would ever have been built if prevalidation were necessary. In most such cases attempts are made at preliminary validation; in some cases such attempts are not made if the equipment is brand new or cannot be pretested. A new model is usually built on a gamble. An occasional piece of equipment is actually not successful in simulation. That is, its validity is quite low. Most often, however, good enough validation has been found to warrant the building of the simulator.

Interestingly enough, and not unexpectedly, the closer the instrument gets to dupli-

cating the operating situation, the more valid it is, for most purposes. But also, it may be very expensive to have faithful simulation, and it may not be necessary. It all depends on one's purposes.

In the case of this simulator, it is fortunate that there are a number of examples of prevalidation of less faithful machines, and of related instruments. But still, a program of preliminary research would accompany construction of a costly simulator, to rule out unnecessary expense leading to fidelity.

The response to certain other simulators bears witness to their felt reality, particularly in emergencies. Some readers have experienced passenger jet flying in simulators which have visual environment represented. They know how realistic this is. And that system was developed only for narrow visual field presentation. Experienced pilots who ride in simulators which have emergency situations built in are routinely known to experience strong internal reactions during these times, indicating a high degree of stress — sweating, heart rate increase, altered galvanic response, breathing changes, etc.

On the other hand, it can be shown that certain attempts at simulation have produced problems. In the simulation of a helicopter, conflicts of a nature not too well understood were introduced but they were probably conflicts which combined motion and visual cues (12).

Motion cues are important, both in helicopter and in driving simulation. Coordination of automobile acceleration simulation with visual display is now under way at UCLA. But even without motion, UCLA's machine still permitted feelings of reality of an acceptable order for some purposes. Especially was this true of emergency reaction. The realism of such emergencies increases many-fold the feeling of realism experienced during casual driving in a simulator, as the author had occasion to find out when he drove the simplified system at UCLA. During the run the camera car had a real emergency, and as driver, he became rather frightened when the car did not respond to corrective braking and kept on going toward the rear of the car in front, which was stopped for a light. The imminent crash caused a panicky turning of the wheel toward an open space at the side — which was exactly what the camera car had done. He was completely lost in the drama of the emergency. Hulbert has examined galvanic skin responses to such occasions, as an objective indicator of internal response (14).

Other Uses of a Simulator

It has been suggested elsewhere (11) that certain developments might be expected from a simulator. Knowledge of factors related to training will be of great help to driving education theory, as well, perhaps, as to other training activities. The need for training in tasks encountered in the Armed Forces is well-known.

It is not inconceivable that simple, inexpensive devices will be suggested, if they do not actually originate from, a simulator of one sort or another. Whether these will be useful for screening, training, or testing cannot be predicted now. But enough is known now to look for such a development. Certain industries, after techniques are developed for limited displays, could use such devices for advertising purposes. Particular stress should be laid on screening devices and training techniques.

If appropriately managed, demonstrations on an instrument with so much obvious popular interest and appeal could do much to inform the public in public health matters related to driving.

A Note on Cost

It is important to note that a simulator of design described above would probably cost about one-fifth as much as the more complex conception, and would cost about one-fourth the annual amount to run. Thus, not only is this kind of simpler machine feasible technically, but it is considerably more feasible financially.

The Future in Simulation

What effect will a simulator have on the strategy of highway research, and how would research strategy be hindered without this instrument?

It is believed that its presence would be a strong stimulant to interest in safety research for many who have little knowledge or background in this area. With regular scheduling of research, questions would be quickly and easily answered which today must wait for months and years before even attempts are made at answers — particularly human factors questions. Success of one instrument, experience in its operation, and reduced cost of production will all lead to rapid production of other models for other purposes.

Without such an instrument, progress in the field of accident prevention, especially research on driver behavior, would suffer a severe delay. A few such researches which have been attempted were undertaken in spite of the great difficulties attendant on this type of work. Current knowledge about the driver would again increase at a snail's pace. The many statements that such research is needed would be repeated anew.

A whole set of pending decisions regarding screening, licensing, training, traffic engineering, signing, medical restrictions, and other matters would be delayed for a period considerably longer than anyone would like to see.

REFERENCES

1. American Institute for Research, "Proposal for a Human Factors Feasibility Study of a Research Driving Simulator." Pittsburgh (1957).
2. Baker, J.S., Personal Communication (1959).
3. Blackwell, H.R., Personal Communication (1959).
4. "Coordinate Index and Abstracts of Training Device Literature." U.S. Naval Training Device Center, Port Washington, N.Y. (1957).
5. De Silva, H.R., "On an Investigation of Driving Skill." *Human Factor*, 10: 1-13, 50-63 (1936).
6. Ernst, A.A., "Feasibility Study for a Man-Machine Systems Research Facility." Aero-Medical Lab., Wright Air Development Center, Ohio (1959).
7. Forbes, T.W., "Measuring Drivers' Reactions." *Personnel Journal*, 11: 111-119 (1932).
8. Forbes, T.W., "Analysis of 'Near Accident' Reports." *HRB Bul.* 152 (1956).
9. Forbes, T.W., Personal Communication (1960).
10. Forbes, T.W., Katz, M.S., Cullen, J.W., and Deterline, W.A., "Sleep Deprivation Effects on Components of Driving Behavior." Presented at Ann. Mtg., Amer. Psychol. Ass. (Sept. 4, 1957).
11. Goddard, J.L., and Fox, B.H., "The Driving Simulator." Preprint, SAE (June, 1958).
12. Havron, M.D., and Butler, L.F., "Evaluation of Training Effectiveness of the 2-FH-2 Helicopter Flight Trainer Research Tool." *Psychol. Res. Assoc., PRA Report* 56-17 (1957).
13. Herbert, M.J., Hartman, B.O., and Jaynes, W.E., "Preliminary Work on the Study of Factors in Skill Fatigue." U.S. Army Medical Research Lab., Fort Knox, Ky. (1957).
14. Hulbert, S.F., "Drivers' G.S.R.'s in Traffic." *Perceptual and Motor Skills*, 7:4, 305-315 (1957).
15. Hulbert, S.F., and Burg, A., "The Effects of Underlining on the Readability of Highway Destination Signs." *HRB Proc.*, 36: 561-574 (1957).
16. Hulbert, S.F., and Mathewson, J.H., "The Driving Simulator." *Inst. of Trans. and Traffic Eng., Univ. of California*, Reprint No. 65 (1958).
17. Hutchinson, C.H., Whitcomb, D.W., and Milliken, W.F., "Automobile Driving Simulator Feasibility Study." *Cornell Aeronautical Lab., Inc. Report* No. YM-12244-V-6 (1958).
18. Kohr, R.H., "Analysis and Simulation of Automobile Ride Mechanics." *Research Laboratories, General Motors Corp., Detroit* (1959).
19. Loomis, T.A., and West, T.C., "The Influence of Alcohol on Automobile Driving Ability: An Experimental Study for the Evaluation of Certain Medicological Aspects." *Quarterly Journal of Studies on Alcohol*, 19: 30-46 (1958).

20. Lybrand, W. A., Havron, M. D., Gartner, W. B., Scarr, H. A., and Hackman, R. C., "Simulation of Extra-Cockpit Visual Cues in Contact Flight Transition Trainers." Air Force Personnel and Training Res. Center, Randolph AFB, Texas (1958).
21. McFarland, R. A., "Human Factors in Vehicular Design and Operation, with Special Reference to Accidents." Commission on Accidental Trauma, Armed Forces Epidemiological Board (1958).
22. Mackworth, J. F., and Mackworth, N. H., "Eye Fixations Recorded on Changing Visual Scenes by the Television Eye-Marker." Flying Personnel Research Committee, FPRC 1032, England (1958).
23. Marinacci, A. A., "Electroencephalography in Alcoholism." Alcoholism, pp. 484-536, Charles C. Thomas, Springfield, Ill. (1956).
24. Molnar, A. R., and Lybrand, W. A., "Basic Development Accomplished on Wide-Angle, Non-Programmed, Visual Presentations." U.S. Naval Training Device Center, Vols. I and II, Port Washington, N. Y. (1959).
25. Moseley, A. L., "Near Accidents in Bus Transportation." Proc. 22nd Ann. Mtg., National Assoc. of Motor Bus Operators (1951).
26. Platt, F. N., Personal Communication (1959).
27. Sem-Jacobsen, C. W., "Electroencephalographic Study of Pilot Stress in Flight." Aerospace Medicine, 30:11, 797-801 (1959).
28. Shaw, W. J., "Objective Measurement of Driving Skill." International Road Safety and Traffic Review, 5:3, 21-30 (1957).
29. Sutro, P. J., "Human Visual Capacities as a Basis for the Safer Design of Vehicles." Commission on Accidental Trauma, Armed Forces Epidemiological Board (1958).
30. Uhlaner, J., Personal Communication (1960).
31. Vincent, D. F., "The Institute's Apparatus for Testing and Training Drivers." The Human Factor, 10, 64-65 (1936).

Discussion

C. H. HUTCHINSON, Cornell Aeronautical Laboratory, Inc., Vehicle Dynamics Department, Buffalo, N. Y. — The two prerequisites for realizing an acceptable simulator are: (1) the ability to realistically control the simulated vehicle within the environment, and (2) the ability to create meaningful situations that require some form of control action.

The first requirement is directly related to the dynamics of the vehicle — both the lateral or maneuvering control dynamics and the longitudinal or performance dynamics.

The second requirement is concerned primarily with the static and dynamic aspects of the visual display.

The range of situations for which any simulator may be considered as a valid research tool is, of course, a function of how well the sum of the two prerequisites is satisfied.

The word "sum" is emphasized inasmuch as it is the total effect produced by the simulator rather than the individual excellence of components that is important.

The problem, then, of making an a priori assessment of the validity of a simulator is seen to be extremely difficult. In fact, it amounts to an attempt to make a subjective evaluation of a physical device that is not yet in existence. The only apparent path open to the developer of a simulator is to first of all provide the best simulation practicable on an objective level and follow this by an evaluation on the subjective plane.

Certain aspects of an automotive driving situation simulator are now capable of implementation — particularly the control and ride dynamics of the vehicle. The cost of this portion of the simulator may be large but it is a relatively small proportion of the total cost.

A large portion of the performance dynamics — particularly those aspects that result in the indication of velocity — are also presently feasible. Longitudinal accelerations will, however, never be reproduced accurately, they can only be approximated.

The visual display, in contrast with the vehicle simulator must be evaluated to a

large extent by subjective methods. Some direct quantitative measurements can be made such as resolution, contrast, brightness and distortion, however, because the scene presented is not real in the same sense as vehicle motions are real, the visual impressions become the determining factor.

At the same time, the visual display is the most expensive portion of the complete simulator system. Thus, the total dollars that must be invested in producing hardware for initial validity studies is relatively large.

The question was asked at an appropriations sub-committee hearing — "How much will it cost and how long will it take to construct such a simulator?" The answer specified a few million dollars during a four-year period. To which the questioner replied, "How can it take so long to spend so little!"

T. W. FORBES, Assistant Director (Research), Highway Traffic Safety Center, Michigan State University, East Lansing — The following discussions of Dr. Fox's paper range from a simple statement of the importance of developing driving simulators to pointing out additional important applications in human factor research and for design and traffic engineers. Finally, the very important "break-through" which the development of driving simulators probably will bring to the whole field of research in highway operations, driver and vehicle behavior and safety is suggested.

Additional comments indicate that others also concur in the importance of the development of such accurate driving simulators. Some feel that the very inconclusiveness of the paper might lead some, in the traffic engineering field especially, to feel that it was over-emphasizing the needs for a driving research simulator. The Committee, however, feels that the need for and importance of such research simulators could hardly be over-emphasized.

Two Types of Simulation Interrelated

In introducing the following individual comments and discussions, perhaps it should be pointed out that the driving simulator involves a different type of simulation from the mathematical simulation of traffic flow by means of electronic computers. The latter, too, is of major importance and is receiving the attention of other committees. Both types of simulation are needed and each will also contribute to the success of the other. The driving simulator will make it possible to test out, previous to construction, new highway designs to see how well drivers will be able to use them and to find defects which would otherwise occur only after the human factor of actual use of the highway would show them up. As indicated in the discussions, a new and much more powerful approach for research on driver behavior and human factor problems affecting highway traffic efficiency and safety will be provided. Resulting measurement will provide mathematical data for use in mathematical models and computer simulation of traffic flow while computer simulation will increase accuracy when added to other techniques in driving simulation. Both together may lead to completely new research approaches.

J. L. MALFETTI, Executive Officer, Safety Research and Education Project, Teachers College, Columbia University, New York City — The writer found Dr. Fox's paper very comprehensive and hopes a simulator program materializes for it would assist in the analysis of the driving task, an area in which there is a dearth of research and not even a reasonable starting place.

J. E. UHLANER, Research Manager, Personnel Research Branch, Department of the Army, Office of the Adjutant General, Washington, D. C. — The development of a driving simulator such as that discussed by Dr. Fox can serve as a tremendous impetus for interest in, design of, and support of much needed controlled research in the area of traffic safety. In addition to the achievement of research objectives otherwise difficult or impossible to accomplish, such a device can serve — perhaps even more importantly — to make research findings readily acceptable to the driving public.

H. W. CASE, Acting Assistant Director, and S. HULBERT, Assistant Research Psy-

chologist, Institute of Transportation and Traffic Engineering, University of California, Los Angeles — The writers read Dr. Fox's paper, and found it very good.

In his paper, Dr. Fox indicates that it would be possible to conceive a simulator of a fairly simple type. Perhaps it should be indicated here that there are two devices now in operation at UCLA, one of which is a simulator almost of the type described and on which actual experiments are being run.

The writers have sent the author certain suggestions for minor changes and suggested a reference to Forbes' early work that might be appropriate since it predates both De Silva's and Vincent's work. Under "A Note on Cost," we get the impression that the author is saying that it would be more feasible to build a simple machine from both technical and financial viewpoints. It is believed he means that probably the first step toward obtaining a complex and highly developed simulator would be to build one or more simple ones, but not that they would fulfill the same research needs.

The over-all presentation is an important contribution toward advancing the simulator program and the author is to be highly congratulated.

S. M. BREUNING, Associate Professor of Civil Engineering, Michigan State University, East Lansing — Although the paper is very exhaustive, the writer feels that the psychological uses are stressed much more strongly in this paper than the engineering uses. Initially driving simulator has meant little to the writer and was considered a machine with little use for the engineer. However, in thinking about the simulator during the last few months, he is beginning to get enthusiastic about the potentialities in the traffic engineering and in the geometric design fields. It is believed that there is great need to acquaint other engineers with the potentialities of the simulator.

A graduate assistant who read the paper said that he did not comprehend from the paper that the simulator might use an actual three-dimensional model rather than just films. It appeared to him that all simulators would use films for presentation of the environment through which the car is driving. In other words, the concept of driving an actual model car on a small-scale model scenery did not become clear to him. This is a point that could be easily corrected in the paper, and one might suggest that a photograph of the model demonstrated in Washington might do well for this purpose.

L. BRODY, Director of Research, Center for Safety Education, New York University, New York City — Dr. Fox's paper is the best statement on the subject that the writer has read.

A few specific comments: (1) The writer subscribes fully to the author's statement that a simulator will permit research which is unsafe to do otherwise and that this is its most important justification. With regard to impracticality and limited control of other research techniques, the writer is not sure that this has been fully explored. For example, it is felt that the use of dual-control cars in off-street test areas is also applicable to at least some of the conditions listed. While full realism would not be achieved, such a program might come closer to it than a simulator. (2) Dr. Fox states that a first concern must be to describe properly the behavior of drivers and emphasizes the need to set up behavior measures. The writer agrees, and by implication this means that the development of a simulator is secondary. (3) The author justly highlights the dynamics of traffic. This presents a real challenge in the development of a simulator. Needless to say, where the latter employs motion picture film, the filmed driving situations to which the subject responds are a stimulus pattern sequence that is fixed by the film and imposed on the subject, whereas the selective choice by the driver of the stimulus patterns to which to respond is an important feature and determinant of real driving dynamics.

J. E. BARMACK, Assistant Vice President, Dunlap and Associates, Inc., Stamford, Conn. — Some detailed reactions to this paper are:

1. Under "Classes of Research Which Would Be Done on a Simulator" there might be added the interaction effects of delayed sleep, alcohol, darkness, and the unstimulating road. This combination turned up rather heavily in our own study.

2. Again the writer would suggest a category of studying the interaction of alcohol with certain biographical and personality characteristics.

One of the important advantages and shortcomings of a simulator is that the experimenter selects the driver and the situation. In the real world the individual selects the environment and the accident selects the driver.

One of the issues that may be examined is the relationship between broken homes, drinking and accidents. Is the drinking a response to grief or whatever the disrupted home generates? Can we impute the accident solely to alcohol? Is there some selective interaction between broken homes and drinking which makes the performance of individuals from a broken home more vulnerable? How can we account for the fact that some individuals who had been drinking can sustain vigilant sets and others cannot? What factors differentiate the individuals who decide to drive or not to drive after drinking? What factors differentiate individuals who speed with alcohol vs those who drive carefully?

These are some of the issues which have impressed people as close to the types of accidents which are of concern. A series of studies on these factors can help overcome the intrinsic "selective" shortcomings of the simulator approach.

R. MICHAELS, Research Psychologist, Bureau of Public Roads, Washington, D.C. — Dr. Fox has written a rational analysis of the needs for and values of a driving simulator. It is a combination of a philosophy of research and an operational program for the conduct of research that is rarely seen in the highway research field. A philosophical paper, however, has a couple of disadvantages. One is that it stimulates the reader to find flaws in the logic. (This reader has found only a few over which to quibble.) A second disadvantage is that it stimulates the reader to read between the lines.

In regard to logic, the definition of a simulator seems disconcerting. Dr. Fox implies that a simulator simulates according to the intent of the experimenter. This apparent subjectivity is quite shocking. Actually, a simulator is a device whose transfer function is analogous to the real system which it mimics. Such a device simulates insofar as the input-output equations approach those of the real system. It would seem that this is the continuum along which simulation should be scaled, not a researcher's or observer's biases.

The basic aim of any driving simulator is to reproduce the machine-environment system so closely that the behavioral determinants of over-all system functioning can be operated on independently. In conceiving of a simulator two problems present themselves. One concern is the machine-environment part of the system. Is enough known about its interactions to develop a rational model of its behavior? To this there seems to be a qualified positive answer. The second question is do we know how (or what) to analyze human behavior within the constraints of the driving system? Here the answer is probably much more nearly the negative. This in itself constitutes the ultimate need for a near perfect machine-environment simulator. If some basic knowledge were available about the performance equations of the man-machine system (opposed to the machine-environment system) research on driving without total simulation could be undertaken. Ignorance about driving performance forces a demand for near-perfect simulation.

Thus, the proposed simulator represents a basic research tool and its availability does not automatically insure valuable results. It is here that the writer parts company with the program proposed by Dr. Fox. The list of studies he presents implies, at least, that the simulator is a device for discriminating among factors affecting driving behavior. The writer would contend that the real power of this simulator is to aid the scientist in the generation or discovery of the equations of human performance that determine over-all system performance. Anything less leads only to the normalizing of behavior. It is not enough, for example, to tell a highway engineer that a diamond-type interchange is better than a partial cloverleaf. He needs to know the behavioral criteria that must be employed in order to optimize interchange design. It is the criteria that the research scientist must supply, not normative comparisons of one design vs another, or one group of people vs another.

Implicit in this paper are two values of a simulator which are of a transcendent importance for the goals stated previously. One is the experimental control that can be exerted over the research. From a purely technical standpoint, field studies of driving can rarely be carried out with adequate control over all the system variables. Such field studies, therefore, have low reliability and lead to generalizable conclusions of only the crudest sort. With a simulator and good science this restriction can be lifted, and definitive research is possible. The consequence for highway transport can be tremendous.

Second is the freedom that a simulator gives to the scientist. With this device, the scientist will be able to pursue the logic of his research to a conclusion inconceivable in any other way. In the long run, it is this freedom that will lead to a precise, operational, statement of driving system performance. And it is at this point that it will be possible to tell the engineer not which is a better design, but rather what behavioral considerations determine optimum design. The consequences of this for increasing the efficiency of highway transportation are also tremendous.

The writer thinks that the studies enumerated in this paper will not ultimately be the ones carried out with a simulator. Those who have the conception that a simulator will be used for accident prevention, design data, or driver licensing will very early be disabused. Such engineering considerations will derive as an indirect consequence of scientific research done with a simulator. Furthermore, as has been the case historically, the advent of a powerful research tool quickly leads to a sophistication in scientific experimentation which moves far outside of lay comprehension. This will be doubly salutary: first because it will allow the research scientist to expend his energy on research and will insulate him from the pragmatic concerns of the managers, publicists, and salesmen. Dr. Fox's paper is a remarkable document in this respect, for it shows clearly the pressure under which he has been put to satisfy these people's material demands. It is fortunate to have a man of Dr. Fox's persuasiveness. Most scientists are not so apt; they see no necessity to justify the very patent needs that this tool will fulfill.

The second salutary benefit of this ultimate research will be that it will force an increase in sophistication in many areas of the highway research field. In this regard, there are some striking similarities between certain research in the highway field and the field of optics and sound. These latter, for many years, were considered "dead" fields of physics, ones for which all the important answers were known, and engineering considerations the only ones left. With the advent of more powerful tools of analysis, these areas are reawakening interest, drawing in more active and original scientists, and ultimately generating more sophisticated uses. The driving simulator can do the same in some phases of highway research. If this occurs it would be a most desirable consequence of inestimable benefit to all of highway transport.

In this discussion of Dr. Fox's paper, the writer has tried to read between the lines, and has read more perhaps than the author intended. There is little that he said that can be quarreled with. He has been more pragmatic in the program he states in this paper than the writer thinks he will be when the simulator is available. But he has, in general, stated well the need for tools in this field of research. If his statement furthers the progress toward them, everyone will owe him a great debt.

D. B. LEARNER, Human Factors Group, Research Laboratories, General Motors Corporation, Warren, Mich. — (The following was contributed as expressing Dr. Learner's point of view on driving simulators. It is taken from a paper by him on "Development of the GMR Minimum Analog Driving Simulator" presented before the Institute of Radio Engineers, March 25, 1960, in New York City.)

In the brief history of man-machine system simulation it has been characteristic that practically all applications of this approach may be categorized as either operator training or control system research. Training simulators have generally been developed in an effort to provide familiarization with specific new tasks that an operator is likely to encounter. In recent years

there has been a divisive trend in the development of such task training simulators. This results from one point of view that believes the whole environment must be simulated to the last degree of realism, as characterized by the current DC-8 simulators. On the other hand there are those that believe part task simulation for training purposes has great value in most applications. This approach simply means that certain elements of the task are simulated so that the operator may be realistically acquainted with critical procedures.

Research simulators however have primarily been developed in an effort to learn more about the interaction among man, the vehicle he controls, and its operating environment. Here too there has been a divergence of opinion related to the extent of realism required to simulate an operational system. If the prime importance of research simulation is viewed as determining man-machine interactions, and the effects of varied vehicle dynamics on operator performance, then it seems realistic to believe that minimum simulation may be as adequate for research as it is for training.

Whether the simulator has been constructed for training or research purposes, one required provision is for some method of validating the results of simulation with the real world counterpart. Such provisions for determining the extent of relation to the real world are often lacking in both training and research simulators. In fact if any single area of research on simulation techniques should be underscored as deficient it is the state of the art of simulation validation.

When the problem of a driving simulator is considered it must be viewed against the background of the cost of simulation relative to the cost of a full-scale automobile. The problem is one of conducting controlled investigations of driving performance under systematically varied conditions. There seem to be three alternative procedures for investigating problems of driving performance and these may be classified as descriptive studies, full-scale studies, and laboratory studies. Related to each of these solutions are a number of advantages and shortcomings. Descriptive studies in the operating system of today have a number of significant advantages. A multitude of variations and observations may be made at minimum cost. However, systematic variability is clearly impossible under operating conditions. If for no other reason than the utility of highway transportation systems prevents the imposition of experimental conditions that may lead to inefficient use.

Full-scale simulation studies have a variety of advantages. Such studies have been carried out for some time with variable stability aircraft and are currently under way with a similar variable stability automobile. Such an approach allows for wide variation in system dynamics and control configurations. However this full-scale simulation must always operate within the constraints of the environment. Furthermore there are significant research problems that cannot be comprehensively investigated with a full-scale simulator on the road. Such problems mainly fall in the area of safety, fatigue and vigilance.

A third approach to controlled investigations of driving performance would be to carry the entire system into the laboratory and reproduce every detail. Many disadvantages of

the foregoing alternatives would be eliminated under these conditions. At the same time it seems unrealistic to spend large sums of money on simulating an item that can be purchased at a local dealer for \$ 3,000 or less. As a result some estimate of the extent of realism required in laboratory simulation must be attempted.

It should be pointed out these solutions are not necessarily mutually exclusive. All three approaches should be used and cross-validated from one mode to another.

(The remainder of Dr. Learner's paper discusses the three requirements which were thought necessary for the GMR Minimum Analog Driving Simulator; namely, accurate response reproduction, validity and flexibility allowing simulation of the wide variety of vehicles. The design of the Minimum Analog Driving Simulator is described with attention to the way in which the environment, the vehicle and the vehicle controls are simulated to satisfy the criteria and requirements. Copies of his paper may be requested from General Motors Research Laboratories, Warren, Mich.)

CLOSURE, Bernard H. Fox — It is gratifying to know that the respondents are in agreement about the great importance of pursuing simulation techniques. Drs. Forbes, Malfetti, and Uhlaner have underscored this importance. It is further gratifying that the committee has felt the subject to be of great enough potential value to spend time on making judgments. The author appreciates very much the chance to take advantage of their rich experience and valuable criticism.

Dr. Case and Dr. Hulbert, being in the center of progress on simulation methods, are correct in inferring my intent in the description of the simpler types of simulators. These types are without doubt less useful, and can give fewer — and often not as good — answers to the questions which one would like to ask about driving behavior. Simulators which are highly programmed like the current motion picture devices worked on at UCLA are peculiarly limited in the variety and types of questions which they can answer about driving behavior, as was pointed out in the section on "Limitations on Experimentation" under "Programming." But as they infer from this section, greater usefulness and greater versatility by far can be found in a device which will permit not only unprogrammed action by the subject's vehicle, but unprogrammed interaction of great variety with other parts of the environment, usually other cars. Such a device, from the present vantage, is considerably more complex. Furthermore, it is much more expensive, in part because it requires a great deal of original and developmental research, and in part because of the more extended structural requirements for such a complex simulator: computer, environment, pickup and transmittal device, and vehicle simulator.

Professor Breuning is apparently regretful that the balance of emphasis went toward psychological rather than engineering uses of simulating techniques. Rather than planned imbalance, the reason for the emphasis was more a matter of ignorance on the author's part. An experimental psychologist is likely to see more clearly the human factors applications of simulating techniques than the engineering applications. But far from choosing to maintain such a state, the author encourages most warmly the contributions of other disciplines to a discussion of potential of simulating techniques. Certainly such contributions will increase the urgency of the need to carry forward work in simulation.

His suggestion that a picture of one advanced concept of a simulator be added is excellent. It is appended, with a brief description of the way this particular simulator is intended to work.

Dr. Brody's comments are most welcome, but more important, they point up a communications problem. Certainly adequate research itself is the objective, and not the means of reaching it — simulation or other approaches. It was for this reason that so much of the paper's emphasis related to the various problems which might be attacked by simulation. It was a failure of communication if the paper seemed to imply that research using other techniques, such as on-the-road research, was impractical or had

limited control in toto. Simulation, like any other method of research, has a place if it can produce research results in which researchers have as much confidence as those arrived at by other means, other things being equal. It must be admitted, regrettably, that in many cases on-the-road research does have limited control, and is impractical. In such cases, if simulation can correct those difficulties, and not introduce worse ones, it is preferable to less adequate research. On the other hand, as Dr. Brody has pointed out, where a particular attack on a question would produce results which are scientifically as acceptable as those produced with another attack, the former should not be discarded without very sound reason. Perhaps the comparison between simulation and other techniques might be placed into the whole context of comparison between any two techniques. The discussions under the headings "Values in the Strategy of Planning Traffic Research;" "Limiting Costs for Research Priorities;" and "Alternative Techniques of Research" would have more impact if their applicability to comparison between particular techniques were emphasized more. The author agrees with Dr. Brody, and feels that where possible, under the criteria of an acceptable cost-gain equation, as mentioned in these discussions, nonsimulation techniques can also be applied.

Dr. Barmack's suggestions were very stimulating. Without a doubt, if research into the variables which he mentions as important can be done, it should be done. While most of these variables (delayed sleep, alcohol, darkness, monotony, and biographical and personality factors) and their interaction were mentioned briefly in a previous paper (Goddard and Fox), it certainly does no harm to re-emphasize the need to study interactive effects, particularly when tentative results of two independent researchers* have shown interaction between personality attributes and effects of alcohol.

Dr. Barmack has done research which seems to point to certain personal variables as extremely important ones in the field relating drinking and accidents. He would like to see more research done on these variables. He mentions that advantages and disadvantages exist when subjects are selected by the experimenter rather than by membership in a criterion group. He then stresses the disadvantages, ignoring the advantages, and implies directly, in his last statement, that doing studies which attempt to answer his series of questions would help overcome the selection difficulty which inheres in the use of simulation techniques. One might almost infer an intent to say that simulation studies on these matters would be less valid because of the selection difficulty.

Assume that a sample is drawn based on a hypothesis about certain variables, and it is selected according to a predictor difference. An attempt is then made to relate the existing predictor difference to a criterion difference. In this case the predictors would be broken homes, drinking patterns, and personality, and the criterion would be accidents. This kind of research is spoken of as a prospective study. When a sample is drawn according to its membership in a criterion group and the relationship is examined between criterion measure and sample characteristics which are later determined, even when one starts with a hypothesis of relationship, this is called a retrospective study. Both kinds of study are possible with simulation techniques and with other techniques. Dr. Barmack's objection to predictor selection of subjects implies that he does not want to pre-select them as in a prospective study, but would rather have them select themselves because they became separated from others as a result of their criterion characteristics. This is precisely the way his study was done, and is definitely the description of a retrospective study. But if he were to attempt to examine more exactly the relationship of the pertinent variables to the criterion, the only way to avoid all bias and to create an unconfounded design would be to do a prospective study. It is in this very selection that simulation techniques excel, because the selection allows control of the variables to be investigated, and permits all the advantages of a prospective study. In this sense prior predictor selection and later criterion selection are more, rather than less advantageous than prior criterion selection and later predictor selection.

* Drew, G.C., Colquhoun, W.P., and Long, H.A., "Effect of Small Doses of Alcohol on a Skill Resembling Driving." Med. Research Council Memo. No. 38, Her Majesty's Stat. Off., London (1959); and Barmack, J.E., Public Service Research Institute, Stamford, Conn.

Only two kinds of studies, in the present context, cannot be done by simulation: (1) those in which driving behavior by the individual or his accidents are not the criterion, for example, questions #1 and #5 in Dr. Barmack's list (it has never been presumed by anyone that a simulator could be of any use in such cases); and (2) those which involve behavior states which are not producible in the laboratory, such as grief or transient emotionality of certain kinds. Subjects reflecting degrees of the latter variable are as available or as unavailable to the simulation experimenter as to anyone else. For the former the natural sequence of events may be altered, whereas it need not be for the latter. For all other questions which Dr. Barmack posed, studies can be done by simulation techniques as well as by other techniques. In this connection, the accident selects the individual more, rather than less easily with simulation than with other techniques, because there are more critical events possible, and the driver has an accident as a result of his driving habits, just as in the real world.

Nevertheless, it is well to restate Dr. Barmack's point. It is important to examine interactive aspects of alcohol effect beyond those which might be considered purely perceptual or perceptual-motor, particularly personal history and personal attributes. The author maintains, however, contrary to what he perceives to be Barmack's implication, that simulation techniques offer as great or greater opportunity for controlled studies of accident tending behavior than naturalistic study, even with respect to many of the more molar aspects of the person. It is just as easy to test a person from a broken home in the laboratory as on the road. (The probable relative success of such tests or techniques of conducting them are not at the moment under discussion.)

And to be sure, prospective studies on a simulator take much less time than similar ones using a real accident criterion.

Dr. Michaels' comments are most provocative and gave the author much pause. In the same way that he has done, the author tried to examine them for between-the-lines and for in-the-lines intent. Different portions of the comments produced different reactions.

His first remarks produced the reaction that as little as one can argue with a postulate, still less can one argue with a definition. The writer and the author have agreed on different criteria for defining a machine as a simulator. But it may be possible to show reasons for taking one view or another.

In deciding on the degree to which a machine is to be regarded as a simulator, the author believes that one needs the combined value of at least two measures: the intent of the investigator and the objective similarity of the instrument inputs, outputs, and their relation to the driving situation. Dr. Michaels seems distressed that the author considers the first important and writes as if the author did not recognize the second. He says that the second is the criterion of importance, seeming to ignore the fact that the author included it as a basic part of his definition of measure. Thus on one basic measure both have insisted on the same thing.

In respect to the other, it is possible to ask two questions: (1) To what degree should a machine be regarded as a simulator? and (2) To what degree does a machine simulate? The author believes that Dr. Michaels is answering the latter question, and that he is answering the former. The second question already assumes a value for the measure of the investigator's intent, but does require a measure of input-output similarity. The first question, on the other hand, requires both measures.

Another problem, however, which bears on the difficulty of measuring such similarity, and which may make a comparison of input-output equations not the best measure of how well a machine simulates, is the problem that has to do with how different zero is from zero. Assume that one simulator has no acceleration input and simulates travel over a moderately curvy, hilly road, with considerable stop and go travel. It has fairly good sound simulation, however. Another simulator has essentially a constant sound output close to threshold, but represents accelerations fairly well. The author does not say that a comparison is impossible, but the process of making bananas and apples into fruit, which is the obvious step of transforming disparate measures into a common measure, is a difficult job. The process may even result in an artificial communality more difficult to handle and assess in measure than a subjective evaluation of likeness, where the judgment is based on input-output equations in part, but considers other things. At any rate, the problem is not so straightforward as it seems.

To keep the record straight, invent an example where intent of experimenter is crucial in the decision to regard a machine as a simulator. This case shows that equation similarity becomes irrelevant when the instrument is not used as a mimicking machine, and that intended use will determine how important the likeness may be. Assume that optokinetic nystagmus is induced by various configurations of vertical bars, none of which has a counterpart in real life. If the machine imposes a motor task simultaneously, just because the experimenter on nystagmus needs a motor task, and this machine is available, and not because the task happens to resemble driving, has one the right to call the machine a driving simulator? But let the experimenter focus attention on the efficiency of using the machine as a car, and let the nystagmic stimulus be used as a distractor, however poorly it resembles the environment and however badly conceived, then one gets a little closer to the machine's use as a simulator.

Humility in this field is very necessary, however. It is important to point out that merely showing two factors to be better than only one of them may not be enough. Probably someone can show that a third or fourth is required. Therefore the author suggests that the importance of these two factors — similarity and experimenter's intent — may be great or relatively small. Research of the future must determine this.

There is some question about a statement made in the paper which Dr. Michaels also subscribes to. It says that the better the simulation, the more valid the simulator. Some evidence in the field of training* brings this statement into question. We are fairly sure that it is not universally true, but can presume that it is generally true. These exceptions, however, point to the need of a great deal of research.

Dr. Michaels ascribes to me the statement that a simulator is a device for discriminating among factors affecting driving behavior. He then denies that this is a major objective in doing studies on a simulator, asserting that the major objective is to determine equations of performance in order to apply them to a system of performance. These may then be used, he implies, to tell the engineer what behavioral criteria must be applied for optimum design of any road configuration.

It is important to note that one does not necessarily do research on determinants of driving behavior for the exclusive purpose of helping to design roads. It is also possible to help the safety and efficiency of travel by means of enforcement techniques, regulatory systems, signing systems, licensing requirements, removal of drug effects, physical restrictions for drivers, etc. These would all be helped by research directed to other information than a performance system. The author agrees, however, that those who would expect immediate payoff in some of these fields will probably be disappointed. A simulator, except in a few places, is not a quick return device.

A purely descriptive characterization of driver behavior given in terms, say, of car behavior and person behavior (measuring such things as performance, risk, attention field, perception, personal condition, and their relation) can lead to many decisions without necessarily using a systems performance description. Here the author acknowledges gratefully Dr. Michaels' insight between the lines. It is not necessary to stress that nothing prevents both a systems attack and a descriptive attack — this is not to say that quantitation is excluded from the description — from being combined objectives of simulation techniques. Even if this were not between the lines of his comments, the author would feel compelled to make the point. In the lines of his comments was the specific suggestion that system description of behavior will probably be an ultimate goal. The author agrees wholeheartedly. The question of ultimate value of descriptive research such as is discussed in the paper is another matter.

While the author is less sanguine about the ability of the simulation researcher to insulate himself from practical matters, as Dr. Michaels suggests that he do, the author agrees that if he were able to do so, the ultimate aid which he could give to transportation needs would be multiplied significantly in the long run. It is hard to convince the practitioner of this, however.

In sum, there has been less disagreement between the writer and the author than might appear from the discussion.

Dr. Learner's remarks are over-all correct. I would make one or two suggestions.

While it is true that a car may cost only \$3,000, it takes considerable expense to

* Drew, G.C. Personal communication (1960).

do research on this piece of equipment. One needs, at various times, people skilled in engineering, instrumentation, psychology, data analysis, etc. In addition, the instrumentation itself needs development and construction. There is no doubt that work on a real car is less expensive than work on a fixed simulator of high fidelity. Yet this leads to a second point.

Dr. Learner's classification of research into driving performance makes no provision for less than high-fidelity fixed simulation. In the same way that it has been found that in training there are cases where full-scale simulation is best and cases where limited simulation is best, so in research one may expect to find the same thing. Depending on the objective of the research, the validity of the simulator in respect to the measures to be undertaken, and other entries in the cost-gain equation, it is likely that certain researches can be undertaken with limited performance laboratory simulators, others with very faithful laboratory simulators, others with on-the-road simulators, and still others with on-the-road real cars.

It is for this very reason that the author has been at such great pains in this commentary to point to the need for simulation techniques rather than a simulator (although he was not at such great pains in the original paper. But see the section on "Programming Priority.") These techniques, of course, include the kind of work that Dr. Learner has been carrying on.

One more thing which bears on the use of simulation in conjunction with live car research needs emphasis. Even if certain research can be done by means other than simulation, it has often not been possible to do such work. The reason is not of the greatest importance. Possibly it had to do with cost, possibly with past failure (not necessarily inability) to develop techniques, possibly with other things. But if simulation techniques were available, and a program of research were entered on, it is very likely that one could schedule research activities which are needed but haven't been done.

The author gets the impression that Dr. Learner's sights are more sharply focused on problems of driver relation to car handling, vehicle characteristics, and dynamic car behavior than on some of the other researchable features of driver perception and performance, although he has not completely ignored the latter. Some of his points are cogent if taken against the background of car characteristics. They must take their place in importance alongside other considerations when seen in the context of the whole spectrum of possible driver research. Fundamentally the author and the writer are in agreement on the place of on-the-road research relating to car characteristics, as seen from the section on "Alternative Techniques of Research."

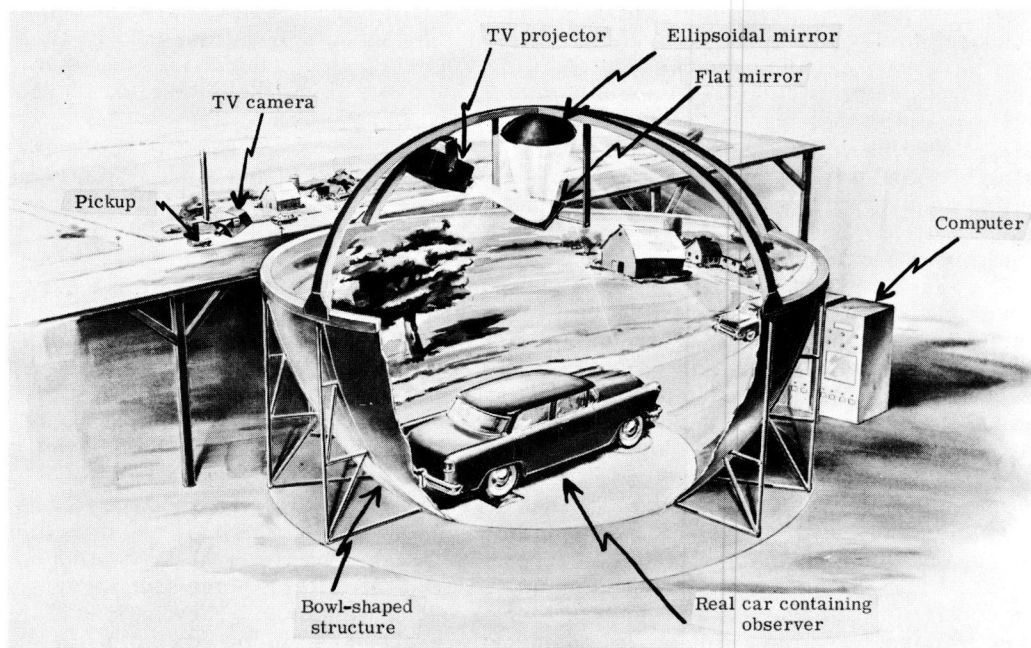
Aside from a few considerations mentioned previously, the author is very much in agreement with Dr. Learner's analysis of the general picture.

The author has a last general between-the-lines comment. The point was brought to the attention of a group which was meeting under the auspices of the Automotive Safety Foundation during a presentation by Dr. G.C. Drew, who did work with a point source of light simulator for the British Medical Research Council at the facilities of the Road Research Laboratory. It was the suggestion of the group that one should not attempt to promote "the simulator" or "a simulator," but rather "simulation techniques." Merely pointing out, as I did in the sections on "Preliminary Simulator Configuration" and "Research Possibilities" under "Planning for Simulator Research," and "Validity" under "Other Considerations," that several simulators need to be built at several levels of fidelity, each with its own design to achieve its own purpose, is not enough. Researchers must constantly be on guard that the professional, and particularly the lay public do not conceive that there is one instrument, one design, which the researchers would like to see created. For this reason, throughout the preceding discussion, the author has been careful in phrasing references to simulators and simulation. It is simulation techniques which are needed, not a particular simulator.

The author's thanks go again to the committee members for their interest and the further light they have thrown on the simulation problem.

A number of approaches to fixed simulation can be taken: point source of light, film, models, etc. Different techniques of transmitting the original image and projecting it are possible.

The conceptual schema pictured here is one which was described in some detail in a study done by the Cornell Aeronautical Laboratory for the Public Health Service. (The photograph depicts the same conception which appears as the frontispiece of the study: "Automobile Driving Simulator Feasibility Study," Cornell Aeronautical Laboratory, 1958; project direction, C.H. Hutchinson.) The notion of a reflecting vertex of a conic section was partially developed by the Bell Aircraft Co. and is still under investigation by the Cornell group.



In this conception a model of a road scene with small model cars forms the input to a receiving element or pickup, which is in the position of the driver's car in the model. The pickup is shown directly ahead of the TV camera on the road. Its mirrored surface is the outside of a skewed section of a hyperboloid of revolution, with the vertex pointing forward in order to allow that portion of the surface with best resolving power to receive the most important part of the scene. The image of the road scene is received by the surface of the pickup and is reflected into the TV camera above the road scene, shown pointing at the vertex of the pickup. This image is transmitted to the TV projector above the bowl-shaped structure onto a flat mirror, which throws the distorted image from the pickup upward to another specular surface. This mirror is the inside of an ellipsoid of revolution which is related geometrically to the pickup hyperboloid so that the image which the latter picks up becomes undistorted to the viewer inside the car when projected onto a screen from the ellipsoid as shown.

The person sits in the real car occupying the bottom of the bowl. When he manipulates the controls of the car, the pickup on the scenery behaves in respect to the scenery as it would if a person were doing the same things to the controls of a car on the model itself in the location of the pickup. The pickup is slaved directly to the controls of the subject's car — brakes, accelerator, steering wheel, etc.

Under these conditions the movement of the subject's car is unprogrammed: he can make the pickup, corresponding to the model car under his control, do anything he chooses in response to traffic, road characteristics, signing, etc. Contrasted with this, in a film version he has very little control over what he can do with respect to the driving environment, other than what the camera did which photographed the scene originally.

A computer is also shown. It would function to program scenery changes and traffic movements and to analyze responses of the subject or car.

Some Technical Considerations In Driving Simulation

BERNARD H. FOX, Accident Prevention Program, U.S. Public Health Service

● A REVIEW of the literature shows a number of possible approaches to constructing a driving simulator. Most of these have been mentioned before: film (6), point source of light (1, 2, 11), direct optical viewing (12), TV transmission (8), etc. The troubles with some of these have been discussed at some length (7, 9). The author would like to discuss one aspect of the total simulation problem which has not been treated in the literature. It is a serious consideration, which might well affect basic long-range planning for simulator research.

This problem arises in that conception of a simulator which uses a model as the source of environmental input. In many conceptions, a TV setup is used to transmit the scene to a visual projection for the subject's viewing, with whatever adjunctive techniques might be required. The device pictured in the paper, "Engineering and Psychological Uses of a Driving Simulator" (3), shows one way of using models. Others are known and have been used. The description of model use in that paper is an adequate example of a method which would be applicable to the discussion in the present paper. It should be emphasized, however, that it is only one such example.

The question has been asked whether it is possible, with the model technique, to simulate driving long distances. Such a task is very difficult. Even though it has been concluded, and rightly so, that a combination of model and film, or model and other associated techniques, would be much less expensive than a full model technique (3, 4, 5, 7), it is still necessary to examine the latter thoroughly to see just what might be involved. This examination, it is hoped will justify the conclusion mentioned.

The idea to be discussed here was first introduced, to the author's knowledge, at a meeting in 1958 at which were present James Goddard, Fletcher Platt, and the author. A problem inherent in this idea is examined and two possible solutions given. Other problems will be mentioned.

In order to be able to go long distances on a model setup, one of the things that might be helpful would be to avoid the necessity of creating a full model panel for every mile traveled. Obviously a full model would be quite impossible, say, for more than a few miles. To avoid the necessity, it was suggested that substitutable model elements be used in the total scene. The Cornell Aeronautical Laboratory later coined a useful phrase to describe this process. They called it "terrain synthesis."

A model scene could thus be transformed into another if the model elements were removed and replaced by others. Various means of doing this have been considered. One of these might be computer programming of terrain in advance, removal of terrain elements to a terrain bank by automatic mechanism under time control and position control of the computer, and replacement from the same bank. After the TV pickup representing the moving car has traversed the scene, the panel is transformed into a new scene by this technique and made suitable for another trip over it by the TV pickup, which has meanwhile traversed another panel.

Certain other ideas were added. For example, Cornell Aeronautical Laboratory has suggested that storage could be arranged as part of a panel. A scenic element could be quickly replaced by rotating it around an axis imbedded in and parallel to the plane of the panel. Building walls of different colors inside and out could be swiveled on such a pin axis to give different building appearances quickly and simply. All of the foregoing devices combined could produce a programmed situation where it would not be necessary to build a long line of successive different model panels over which a pickup would have to travel to simulate long drives.

First, it may be instructive to look at some of the figures involved. Because it would be so difficult to achieve the extreme detail which would be needed, it is almost impossible to conceive of a model whose scale ratio would be much greater than 100 to 1. On the other hand, in order to limit the size of the panels on which the models would be set, it is almost inconceivable that one could go to a scale ratio much smaller than 50 to 1. These limits give an approximate order of magnitude within which computation of other estimates can be made, say 75 to 1 as the model size.

Even with panel substitution, however, the need for at least two or three panels remains. The size of a panel might be governed by ease of moving or changing. At a 75 to 1 scale, a world mile is equivalent to about 70 ft of model, probably the upper limit for panel size. In a 300-ft building, 200 ft would accommodate three panels endwise. The problem, then, is how to devise a technique so that panels will be replaced and the pickup will be able to move along continuously, going from one panel to the next repeatedly.

Two methods come to mind, although no doubt there are many other techniques for accomplishing this task.

One method involves longitudinal relative movement of the pickup which represents the car. The pickup moves along over a panel which slides backward simultaneously at greater than pickup speed. Maximum pickup speed is the equivalent of a live car speed of about 70 mph. The pickup may move as it likes below this speed. At a scale of 75 to 1, the panel would thus actually move more than 1.4 ft per second at maximum speed. This speed may be regarded as relatively large or not large, depending on the engineering of the situation — both computer and mechanical. That the latter is a consideration here will become clear. The rearward movement of the panel is important because one must provide a means for the pickup to maintain continuous motion. Simultaneously, another panel, after having been stocked with terrain elements, is in position ready to replace the original panel, so that the car will have a panel onto which it can cross when it reaches the end of the first one. When it crosses the panel junction, the second panel, now the carrier panel, begins its rearward movement. At the same time a third panel, having been in the process of acquiring synthesized terrain from the computers, now starts to move toward the soon to be vacated position of the current carrier panel.

An interval must be allowed for such panel substitution, which would take place either from below or from the side. If the pickup moves at maximum speed, a further interval must be provided for the replacement panel to move into position before the pickup reaches the end of its carrier panel. This is the reason that the carrier panel must be able to move at a speed greater than 1.4 ft per second.

A second method can be used which, in terms of engineering considerations, is perhaps more feasible in some ways, even though somewhat more complicated equations of motion are required.

Assume that two panels are laid end to end. The pickup starts at the juncture of the panels, going outward on the carrier panel. With respect to the surrounding terrain, it travels in a straight line until it reaches the end of the panel road and then crosses over onto the next carrier panel. But in order that motion with respect to the panel coordinates of travel shall be a continuous straight line, the panel itself must have been reoriented so that the pickup moves toward the receiver panel at the time of crossing, not away, as it started to do. This situation is achieved by a continuous rotation of the panel through 180 deg around an axis at its centroid while the pickup travels along the panel. Even at maximum pickup speed, no interval is needed with this method for insertion of a panel holding new terrain, provided that the terrain substitution process itself takes less than a minute or so. If it takes more, then three or more panels may be necessary.

Assume that the pickup moves uniformly just fast enough to traverse the panel during a single half rotation. The resultant true motion can be expressed by simple parametric equations, describing a rosette petal whose vertex is the real point of departure. The vertex is also the real point of arrival after the pickup traverses the length of the whole panel. At the half-way point, the real motion of the pickup is at 90 deg to direction it faced when starting, which was straight along the length of the previously stationary panel. Thus the pickup's greatest longitudinal absolute excursion is one-half a panel length.

When the pickup crosses over onto the receiving panel, the latter begins its rotation around its centroid axis, and the pickup (if at the same constant speed) again describes a rosette petal.

If the driver controlling the pickup decides to travel at a uniform speed such that the panel has rotated through its 180 deg before the pickup reaches the end of the panel, a spiral is described by the pickup, again definable by simple parametric equations, up to the point when the 180-deg rotation is complete. From that point the panel remains stationary and the pickup's true motion is again a straight line until it crosses onto the next panel.

It is obvious that if the pickup changes its speed during the trip along the panel, the equation of motion becomes complex. Certainly, in any case the situation implies a computer to handle the input, output, and feedback relations between pickup and real car. This is true whether the first or second method is used. The situation is made even more complex if the pickup moves laterally with respect to the model road.

The engineering problem is enormous. Think of moving a 70-ft panel at the proper rate of speed with no distortion and with perfect juxtaposition of model surfaces; removing and replacing farm houses, signs, road features, etc., over a 70- by 7-ft area within 1 or 2 min; and controlling the pickup with a movement tolerance of less than 0.003 in. If one were to consider reducing the panel size because of its unwieldiness, say to 35 ft, the time of changing terrain and substituting panels would be reduced, but not in half. Substituting panels takes about the same time for large and small panels, so that the time saving is only in terrain element substitution.

The difficulty of accomplishing the total task can at the present only be guessed at, because, to the author's knowledge, no one has made any actual engineering design attempts along these lines.

Certain problems arise in using a model and in combining film and model which must be considered by any designer or planner.

One of the most important is the closeness of tolerance with which a model using TV pickup must be built. If an object in the model field moves 0.003 in. laterally with respect to another, the relative equivalent change in the projected visual scene is about $\frac{1}{4}$ in. Whenever abnormal motion occurs, it becomes quite noticeable if it occurs rapidly, as might be the case in the model situation. Vibration or poor tolerance can cause such abnormal motion. Ordinarily a small object's limited motion, if its contours do not have especially high contrast with the field, is not particularly noticeable. However, an automobile model in this model scene will usually be a rigid object. If this is the case, a $\frac{1}{4}$ -in. abnormal motion in the image becomes easily detectable inasmuch as the object in question occupies a considerable visual angle.

It is possible to produce accurate tolerances for visual purposes with a TV pickup, as demonstrated by the Link and the Curtiss-Wright jet simulators, where the same problem arose. But the objects in their field do not move suddenly with respect to the field; only the pickup moves. This difference may be critical in designing a model type of simulator for driving.

The question of how much detail must go into the construction of terrain and vehicle elements in the scene is a crucial one. No one has tested various degrees of detail under different conditions of magnification, closeness of the scene to the viewer, and speed of objects in the scene. It is likely that limits of good detail would not be excessive technically, but particular needs might influence costs to a profound degree. The question must be answered by research.

One way out of the dilemma of long trips using models as has been suggested (3, 4, 5, 7), is to alternate periods of using model and film or other inexpensive display. When interaction with other cars takes place which demands feedback to the scene, models would be used (except for simple feedback such as lateral position in a lane, or going faster or slower: these are possible with filmed images). On all other occasions film or other inexpensive display would be used. Whereas this technique reduces model cost considerably, it does not remove the need of having models to begin with, together with a control mechanism for the TV pickup.

Another problem of interest arises because it is desirable to have nonprogrammed rather than preplanned control of some cars with which the driver interacts. If they

do require nonprogrammed control, the question of display and control devices for the control personnel comes up. Such needs increase the cost of the mechanism, although not in exceedingly great measure. The techniques for permitting control must involve a number of decisions of importance — number of control displays, accuracy of display and control, etc. An interesting part of this problem is that the control personnel must not have before them the same scene as the experimental driver sees. They would probably see the model scene enlarged from above or from a distant pickup.

It will be important to look at costs in the present case, because the greatest expense entailed in the creation of this conception of a simulator, that is, a terrain model using TV pickup and projection, will probably lie in the model making, TV pickup movement, and model change. If no synthetic terrain were involved (that is, if only fixed panels were used), the cost would be far too heavy in the model building (always assuming that extended driving is required).

It has been suggested that the width of panels be reduced in size to save cost, and that films or other inexpensive projections be presented at the sides of the model to blend in with the visual projection received from the model. It is the author's opinion that while such a suggestion was made from a desire to reduce costs, one should make the more serious point that to try to create a simulator with input from a model only would be impossible in a practical sense, not merely disadvantageous, or uncomfortably expensive. It is not so much that a technique of melding film, for example, and model is desirable; it is that cold figures put out of the question the use of full models. The reason is that a model of this type, requiring buildings with razor-sharp edges — a necessary technical feature here (10) — costs on the order of \$200 per square foot. For a 70-ft panel, extending over a world distance of a mile, if one were to represent $\frac{1}{4}$ mi of terrain on either side of the road, giving a 5,000 sq ft model panel, one would need to spend \$1,000,000 per panel. Even with grosser detail at a distance, which might lead to as little as one-half price per unit, three panels would be inordinately expensive. To create the terrain substitution system would still involve building a number of elements two or three times greater than the number containable in three panels. All of this cost is materials expenditure, over and above any research or developmental costs which have been quoted with some confidence for certain aspects of the developmental program (7).

Thus the designer is forced to use a narrow model width and blend the model scene with the remainder of the scene, which has been filmed or otherwise inexpensively projected. The latter is that portion of the total scene which is affected by very little or no input from the driver, and which should feed little or nothing back into the driver's world of action and reaction except to give him perceptual orientation. Assume that instead of $\frac{1}{4}$ mi of world scene (that is, 35 ft of model, on either side of the road), the model only encompasses, say 75 world yards on either side of the 25-yd road. This space would give a total model width of something like 7 ft. Now a panel will cost about \$100,000, somewhat more reasonable than \$1,000,000 or even \$500,000. To this must be added the cost of film projection, film registration, film editing (there will have to be careful lateral editing to achieve good melding with the model), and the extra initial cost of setting up a technique for joining the two parts of the scene properly. The total will still be considerably below the ultimate cost of a full model system if the latter were to be built.

The figures used here are very rough. If a different scale size is taken, say 100:1 instead of 75:1; and a different lateral extent of scenery, say 400 ft instead of 525 ft; the cost of a panel a world mile in length would change by an order of value to something like \$40,000, as opposed to \$100,000 (7, p. 89). Other costs which are at present also guesses have to do with the kind of terrain, cost of unit terrain area, and similar matters. It is obviously a matter for research to decide what limits of lateral model extension are required or sufficient for the perceptual tasks involved, as well as other problems such as mentioned previously.

As far as is known no one has attempted detailed alternative analyses of engineering costs associated with the requirements described, even with respect to conceptual designs, let alone actual designs. Such cost analyses are badly needed.

The problem of combining film projection and model projection takes different forms

for different techniques of alternating panels. If a linear panel motion is used, the projection can be stationary in space, with the panel motion and pickup motion in synchrony along the panel axis. In this case the absolute motion of the pickup along the panel axis, as well as the projector motion, would be zero. On the other hand, one might transmit to a moving projector or reflector with compensated position. Other means are also possible.

If rotating panels are used, the difficulties become greater. The direct attack would be to have the projector move with the pickup, both on the rotating panel. However, projection channels could be set up outside the panel and the projection moved by combined electronic and optical means. A number of other attacks can no doubt be conceived.

One major problem, which is not likely to be solved early, is the good enough simulation of city traffic. Fortunately, work in other areas can proceed without its solution. First, it will not quickly be solved because it will not be attacked early. But the more important reason for a late solution will probably be the fact that it is a most difficult problem. Pedestrian involvement can probably be handled by combining of TV images, using known techniques. But in respect to cars or other objects situated a few feet away, very serious difficulties will be encountered.

It has been suggested that a simpler device with only night driving might be a feasible first step toward multi-situation simulation. The problems attending the simulation of car, street, and sign lights are considerable — particularly car lights. Although the author is familiar with at least three occasions when "skull sessions" were held to try to dream up ways of handling these questions, it is probable that none of them has been described in published material. They are worthy of any scientist's mettle.

Aside from the questions brought up in the foregoing, a number of items await research before answers will permit plans for design of any of several more advanced simulation methods. These items are mentioned in some detail in the review by Molnar and Lybrand, as well as by Hutchinson. In the visual field they have to do with color, intensity, definition, contrast, resolution, field magnitude, etc.

In sum, a vast area has been opened up for the broadest scale approach by research and development teams. This area, the whole notion of driving simulation, deals with a large number of theoretical and practical problems in many fields: light, sound, mechanics, electronics, thermodynamics, human engineering, industrial engineering, psychology, cost analysis, management planning, research programming, etc.

It would be of the greatest interest to follow, and if possible, be a part of, the inevitable progress among the many fields and techniques contributing to driving simulation.

REFERENCES

1. Havron, M.D., and Butler, L.F., "Evaluation of Training Effectiveness of the 2-FH-2 Helicopter Flight Trainer Research Tool." Psychological Research Associates, PRA Report 56-17, NAVTRADEVCEEN 1915-00-1 (1957).
2. Drew, G.C., Colquhoun, W.P., and Long, H.A., "Effect of Small Doses of Alcohol on a Skill Resembling Driving." Medical Research Council Memo. 38, Her Majesty's Stat. Off., London (1959).
3. Fox, B.H., "Engineering and Psychological Uses of a Driving Simulator." HRB Bul. 261, (1960).
4. Goddard, J.L., and Fox, B.H., "The Driving Simulator." Preprint, SAE (June 1958).
5. Hulbert, S., and Wojcik, C., "Driving Simulator Research." HRB Bul. 261 (1960).
6. Hulbert, S.F., and Mathewson, J.H., "The Driving Simulator." Inst. Transport. and Traffic Eng., Univ. of Calif., Reprint No. 65 (1958).
7. Hutchinson, C.H., "Automobile Driving Simulator Feasibility Study." Contract No. SAPH 69692, for U.S. Dept. of Health, Education, and Welfare, by Cornell Aeronautical Laboratory, Buffalo (1958).
8. Link Division of General Precision, Inc. Notes on a simulator for training jet pilots using a TV transmission system.

9. Lybrand, W.A., Havron, M.D., Gartner, W.B., Scarr, H.A., and Hackman, R. C., "Simulation of Extra-Cockpit Visual Cues in Contact Flight Transition Trainers." Air Force Personnel and Training Research Center, Randolph AFB, Texas (1958). Also: Molnar, A.R. and Lybrand, W.A., "Basic Development Accomplished on Wide-Angle, Non-Programmed, Visual Presentations." NAVTRADEVCEEN, Vols. I and II (1959).
10. Thomson, K. F., Personal Communication, U.S. Naval Training Device Center, Port Washington, N. Y. (1959).
11. Vincent, D. F., "The Institute's Apparatus for Testing and Training Drivers." The Human Factor, 10: 64-65 (1936).
12. H. A. Wagner Co., now a subsidiary of Curtiss-Wright. Constructed a pilot model of a system using as an image source a miniature tank platoon environment.

Standard Electronic Units Interconnect to Provide Flexible Digital Recording

RICHARD C. HOPKINS, Chief, Instrumentation Branch, Division of Traffic Operations, U.S. Bureau of Public Roads, Washington, D.C.

● **THE PURPOSE** of this paper is to introduce those familiar with analogue recording techniques to some of the Standard Electronic Units which may be combined to form Flexible Digital Recording Systems.

The Bureau of Public Roads has been digitally recording traffic survey data since 1946 when O. K. Normann had special solenoids mounted on standard adding machines after trying in vain to find a similar piece of commercially available equipment. In 1956, because of a need to use 14 bank adding machines, it was still necessary for the Bureau of Public Roads to provide its own solenoids when this equipment was improved and expanded. Today, only three years later, the manufacturers of adding machines provide for the remote electrical actuation of nearly all models and, almost all, either provide for a direct output to a motorized tape punch or have an auxiliary unit to provide this output. And this rapid trend toward the remote or automatic handling of data by office machines is only mildly indicative of the advances being made in electronic computer print-outs or recorders designed for digital systems.

These newer recorders are briefly discussed and a few typical systems are shown that can be used individually or in combination to produce direct printed records of measures of physical quantities.

It is difficult to observe any digital system without becoming fascinated by the regularity and positiveness with which the data are printed and to admire the complex mechanism which so faithfully transfers electrical intelligence into numerals. In fact, the effect is to often overweight the importance of the recorder which may mask a much more complicated system of data collection. So, because of the straightforward design of these recorders, it is possible for the purpose of this paper to consider only a few external features that are pertinent to any digital system and then consider in more detail such systems and possible alternates.

The selection of one's first digital recorder will probably be dictated by the output of the system that has determined its need. Therefore, it will be only necessary to refer to recorders in terms of "staircase," "10-line," or "binary code," as the features of accepting and storing digits to be printed on command are common to all.

By a "staircase" input, (Fig. 1) is meant that each digit in each column is represented by some particular voltage with respect to a zero level. A typical example is the use of +138V to represent "0," +54V to represent "9," and the other digits represented by voltages equally separated between these two. The "10-line" recorder provides a common terminal for a battery connection and 10 digit terminals for each column. A digit is stored in such a recorder by simply completing the circuit from the other terminal of the battery to the proper digit terminal. A "binary code" input is such as its name implies. In this system, the sum of the code units is the decimal equivalent of the binary number produced by the electronic system. Because of electronic expediency, code values of 1-2-2-4 are usual although recorders with a 1-2-4-8 input are available.

Physically, digital recorders are about 20 in. long by 12 in. high by 15 in. deep and may be obtained in individual cabinets or with panels for relay rack mounting. They normally operate from 120V 60 cycle power with a demand of the order of 150 watts. Models are commonly available to print from 6 to 12 digits as rapidly as 5 times per second with some special computer print-outs capable of much higher recording rates.

In considering in some detail the systems that will collect and prepare the data to be

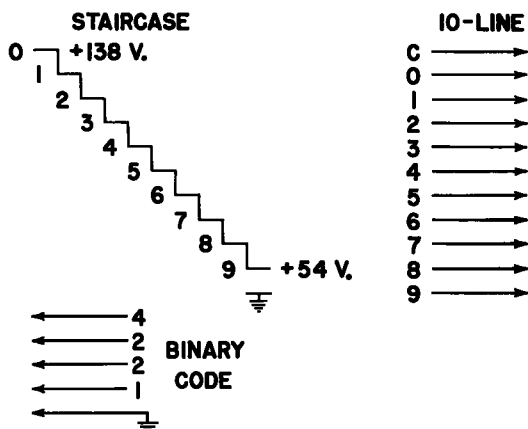


Figure 1. Standard recorder inputs.

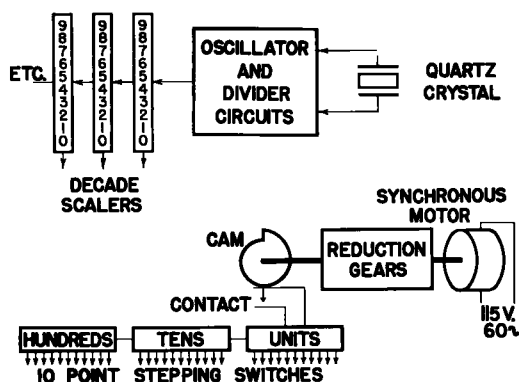


Figure 2. Time bases.

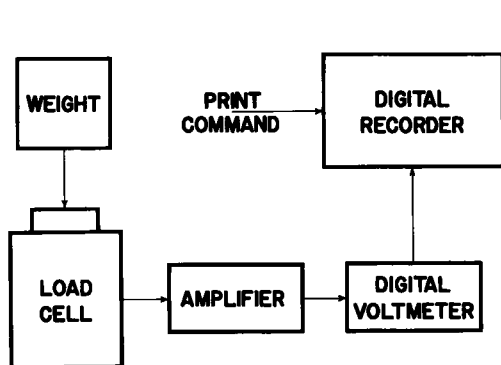


Figure 3. Weight recording.

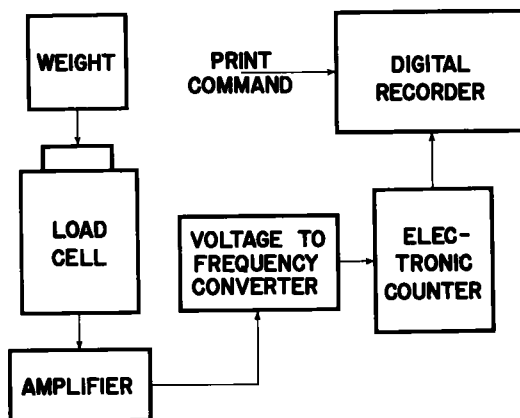


Figure 4. Weight recording.

recorded, the measurement of time should probably be considered first — time being the abscissa of almost all of the common analogue records. Unit time in the analogue is unit length and its measure is dramatically illustrated by the bulk of the recorded chart.

In a digital system, time, like all other quantities, must be recorded in its numerical value. An exception to this would be a situation which permitted the recorder print command to be controlled by time units. Each record would then indicate the passage of one time unit and elapsed time could be determined in the data reduction process by totaling the individual recordings.

In the general case, however, a time base generator or digital clock must be included as a part of the data collection system and its significant figures recorded. Two typical time bases are shown in Figure 2. A quartz crystal oscillator (usually 100 kc) is connected to suitable electronic frequency divider circuits to produce the time unit required. These time units are counted by an electronic decade scaler with an output for each count of ten carried over to another similar scaler. As many as necessary of these decades may be interconnected and the output of each (staircase or binary code) is always available for transfer to a proper digital recorder.

A second practical, and somewhat more mechanical system would utilize a synchronous motor, proper reduction gears, and an electrical contact closed by the driver cam. Ten contact, spring-driven stepping switches would then be used in each decade and a 10-line output to a digital recorder would be available.

As circumstances might require, the stepping switches could be actuated by the crystal oscillator and divider circuits or the electronic decade scalars could count the contact point closures. Other suitable time base circuits make use of capacitor discharge time, tuning forks, direct counting of the power line frequency, etc.

Weight can be directly detected by load cells. These and the necessary oscillator-amplifier systems for their use in conjunction with direct writing oscillographs are commonly used in many highway research laboratories. Two alternative methods of converting this typical laboratory analogue system to digital recording are possible. Both are equally accurate and the choice will be dictated by future utilization of the equipment which is to be procured.

A direct substitution approach (Fig. 3) is simply to replace the direct writing oscillograph with a digital voltmeter. For a minimum of data collection, the weight values can be manually recorded from the digital indication on the voltmeter. However, because it is assumed that large quantities of data are to be collected and that a digital recorder has also been obtained, the digital voltmeter will be directly connected to a compatible digital recorder and automatic data collection will be accomplished on each print command.

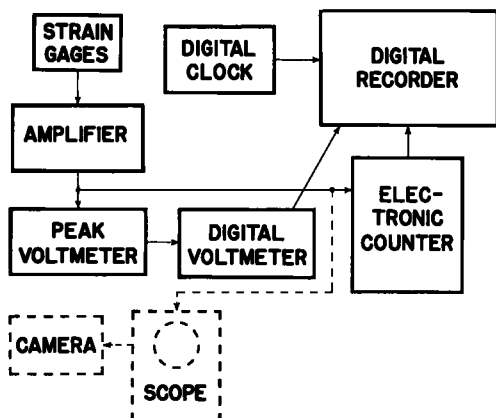


Figure 5. Digital recording of vibration or dynamic strains.

The less direct, but in some respects more desirable method (Fig. 4) is to substitute a voltage to frequency converter for the oscillograph. An additional unit of the electronic counter type is then used to measure the output frequency and transfer the weight data to the digital recorder. Although requiring an additional unit, this method is favored because the counter unit will have many more laboratory applications than a digital voltmeter and the extra original expense will result in later economies. Furthermore, the two units will always combine for a direct measurement of voltage.

Vibration or dynamic strain investigations have encouraged the purchase of much of the electronic equipment now used in highway and structural laboratories. Again, the usual system is standard carrier-amplifier equipment with either a direct writing or galvanometer-type oscillograph output. The digital system for these data recording (Fig. 5) requires a direct measurement of two values, amplitude and frequency. The amplitude is detected by a peak voltmeter for measurement by a standard digital voltmeter and the frequency is directly determined by one of the standard electronic counters. Both amplitude and frequency can then be recorded as desired and the time saved can be best appreciated by those who have counted cycles on analogue charts to determine frequency. The addition of a cathode ray oscilloscope will permit the observation of wave form and a camera will provide the few necessary illustrations for technical reports.

Liquid levels, large displacements in operating mechanisms, etc., can be measured and recorded by the system shown in Figure 6. A precision, ten turn potentiometer

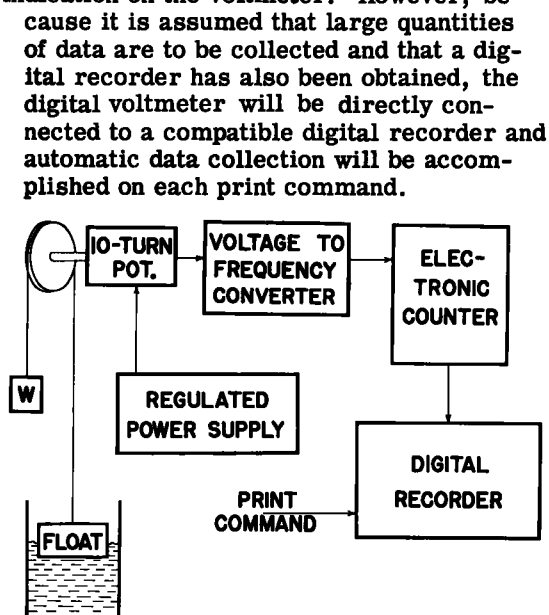


Figure 6. Height recording.

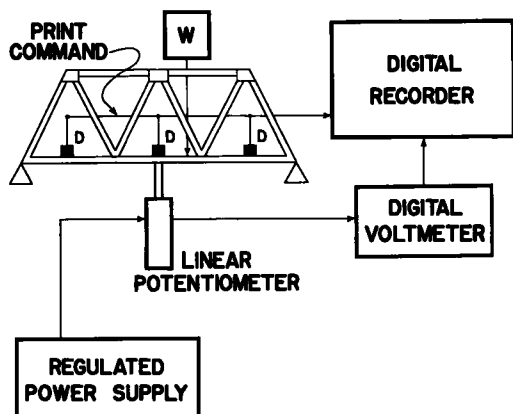


Figure 7. Deflection recording.

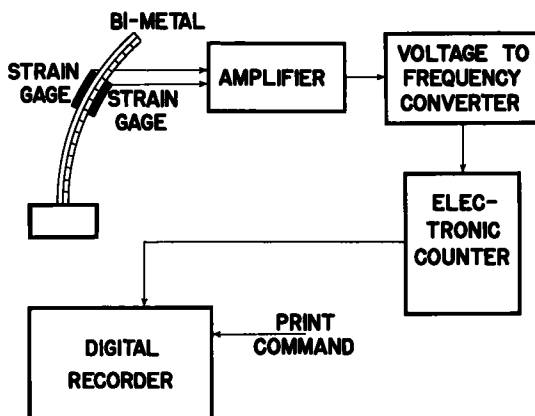


Figure 8. Temperature recording.

meter divides the voltage output of the regulated power supply in direct ratio to the level being measured. The print command would usually be controlled by some digital clock and a direct printed record is the result.

Figure 7 shows a similar system that is more practical for small displacements or deflections. In this case a linear precision potentiometer, or an LVDT (linear variable differential transformer) in a carrier-amplifier system provides a direct reading of movement. The print command in this instance could be controlled by position detectors "D" to provide a deflection record of a structural member.

Any system of temperature detection with an electrical output can be adapted for digital recording. Figure 8 shows one typical system in which strain gages are attached to a bi-metal strip. A standard bridge-amplifier couples such a detector to a digital voltmeter for transfer to the recorder at any desired time. Other detectors, such as thermistors or thermocouples, can be as easily accommodated.

Shaft speeds are detected by a tachometer as in analogue systems. However, for digital recording it is generally more convenient to use a digital tachometer rather than converting an analogue output. The tachometer generator, which is more familiar, produces an increasing voltage with increasing shaft speed; the digital tachometer produces one or more pulses per revolution of the shaft. The digital recording system is completed by connecting a digital tachometer to an electronic counter which has a time base and gating circuits to count pulses per unit of time. The shaft speed then becomes direct reading for transfer to the printing recorder. A typical system is shown in Figure 9.

Notations, which must be entered by hand on an analogue chart, can usually be more conveniently handled in a digital system by entering numerical codes directly in the recorder. This can always be done by providing decades of push buttons connected to produce the proper digital code for the type of recorder used as shown in Figure 10.

It is a rare occasion when a physical investigation requires the recording of but a single channel of information. More likely the capacity of any given recorder will be strained and some complicated system for programming the data entries will become desirable. However, most problems can be reasonably limited to the capacity of the 11 or 12 digit recorders available.

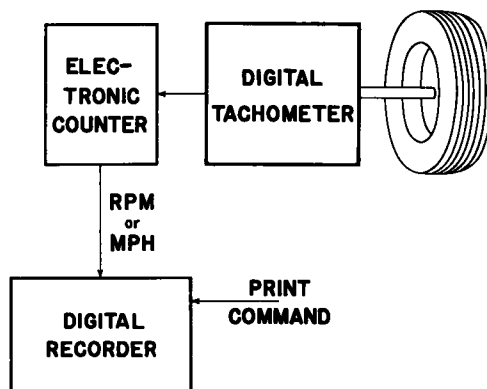


Figure 9. Speed recording.

An example of several data being simultaneously entered on a digital recorder is provided in the Traffic Impedance Analyzer developed by the Bureau of Public Roads for speed and delay or operating economy studies. This digital data collecting and recording system is mounted in a vehicle (Fig. 11) and at one-second intervals prints the vehicle speed in miles per hour, accumulated mileage in three significant figures, two decades of manual code, time in seconds for a sequence check, and three significant figures of fuel consumption. These data are shown in a typical recording sample (Fig. 12).

Figure 13 reverts to a block diagram presentation of this instrument and will simplify the explanation of its operation. As both speed and delay, and operating economy studies would require speed and distance to be recorded as a part of the data, primary consideration was given to recording these quantities. The speedometer cable of American cars is designed to make 1,000 revolutions per mile. On this

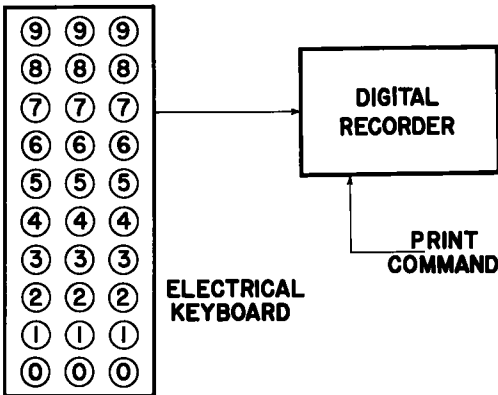


Figure 10. Manual coding.

basis a special digital tachometer was designed that would provide direct speed and distance outputs. For the measurement of speed, a disc with 36 holes near its outer edge was rotated by a shaft input. With a light source on one side of the disc and a photoelectric cell on the other, electronic pulses in direct representation of speed in miles per hour could be generated each $\frac{1}{10}$ second with a shaft input rate of 1,000 revolutions per mile. The first disc was coupled to a second disc with one hold near its outer edge by a 10:1 gear reduction unit. A second photoelectric cell on the outer side of the second disc therefore generated an electronic pulse for each $\frac{1}{100}$ of a mile of vehicle travel. The shaft input of this digital tachometer was coupled to the regular speedometer cable of the vehicle by a 1:1 geared "T" at the speedometer head.

The electronic pulses from the speed detecting photoelectric cell were connected to the input of an electronic counter. This counter included a quartz crystal time base and generated usable pulses at $\frac{1}{10}$ -, 1-, and 10-sec intervals. The $\frac{1}{10}$ -sec pulses were used internally to operate the "count" and "stop" gates so that the number of "speed" pulses for any $\frac{1}{10}$ -sec period could be accurately counted. The 1-sec pulses were connected to the control box and used to initiate a recording period. Therefore, at the beginning of each second the electronic counter was reset and the "count" gate opened to accumulate "speed" pulses. One-tenth sec later the "count" gate was closed and a print command recorded the speed of the vehicle and all other data which were available at the recorder inputs.

The electronic pulses from the distance detecting photoelectric cell were connected

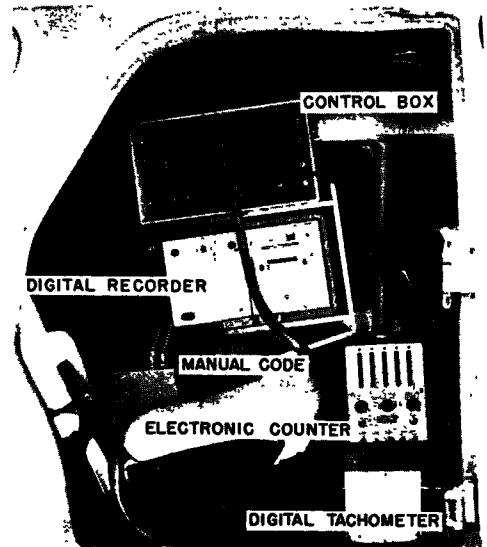


Figure 11. Traffic impedance analyzer.

to 3 decades of electronic counting in the control box where they were accumulated. This distance accumulation was continually available for recording.

The traffic, geometric, control, weather, and other pertinent data could be coded by 2 decades of push buttons which would transfer like digits to the recorder at any

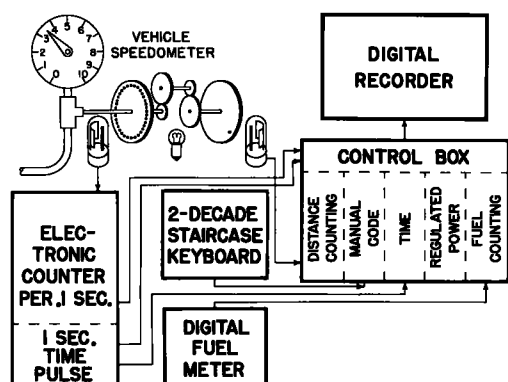


Figure 13. Traffic impedance analyzer.

4 9 7 8 3 2 2 0 8 0 0	
4 9 7 7 3 2 2 0 8 0 3	
4 9 7 6 3 2 2 0 8 0 5	← SPEED
4 9 7 5 3 2 2 0 8 0 6	
4 9 7 4 3 2 2 0 8 0 7	
4 9 7 3 3 2 2 0 8 0 9	— DISTANCE
4 9 7 2 3 2 2 0 8 1 1	
4 9 6 1 3 0 2 0 8 1 4	
4 9 6 0 3 0 2 0 8 1 6	— MANUAL CODE
4 9 6 9 3 0 2 0 7 1 8	
4 9 5 8 3 0 2 0 7 2 1	
4 9 5 7 3 0 2 0 6 2 3	— TIME
4 9 5 6 3 0 2 0 6 2 4	
4 9 5 5 3 0 2 0 5 2 6	
4 9 4 4 6 0 2 0 4 2 7	— FUEL CONSUMPTION
4 9 4 3 6 0 2 0 3 2 8	
4 9 4 2 6 0 2 0 3 3 1	
4 9 4 1 6 0 2 0 2 3 2	
4 9 4 0 6 0 2 0 1 3 3	
4 9 3 9 6 0 2 0 0 3 6	
4 9 3 8 6 0 1 9 9 3 7	
4 9 3 7 6 0 1 9 8 3 8	
4 9 2 6 6 0 1 9 7 4 0	
4 9 2 5 6 0 1 9 6 4 0	

Figure 12. Typical recording.

printing cycle.

One decade of time counting was provided in the control box as a printing sequence check. The circuitry also provided for this to be extended to 4 decades as an alternative to fuel recording when it was more convenient, for field observation, to have elapsed time recorded during speed and delay studies.

A digital fuel meter was mounted between the fuel pump and carburetor. The particular one used in this instance produced an electrical pulse for each $\frac{1}{2000}$ gallon of gasoline passing through it. These pulses were accumulated in 3 decades of electronic counters in the control box so that a total of fuel consumption was available for transfer to the recorder at each print command.

The complete equipment was powered by a 1250-watt gasoline-driven generator weighing 85 lb which was carried on a standard roof mount luggage rack. This self-contained unit well illustrates the advantages of digital recording and the possibilities of adapting a few standard electronic instruments to the myriad data-collecting problems encountered by the highway research engineer.

Fully automatic data reduction can, of course, be realized by adding standard tape punch units to the digital recorders shown here. The punched tape then may be used as a computer input or its data may be automatically transferred to magnetic tape or punch cards as individual cases require. The equipments to accomplish these processes are available to those who may wish to extend their systems to include them; but, for the purpose of this paper, it was felt that a simple introduction to digital recording would better serve the greater number of highway engineers.

Electronic Highways

JOSEPH B. BIDWELL, Head, Engineering Mechanics Department; ALBERT F. WELCH, Head, Electronics-Instrumentation Dept.; and EUGENE A. HANYSZ, Supervisor, Electro-Physical Research, General Motors Research Laboratories

During the past few years considerable work has gone on in a number of laboratories toward devising equipment to automatically control vehicles on highways or to improve the manual control of vehicles through the use of electronic devices. General Motors Research Laboratories has devised an automatic control system for use with mixed automatic and manual vehicles on limited-access highways. A $\frac{1}{40}$ th scale model has been built to demonstrate the guidance, obstacle detection, and speed control functions of this system.

Recognizing the transition problem from manual to automatic control, a number of devices have been considered which will provide the driver of conventional vehicles with some aid during the transition period. A communication system, "Hy-Com," using low frequency magnetic induction can provide road sign and emergency information in carefully localized areas along the highway. In addition, a path error warning device has been built which could also utilize a single wire in the roadway to indicate to the driver when his vehicle deviated beyond a safe amount from the centerline of the road. Both of these devices could utilize signals originating in the road wire, which could also eventually serve as a guidance wire in an automatic highway system.

● DURING the past few years many investigators have proposed using electronic aids and, indeed, completely automatically controlled vehicles as a means of improving safety and highway transportation efficiency. This paper is concerned principally with a discussion of the design philosophy and construction of a $\frac{1}{40}$ th scale model of an automatic highway system applicable to limited-access highways. In addition, it discusses the design and application of a low-frequency induction radio communication system and a path error detector, both of which are complementary to the complete automatic highway system and which may be applied as a preliminary step toward completely automatic control.

GENERAL DESIGN CONSIDERATIONS

It is unnecessary here to discuss in great detail the reasons for devising automatic vehicle control systems. Briefly, these are based on reduced driver

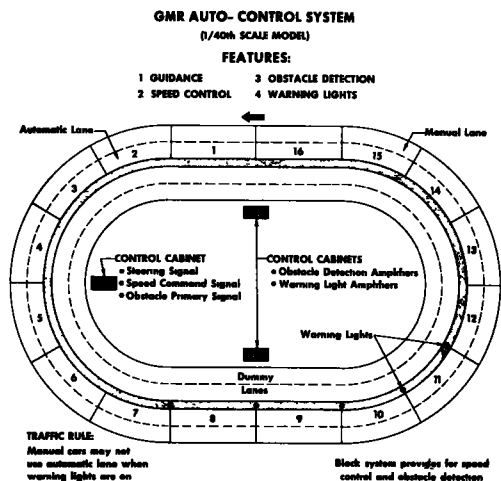


Figure 1. Layout of $\frac{1}{40}$ th scale highway.

effort and improved comfort, potential safety improvement through elimination of driver error, and increase in highway capacity by eliminating driver lags which influence the spacing of vehicles on present roads. In the development of the GMR Auto-Control System, the concern was only with operation of vehicles on a limited-access highway in order to reduce the complexity of the control system. Even such a limited application could prove practical and useful, however, when it is recognized that some 90 percent of inter-city passenger travel is accomplished in private cars. The transition problem is recognized in this design, and therefore the road model was built to accommodate both automatically controlled vehicles and conventional manual cars. Before discussing the details of operation of this highway model, its general physical arrangement is reviewed.

Essential features of the GMR Auto-Control System are embodied in a scale model

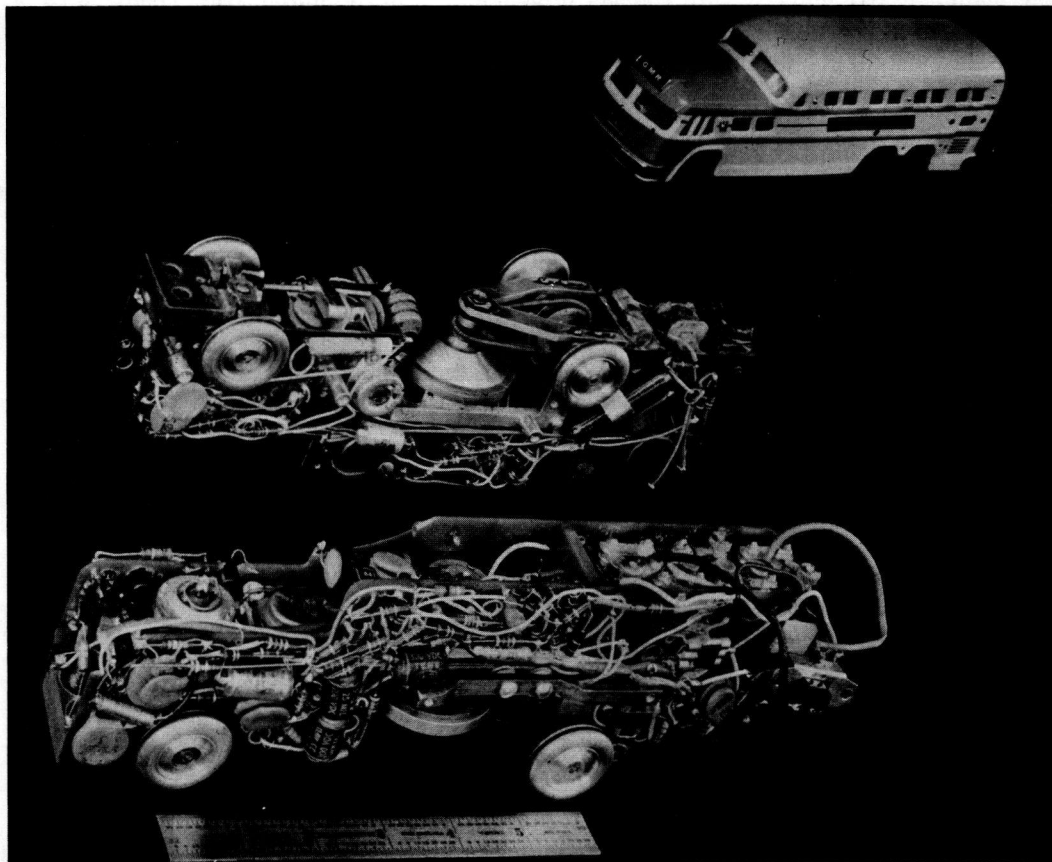


Figure 2. Car-based electronic components.

oval track, approximately 20- by 30-ft over-all, representing a four-lane divided highway. Distances and speeds are $\frac{1}{40}$ th scale. The track is made up of sixteen 5-ft blocks, simulating a stretch of highway $\frac{6}{10}$ ths of a mile long. At $\frac{1}{40}$ th scale, each block represents 200 ft on an actual highway. Suitable wiring is embedded in the blocks to accomplish the various control functions. The general layout of the track is shown in Figure 1. Only the two counterclockwise lanes are equipped for vehicle operation. The right-hand lane has been designated as a manual lane, and the left-hand lane is equipped with sensing and control wiring to provide completely automatic operation of scale model buses. The functions performed automatically consist of:

1. Providing guidance to maintain the proper vehicle path;
2. Detecting obstacles in the automatic control lane;
3. Regulating vehicle speed to prevent collision with other vehicles or obstacles in the automatic control lane; and
4. Providing warning signal lights to control use of the automatic lane as a passing lane for manual cars.

There is clearly a wide variety of means of accomplishing the several functions previously outlined. The particular means adopted for this automatic highway system are considered to be desirable compromises. From the standpoint of ease of transition from manual to automatic control, it would clearly be desirable to have all of the special equipment contained in the car. If neither active nor inactive control equipment were required in the road, vehicles could operate under automatic control on the present road system. On the other hand, there appear to be many shortcomings in such an arrangement, particularly with respect to sensing all of the information required to regulate speed and direction from the vehicle itself. For this reason the control equipment has been divided between the car and the road. In addition, a block system for detection of obstacles and speed control was used rather than a continuous spacing control system for reasons of simplicity and reliability. In fact, a number of design choices involving compromises between reliability and operating efficiency were made in favor of reliability.

MODEL VEHICLES

To provide space for the batteries and electric motors required to drive the vehicles, model buses (Fig. 2) have been used. All of the transistorized electronics sufficient to sense the input signals and provide controls for the power systems of a full-scale car are mounted on two insulating boards which also serve as a frame for the mechanism. An electric torque motor turns the front wheels to provide steering corrections. A silver-zinc battery mounted near the rear supplies power both for the electronics and the drive and steering motors. Additional description of the vehicle details accompanies discussion of the several functions.

STEERING CONTROL

Providing steering control signals from the road is relatively simple. Because the desired path of the car is the same as that of the road, only the position error of the car on the road must be sensed for guidance. The required steering correction can then be determined, taking into account the car response characteristics in order to assure system stability.

The steering control element in the model highway is in the form of a crisscrossed wire that essentially forms two parallel wires embedded in the pavement down the center of the lane. Alternating current of about 50 kc in the wire generates a magnetic field along its entire path. As pointed out in the following section, this same wire is used for speed sensing. The arrangement of all of the control wiring in one block is shown in Figure 3.

Two pickup coils mounted on the underside of the model car straddle the criss-crossed wire. Changes in voltage between the two coils, as determined by their position relative to the cable, automatically adjust the steering mechanism to keep the car on course. Figure 4 shows the various signal pickup coils mounted on the under side of the small model.

This technique is similar to the electromagnetic system demonstrated on a full-size car by GM Research Laboratories in February 1958. In that system, changes in voltage between the two pickup coils were fed into a small electronic analog computer which directed a servo system controlling the car's steering gear. Similar components within the car are envisioned in any future full-scale version of the GMR Auto-Control System (1).

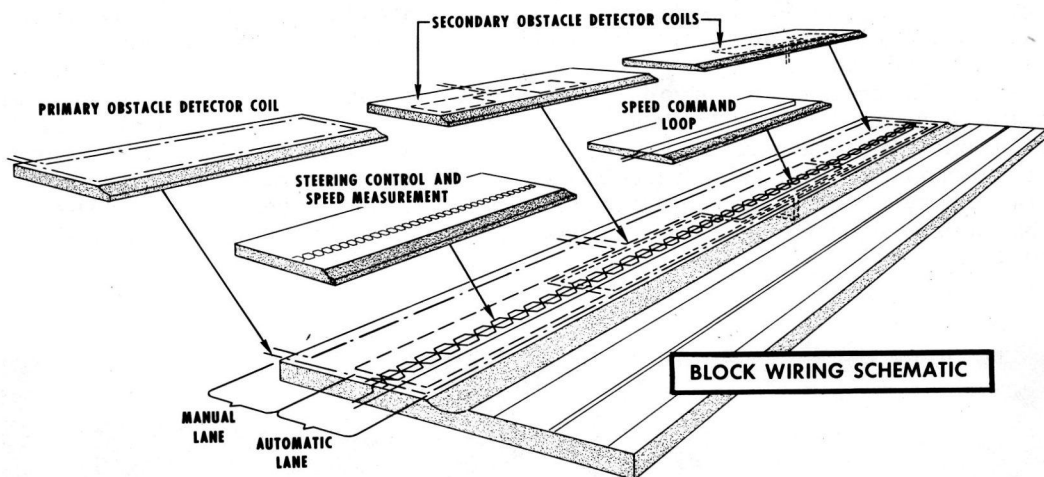
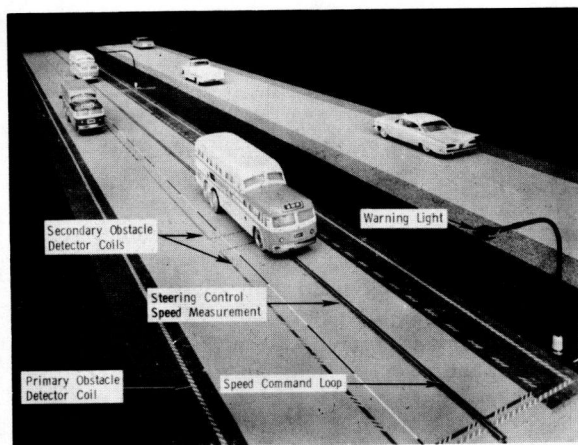


Figure 3. Layout of control wires in one block of the automatic highway.

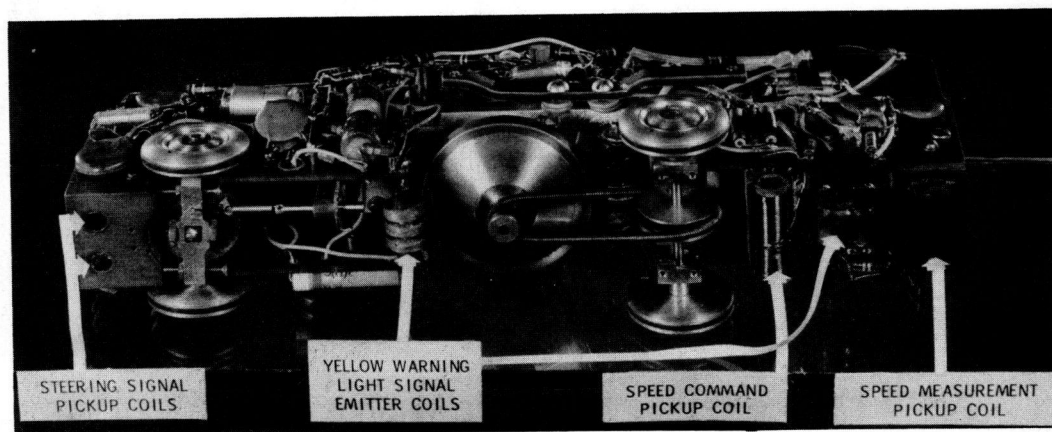


Figure 4. Car-based pickup and emitter coils.

SPEED CONTROL

Rather than permit each vehicle to select its own speed, it was decided that all cars under automatic control should operate at the road speed limit. This eliminates the many passing situations which otherwise develop simplifying the automatic equipment and also prevents delays in the automatic lane due to slow vehicles. Such expeditious handling of automatic traffic is one of the greatest potential virtues of automatic car control.

A scaled top speed of 60 mph was arbitrarily established for the scale vehicles running on the model road. At $\frac{1}{40}$ th scale, however, their actual top speed is only $1\frac{1}{2}$ mph. Provision is also made to automatically impose a 30 mph speed limit or to stop the cars completely under circumstances when 60 mph is unsafe. In a full-scale application, any maximum speed could be selected and varied automatically to compensate for changes in vehicle performance depending on driving conditions, for example, wet pavement, ice, or darkness.

Two basic requirements must be met to provide automatic speed control. These are: precise measurement of the car's actual speed, and a speed command signal telling the car how fast it should be going. Any differential between these two quantities can be used to initiate automatic adjustment of the car's speed through control of accelerator and brakes.

The criss-crossed wire is so installed that its two "branches" cross at equally spaced intervals. The voltage induced in the speed measurement pickup coil on the car (Fig. 3) becomes zero at each crossing of the wire, thus providing a definite marker that can be sensed by a pickup coil and counted. The car measures its own speed precisely by a count of the number of voltage nulls passed per second. The cross spacing is selected so that 1 cycle per sec = 1 mph both in the model and full-scale road.

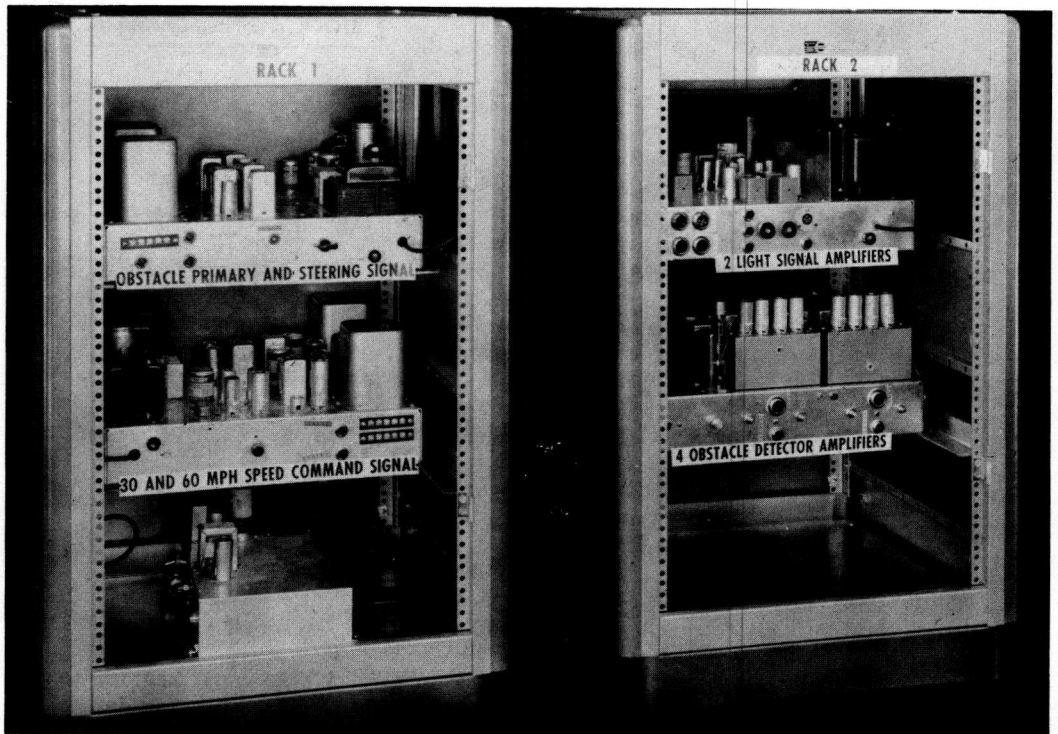


Figure 5. Electronic cabinets for providing signals to the control wires embedded in road.

Another wire, parallel with and centered in the criss-crossed wire, provides a speed command signal that is picked up by another coil on the car. This wire carries a signal of about 90 kc modulated by either of two low frequencies to provide the 60 mph and 30 mph speed command signals. For zero command speed, or "stop," the signal is interrupted. The command speed is determined by the obstacle detectors in adjacent blocks.

If the car's speed is over or under the command speed, an error signal is created proportional to the difference between the frequency of the command speed modulating signal and the number of voltage nulls per second from the criss-crossed wire. The error signal regulates the current to a small electric motor in the model, causing the car's speed to become equal to the road command speed. In a full-size vehicle, this error signal could be used to control the accelerator and brake pedal combination.

The signal frequencies used in the model track are more or less arbitrary values for this particular small-scale application. In a full-scale highway, the actual frequencies used would be dependent on the details of the electronic techniques used.

OBSTACLE DETECTION

The speed and acceleration of individual cars on an automatic highway must be dependent on the position and speed of other vehicles or obstacles on the same road. Therefore, some kind of sensing means is required for determining the relative position and/or speed of other vehicles and objects. It appears that the obstacle detection function must necessarily be part of the road equipment because of certain fundamental limitations in such car-based sensing apparatus as radar, ultrasonics, or infrared (2). The GMR Auto-Control System provides for the electromagnetic detection of vehicles and other metallic objects in the automatic lane only.

Embedded below the surface of each 5-ft block (representing 200 ft on an actual highway) are four obstacle detector coils (secondary) and a larger coil (primary) which encloses the secondary coils (Fig. 3). The four secondary coils are connected in pairs. The two coils in each pair are connected in opposition and are alternately spaced with the two coils of the other pair. Metal objects located in an obstacle detector section have eddy currents induced by the alternating magnetic field produced by the obstacle detector primary coil which is energized with alternating current. This results in a disturbance of the magnetic field through the secondary coil over which the obstacle is located and the resulting unbalance in induced voltage provides a reliable indication of the obstacle whether stationary or moving. The time interval between detection at successive secondaries is also used to give an approximate indication of the speed of the vehicle. Its presence and speed regulate the command speed in following blocks in accord with the following rules.

A car traveling over 30 mph causes a 30 mph (half speed) speed command signal to exist in the first block to the rear and a 60 mph signal in the second block to the rear. A car traveling at 30 mph or below causes a "zero" speed command signal to exist in the first block to the rear and a 30 mph signal in the second block to the rear. Thus, if a car unexpectedly stopped in block 9, for example, the following car would be stopped in block 8, and the next car would be stopped in block 7. If another car were coming up from behind at 60 mph, its speed would be cut to 30 mph in block 5, and it would be stopped in block 6.

To avoid the need for a great deal of road intelligence (with resulting complication) it is proposed that the driver use manual control when fixed obstacles are encountered. The manual lane can be used for getting around the obstacles before resuming automatic operation.

MANUAL CAR OPERATION

In general, drivers of manually controlled cars would drive as usual keeping in the right-hand lane. Their use of the left lane for passing is regulated in the model road by traffic signals which indicate the presence of an automatic car in the immediate vicinity. The warning lights are turned on by a 2 kc signal from a coil on the automatic car to the speed command coil in the road. These lights "travel" along with the car

to warn manual cars in the vicinity that the automatic lane is in use. For example, when an automatic car enters block 8, it turns on the lights in blocks 7, 8, 9, and 10. When it enters block 9, light 7 goes off and light 11 comes on. In an actual installation, one light would be installed for each 200-ft block. The signal lights are used to provide smooth operation in the automatic lane but if a manual car entered against a signal it would be detected as an obstacle and cause following automatic cars to stop.

ROAD ELECTRONICS

The electronic equipment racks used with the road model are shown in Figure 5. These are actually representative of functional full-scale road equipment. No particular attention has been paid to reducing size in this prototype. The two cabinets shown provide all of the road electronics needed for 400 ft (2 block) of controlled road with the exception of the primary guidance signal. This signal can be supplied to many blocks by a single simple oscillator. In a full-scale installation this equipment could be installed below grade and operated from batteries floated on a charger to increase reliability.

RELIABILITY

Practical application of automatic vehicle control depends largely on the ability of engineers to produce both mechanical and electronic equipment with adequate reliability. Unless this is accomplished, attainment of improved safety will not be possible.

Redundancy has been used in the Auto-Control model to increase the steering signal reliability. In addition to the crossed guidance wire signal, the speed command wire may be used for this purpose. In a full-scale installation, automatic switchover could occur in the event of loss of primary system signal.

Protection has also been provided in event of speed command signal failure. Loss of command speed is equivalent to commanding zero speed and vehicles in the affected area stop until manual control is assumed by the driver.

TRANSITION PROBLEMS

One of the most difficult problems with regard to automatic vehicle control is that associated with the transition from the present day manual system. This is a particularly difficult problem if it is necessary to provide some of the control equipment in both the highway and the vehicle. It is clearly not economically feasible to either produce vehicles with automatic control systems or to provide roads equipped for this type of operation unless the other is also available. For this reason, it is necessary to consider the steps which might be taken to finally arrive at a completely automatic system. Consideration of this problem has led to some fairly immediate possible steps in this direction. The following discussion is concerned with two possible immediate uses for the guidance wire necessary in a completely automatic system.

HIGHWAY INFORMATION SYSTEM

Communication of information from the road to the operators of vehicles is presently accomplished primarily through visual senses using signs along the road. This form of communication has a number of shortcomings, particularly under circumstances which limit visibility. For this reason, application of a low-frequency induction radio system for communicating information normally found on roadside signs has been considered, along with additional emergency information. Such a system has many advantages, including the ability to readily change the information to suit current operating conditions, and to provide communication within a controlled area without overloading the driver's visual sense and distracting his attention from his control task.

The system is entirely automatic, delivering a message to the driver regardless of whether the car radio is turned on or not. Messages transmitted by the low-power communication system could be in the form of warnings regarding dangerous driving conditions and speed limits, or they might be of the informative type for announcing freeway exits, unscheduled detours, etc. Such a system is shown schematically in

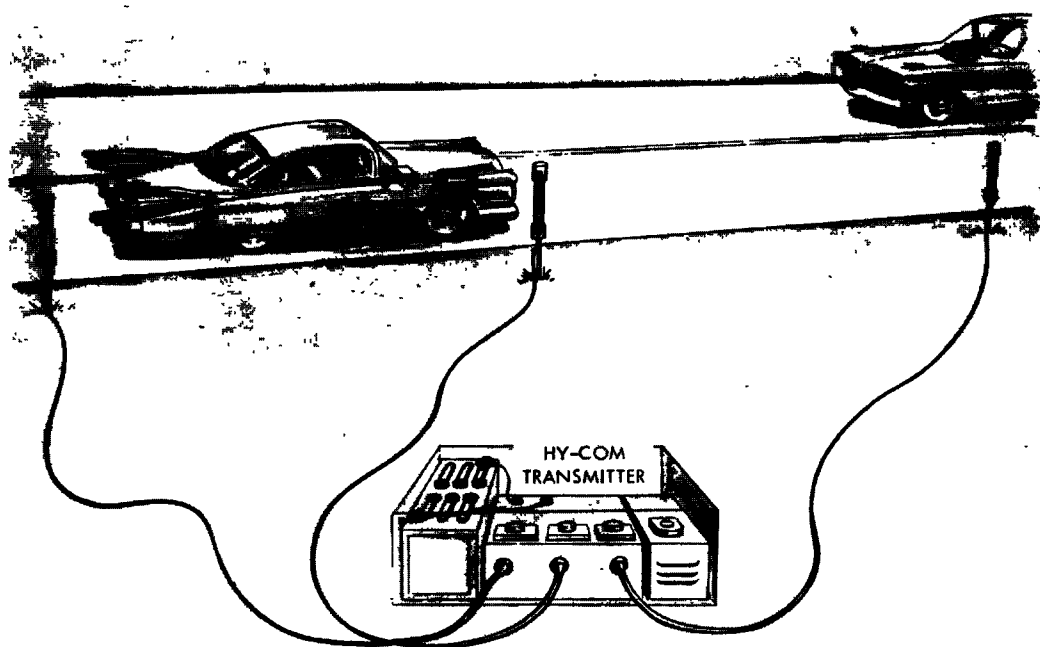


Figure 6. Hy-Com transmitter schematic.

Figure 6. In effect, the system would supplement road signs to give motorists precise instructions relative to the traffic environment, and it would assist police or highway officials in expediting or routing traffic flow.

A unique feature is the voice signal which it is believed would be more effective and flexible than any other type of in-car signal such as buzzers or flashing lights. No array of visual signals would be comprehensive enough to warn a driver of the various emergencies that might arise. A verbal message, on the other hand, could describe any number of situations with instant clarity.

OPERATION

The electromagnetic-induction, low-frequency radio system called Hy-Com, shown in block diagram form in Figure 7, consists of a receiver in the car and a low-frequency transmitter that would be placed alongside the highway. The transistorized transmitter, powered by a 12-volt battery, could be permanently installed above or below ground, or designed as a portable unit for greater application flexibility. A series of individual ferrite core antennas, or a single-loop antenna would be used to cover 300 to 500 ft of roadway. To avoid interference with the many other existing radio communications, the system operates in the 10-20 kilocycle range. And further, by utilizing induction fields instead of radiation, it permits laying down a known and controlled radiation pattern, thereby precluding interference to other services or between adjacent transmitters.

Voice messages can originate from such sources as tape messages repeaters, on-the-spot announcements from microphones, or from a master control station using existing telephone lines. In addition, a coded tone generator could be used to operate automatic warning devices in the vehicle.

Transistors and ferrite loops make possible small, compact transmitter and receiver units. The simple low-frequency receiver may be self-contained and is some-

what less complicated than a car radio. The single-channel, fixed-tuned device uses the standard car radio power amplifier and speaker. The fixed tuned feature insures reception of Hy-Com messages wherever the system is in operation because transmitter frequencies are all the same and not indigenous to locale.

If the radio is operating, the message interrupts the program and the standard broadcast is muted momentarily during the message interval. After the message has been delivered, the standard broadcast is automatically switched back on. When the radio

is not turned on, the transmitter signal automatically turns on the car radio transistorized output stage. In the case of a nontransistorized radio, an adapter plug between the radio and speaker permits interruption of the standard broadcast program. General acceptance of the system would dictate that the receiver be incorporated into the standard car radio.

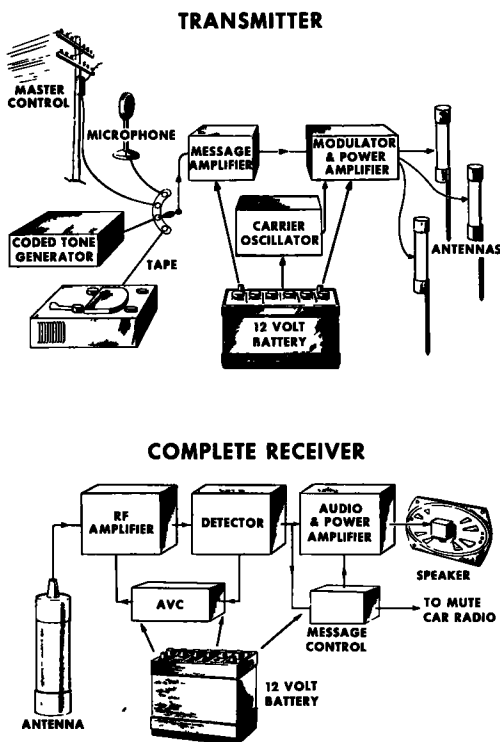


Figure 7. Hy-Com transmitter and complete receiver.

information in manually controlled cars, called "Electro Lane," has already received some development and promises to be a useful adjunct to car instrumentation. This simple device signals a driver when he approaches within a pre-set distance of the edge of a lane or road. It is expected that such a warning would be useful in reducing the large number of single car accidents which occur when driver inattention leads to vehicles leaving their correct lane. In addition, Electro Lane can supplement driver vision under poor visibility conditions and enable a driver to "ride the edge of a lane" at very low speeds.

A prototype of this equipment has been designed to use magnetic path definition of the same type provided by the guidance wire and sensing coils used to provide automatic guidance both in the auto control model and in full-scale cars. This apparatus can be readily installed on existing vehicles and, in fact, can be designed for temporary attachment to existing cars operated on roads equipped with the required guidance wire. This wire may be installed in existing toll roads and turnpikes at nominal cost or may be incorporated readily in new construction. In existing roads the path error wire may be

EDGE OF ROAD DETECTOR

Although much work has been done on both components and systems for electronically controlled automatic highways, such roads are undoubtedly relatively far in the future for both technological and other reasons. It seems likely that various devices designed to help the driver better perform his control task will precede completely automatic control systems.

One such device, to provide path error

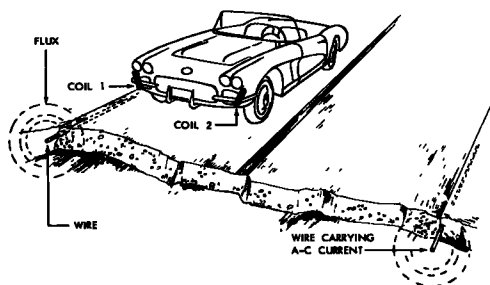


Figure 8. Electro Lane.

installed either in a diamond saw cut in the center of each lane or even lower installation costs may be achieved by using wires installed along the road side.

When a wire is used in the center of each lane, path deviation to the right or left may be indicated by mounting two independent detector systems in the front of the vehicle in a manner similar to that used for automatic guidance. If wires are used outside the road lanes, on multi-lane roads, it is not possible to detect the division between the two lanes but the road extremities could be indicated as shown in Figure 8. The wires shown are parts of a large loop which could be of the order of 1 mi in length. The loop carries an audio frequency current which induces a circular magnetic field around each of the wires. Motion of the vehicle toward either edge results in an increase in the amplitude of the signal detected by the ferrite cored coil nearest the road edge. When this signal reaches a predetermined value corresponding to a particular distance from the edge of the road, a relay is activated to energize a buzzer, light, or other indicating device. The right and left channels are independent. The warning system in the vehicle must be constructed so as to cause an instinctively correct response of the driver. For example, it might be desirable to locate a buzzer indicating too close approach to the left-hand side of the lane in the left-hand side of the passenger compartment. Similarly, the right-hand error signal could appear in the right-hand side of the compartment. Thus the driver would be required to steer away from the indicator. The specific arrangement of the detector coils on the front bumper will be determined by the type of guidance wire provided and by the variation in path which may be permitted. Figure 9 is a block diagram of one of the channels used in the Electro Lane system. The pickup coil is tuned to the road wire frequency. The amplifier is a simple 4-transistor device. The amplified signal magnitude is compared with a reference voltage to provide an accurate signal actuation level.

An additional application of this warning system would appear to be useful on turn-

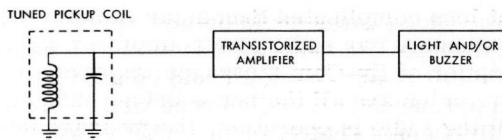


Figure 9. Block diagram of one of the channels used in Electro Lane system.

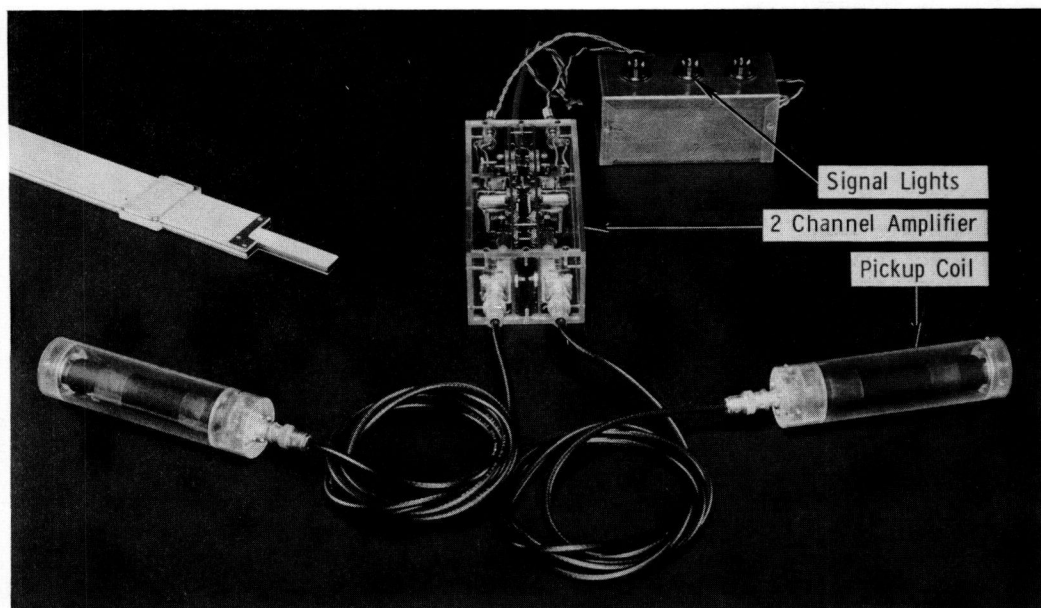


Figure 10. Prototype of Electro Lane system.

pikes. Road wires could be laid crossing the lanes at approaches to toll booths to alert drivers. In fact, the use of such a path error device seems particularly applicable to toll roads where it could be used as a "hang-on" piece of equipment to cooperate with permanently installed road wiring in much the same manner as has been proposed for Hy-Com. Figure 10 is a photograph of prototype Electro Lane equipment which would be suitable for such an application.

CONCLUSION

Although many problems, both technical and non-technical, must be solved before reliable automatic highways can come into general use, the GMR Auto-Control System does illustrate one potentially usable concept. The division of equipment between car and road seems most practical and limitation to operation on controlled-access roads permits retention of reasonable simplicity.

For the immediate future it is possible to utilize a wire in the center of each lane, both for communication to moving cars and in connection with a path error warning system. Hy-Com can make driving simpler and safer by providing audible speed, traffic, and emergency messages to the driver. This system has been further developed by the Delco Radio Division of General Motors. While retaining driver control, Electro Lane can provide a warning to the inattentive operator and help prevent some of the large number of single car accidents.

Both Hy-Com and Electro Lane are particularly appealing for use by toll facilities because they could be readily attached to vehicles using this facility, and can provide road information and path error warning with only a modest amount of road installed equipment.

REFERENCES

1. Bidwell, J. B., "How Will Future Motor Cars Affect Highway Construction?" SAE 1958 Summer Meeting, Atlantic City, N.J. (1958).
2. Bidwell, J. B., "Vehicles and Drivers - 1980." SAE Annual Meeting, Detroit, Mich. (Jan. 13, 1959).

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY-COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.
