Development of a Vehicle Simulator for Evaluating Driver Performance

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• THE MOST desirable approach for assessing the performance of special subgroups of the driving population is to measure behavior while operating within a controlled road-vehicle system. However, the expense, time consumption, complexity, and inherent risks involved suggest more conservative procedures before the highway system is utilized. A practical approach to the study of the problem is to obtain fundamental data in the laboratory with such instruments as universal mock-up devices or simulators. This paper is a summary description of the mechanical, electro-mechanical, tracking and data-computation features of such a simulator developed at the Harvard School of Public Health.

The fundamental design criteria for the simulator are (a) dimensional duplication of vehicle cab interiors, and (b) adequate adjustability range to insure operator comfort. The driver testing procedure must provide experimental task requirements that emphasize biomechanical activity. A study of commercial vehicle cab interiors produced by five major manufacturers indicated insignificant dimensional changes between 1956 and 1960 models. Data previously accumulated by Harvard School of Public Health were therefore considered a valid basis for simulator design (1, 2).

A survey of the human engineering man-machine control system literature led to the adoption of a central, continuous tracking task requiring steering wheel manipulation. A series of pilot studies were conducted at Massachusetts Institute of Technology with Sheridan's (3) apparatus in order to gain familiarization with tracking techniques and methodology. In addition, the studies developed the necessary data for the specification of the equipment components of the proposed simulator.

MECHANICAL FEATURES

The four components (seat, dash panel, pedals, and steering mechanism) of the mock-up were designed and fabricated independently. Each separate component required three physical properties: (a) functional duplication of the truck cab counterpart, (b) remote and/or direct adjustability of the displacements and forces required for activation of control devices, and (c) translational and appropriate angular adjustability. The housing framework was designed contingent on the requirements of each component. Thus, the support structure is spatially compatible with the proper constraint of movable components.

A reference dimension that properly orients each component was established. All ranges of adjustability are measured with respect to the reference values. The referents are equivalent to the optimal dimensions recommended in the data accumulated by Harvard School of Public Health in Table 1. The mock-up interior can, therefore, be arranged to meet the dimensional requirements of a large range of body configurations and can functionally simulate the interior of commercial vehicles.

The degrees of dimensional adjustability of each component, relative to the steering wheel, are given in Table 1.

Seat Mechanism

The seat is a 6-way power unit which was donated for the project by Chrysler Corporation (Figs. 1 through 7). The operator has control of seat position within ranges of 5 in. longitudinally, 2 in. vertically, and 15° rotation about a transverse axis.

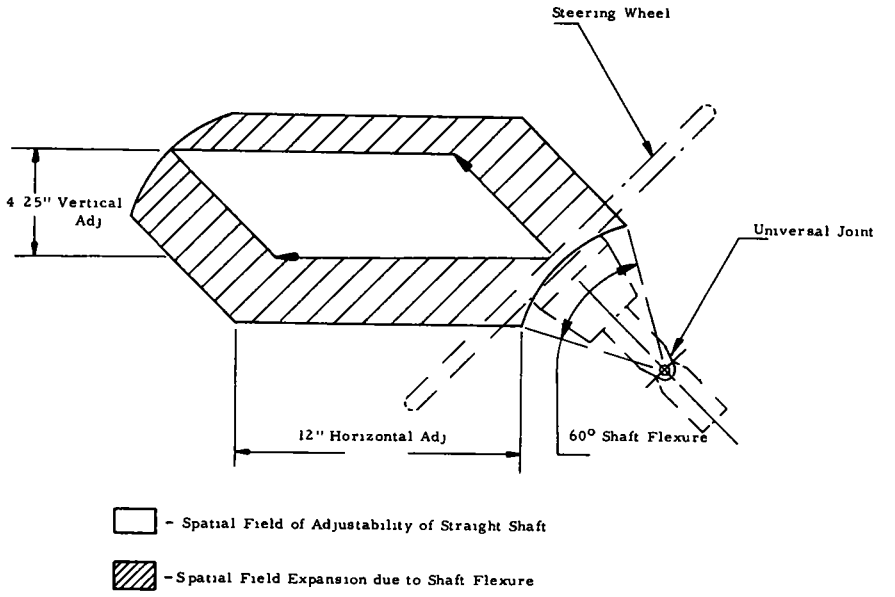

Figure 1. Steering wheel adjustability relative to lowest forward position.

This electrically-powered unit is mounted on a platform that can be moved longitudinally and vertically through ranges of 9 in. and 6 in., respectively. The platform is elevated by a hand-operated pump hydraulically coupled to a power cylinder. The rate of descent of the platform is controlled by throttling the high pressure fluid through a control valve. Longitudinal movement is provided manually through a rack and pinion transmission. The seat platform rests on ball bearing tracks and is driven fore or aft by cranking the pinion anchored to the simulator frame. This arrangement provides for coarse adjustments remotely controlled by the experimenter. Figure 3 shows the seat platform elevated exposing the fine adjustment mechanism of the seat assembly.

Instrument Panel

The variation existing in the instrument panels of commercial vehicles is extensive. Configuration, size, angle, dial clusters, and switching devices vary among manufacturers. The functional differences among manufacturers to be accounted for in the simulator are the relative positions of instrument panel components, accessibility of controls, and the biomechanical mode of manipulation.

Trucks of similar classification that are produced by different manufacturers utilize unlike instrument panel elements for regulating the same control functions. A stockpile of dials, switches, and gauges were accumulated. Interchangeable instrument panels are fabricated to duplicate as many commercial vehicle panels as necessary. Figure 2 shows one instrument panel layout as it appears in the completed simulator.

The frame supporting the instrument panel has two degrees of freedom: (a) rotation about a transverse axis through 40^{0} from vertical, and (b) 12 in. longitudinal translation. These motions are toward or away from the operator.

Floor-Mounted Hand Controls

The lack of standardization of hand brake and shift lever design and location among vehicle manufacturers is compensated for in the simulator.

Shift Mechanism. — The shift mechanism provides for interchangeability of shift levers and variation in operating position. A conventional H-pattern defines the geometric path traversed by the lever knob during a shift sequence. The task required of the subject is to manipulate the lever in a prescribed order to the terminal points of

Figure 2. Frontal view of simulator interior.

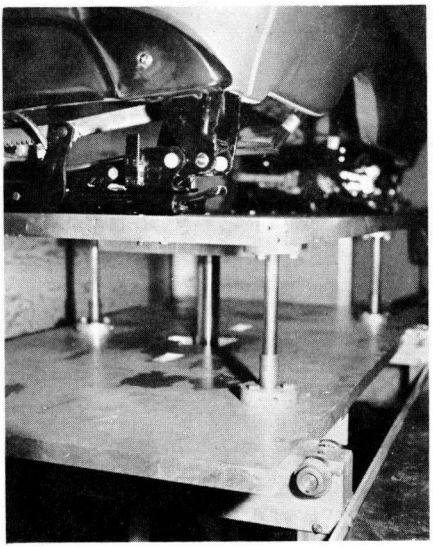

Figure 3. Lateral view of seat mechanism.

the shifting pattern. A wide range of force factors are provided to tax the motor capacity of the operator.

The difficulty in manipulating this device is considered a function of the dimensional limits of lever displacement and the mechanical impedance of the lever but is not necessarily a function of the number of shift poistions. Therefore, the four-position H-pattern was adopted for simplicity. Further, the task required may be any number of movements through any of the possibilities offered by the H-pattern. A control for low and high range may be inserted when required on either lever or push-button form.

Hand Brake.—A generalized mounting bracket designed to accommodate the brake types may be positioned for operation at several alternative locations. Hand brakes have been classified according to four basic types of release mechanisms: (a) rabbit ear grip, (b) pistol grip, (c) button release, and (d) toggle. Specimens of each type

TABLE 1

SPATIAL DIMENSIONS OF CAB SIMULATOR

Variable	Range in Simulator[a]	1956 Commercial Vehicle Variations	Recommendations (1)	Range Civilian Driver Body-Sizing Data
Instrument panel angle (°)	90 - 150	90 - 130	None	None
Seat depth (in.)	18[b] Min.	15.5 - 21.75	18 - 20	—[c]
Seat back height (in.)	22[b] Min.	17.5 - 21.0	18 - 20	20.8 - 26.4 Trunk Ht.
Fore and aft seat adjustment (in.)	14	0.00 - 6.00	6.00	21.3 - 27.6 Knee Ht. 19.3 - 26.0 Butt-Knee Lgth.
Vertical seat adjustment (in.)	10	0.00 - 3.36	4.00	26.4 - 32.9 Norm. Sitting Eye Ht. Abdom.
Seat back to lower edge of s/w horiz. distance (in.)	14 - 28	9.26 - 16.25	12 - 13	6.68 - 13.76 Depth
Vertical distance floor to lower edge of s/w (in.)	20 - 38	20.5 - 27.00	24.5 Min.	19.3 - 26.0 Knee Ht.
Height of seat above floor (in.)	12 - 30	13.5 - 17.75	15 Max.	—[d]
Steering wheel angle (°)	15 - 75	20.5 - 55.0	42.5 - 48.2	45.5[e]
Lower edge of s/w to brake pedal (in.)	18 - 35	19.25 - 30.5	26 Min.	19.3 - 26.3 Knee Ht.
Lower edge of s/w to clutch pedal (in.)	18 - 35	17.0 - 27.6	26 Min.	19.3 - 26.0 Knee Ht.

[a] Dimensions of simulator relative to steering wheel fixed in lowest-forward position (see Fig. 1—s/w range).
[b] Seat depth and seat back height may be altered with cushions.
[c] Buttock-calf distances not taken on commercial driver series by McFarland et al. (1). Comparisons with group of males measured by Hooten in "A Survey of Seating" show this dimension will approximate 17.5 in. for the 5th percentile driver.
[d] Not taken on commercial driver series by McFarland et al. (1). Comparisons with other groups indicate it to be slightly over 17.50 in. (including shoes), suggesting a seat height of 16.50 in.
[e] Kephart and Dunlap (2).

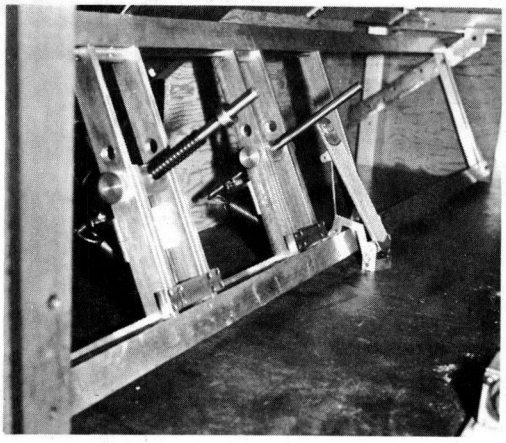

Figure 4. Lateral view of foot pedal arrangement.

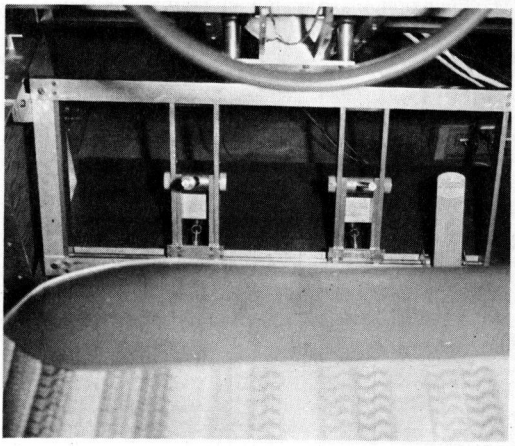

Figure 5. Frontal view of foot pedal arrangement.

have been accumulated. The force required for engaging and releasing levers can be altered by interchanging extension springs of varied force deflection ratios.

Foot-Operated Controls

The foot-operated controls in the simulator are (a) brake, (b) clutch, and (c) accelerator. The clutch and brake elements are similar to one another in construction. Each unit consists of a pedal, shaft, and gimbaled bearing, supported by a carriage. The carriage is mounted in a frame allowing lateral displacement. The frame extends across the cab and forms an integral part of the toe pan at floor level. Various angular and longitudinal positions of the frame are made possible by locking clamps. This type arrangement permits three degrees of freedom for the brake and clutch pedals independent

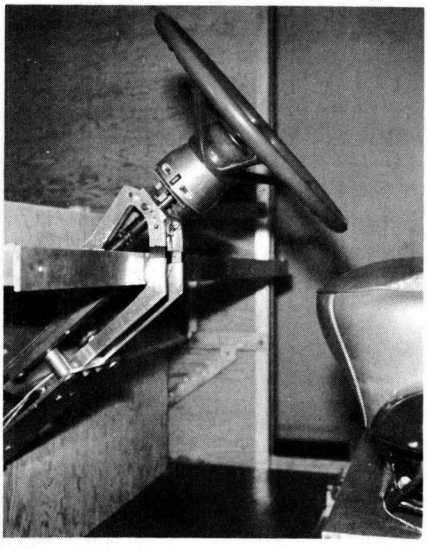

Figure 6. Lateral view of steering wheel mechanism.

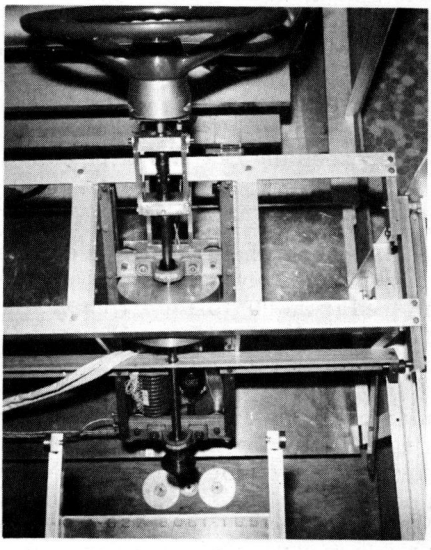

Figure 7. Frontal view of steering wheel mechanism.

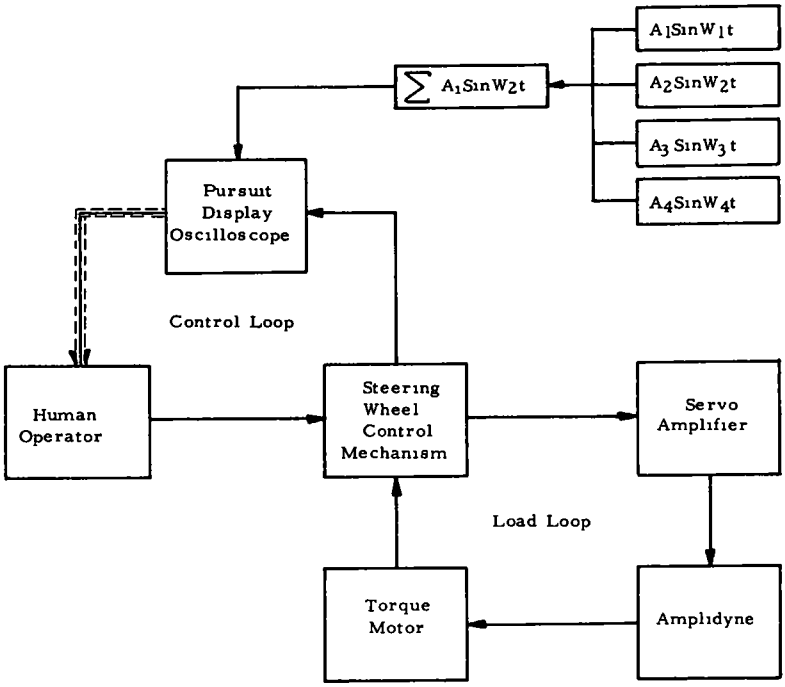

Figure 8. Schematic diagram of tracking apparatus.

of the frame movements. The entire assembly may move in two degrees of freedom.

A perforated aluminum plate fastened to the face of the frame serves two purposes: (a) it provides a backstop for pedal depression and (b) it acts as a toe pan which defines the forward limit of the below instrument panel cab space. Figures 4 and 5 show the assembly with the pedals and toe pan plate removed, to allow better viewing of the assembly.

The clutch, brake, and accelerator pedals are loaded with interchangeable springs that can provide a wide range of force factors. During depression of the brake and clutch the operator experiences two distinct phases. The initial movement of the pedal is opposed by light spring force which is followed by relatively heavy resistance for the remainder of the stroke. This is accomplished by arranging dual springs such that both are compressed only after a predetermined increment of pedal motion. This feature increases the realism of pedal action.

Steering Mechanism

The steering wheel has three degrees of freedom. The shaft may telescope 6 in., the entire assembly moves fore and aft over a 12-in. range, and the wheel angle may be altered from 90^0 to 150^0 from vertical.

The steering wheel is an 18-in. diameter standard International Harvester model. To make the wheel angle variable a universal joint was inserted into the shaft 8 in. from the steering wheel. This allows the steering wheel to be locked in any of seven angular positions ranging between 90^0 and 150^0. The mechanical arrangement for locking the steering wheel in these positions is shown in Figure 6.

A truss-like frame supports the steering assembly at an angle of 45^0. This inclination of the steering assembly approximates the optimum value recommended by Kephart and Dunlap. The frame and steering assembly are supported within the simulator by ball bearing rollers running on tracks placed on the simulator super-structure. This allows the entire steering assembly to be moved fore and aft through a range of 12 in. Figures 6 and 7 show lateral and plane views of the steering apparatus.

The steering shaft is supported by two self-aligning pillow blocks mounted 14 in. apart. The pillow blocks are attached to a framework, which is supported on axial thrust bearings running in lateral tracks. By means of a rack and pinion arrangement the steering unit can be moved 6 in. in a direction parallel to the steering shaft. This action effectively telescopes or extends the steering wheel.

The degrees of adjustment (the 6-in. telescopic action of the steering shaft relative to the frame, the 12-in. fore and aft translation, and the 60^0 flexure of the shaft) are sufficient to duplicate the steering wheel orientation of existing commercial vehicles.

Force factors are simulated by a torque motor coupled to the steering shaft. This allows simulation of forces encountered in actual driving situations. The system that regulates the steering dynamics consists of several electromechanical transducers housed in the steering wheel assembly. These devices appear in the lower part of Figure 7.

Mechanical driver aids, designed for persons with various degrees of physical handicap, have been donated by several manufacturers of this type of equipment. The equipment represents various designs of unknown efficiency and reliability. Each may be installed in the simulator and tested against performance without such equipment, or against the other alternative designs.

ELECTROMECHANICAL FEATURES

Evaluation of operator performance requires the measurement of (a) displacement, velocity, and torque applied to the steering wheel; (b) forces applied to the brake and clutch pedals; and (c) response time to complete manipulative tasks. Measurements are made with various electromechanical transducers. Position of the wheel is measured by a direct coupled potentiometer. Velocity and direction of rotation is proportional to the output of a DC tachometer generator. Applied torque is determined by a strain gage bridge mounted between the steering wheel and shaft.

Electrical signals from the transducers are fed into a computer, analyzer, and/or recorder.

The potentiometer and tachometer generator are driven by the steering shaft through a gear chain. A set of change gears provide steering shaft-to-transducer displacement ratios of 1:2, 1:1, and 2:1, mechanically altering the sensitivity of these elements.

The instantaneous forces applied to brake and clutch pedals are measured by strain gage-equipped load cells mounted directly beneath the pedal surface. The load cells measure applied force as a function of the output of a semiconductor strain gage bonded to a steel diaphragm. The gage acts as one leg of a conventional bridge circuit that is unbalanced when a force-induced strain exists in the diaphragm.

Response time will be recorded for all foot- and hand-operated devices.

Manipulation of these devices will activate microswitches connected to a 20-channel event recorder. The stimulus signals are also recorded.

A two-variable "pursuit" display is used, one variable representing the input (or desired output) and the other representing the actual output of the system. These variables are displayed on a dual-beam oscilloscope in the form of a dot (target) and a line (integrated operator output). Visual representation of the sum of four nonharmonically related sinusoids insures a random appearing motion of the target dot. The operator responds by manipulating the steering wheel which moves the vertical line at a rate proportional to the steering wheel displacement.

The tracking system devised for the laboratory is shown in Figure 8. Detailed information concerning the tracking system will be available in future publications.

Simulated inertia, stiffness, and damping (input impedance) of the steering system are controlled by the torque motor. Power is obtained from a servo-amplifier and amplidyne. The output from the potentiometer and tachometer are the inputs to the servo-amplifier. Simulated impedance can be varied by altering coefficients of the servo-amplifier.

To simulate greater steering wheel impedance than the torque motor can produce, a mechanical system of springs and weights has been added. Despite a slight loss of flexibility the resultant combined mechanical and electrical system provides greater range and accuracy of system response.

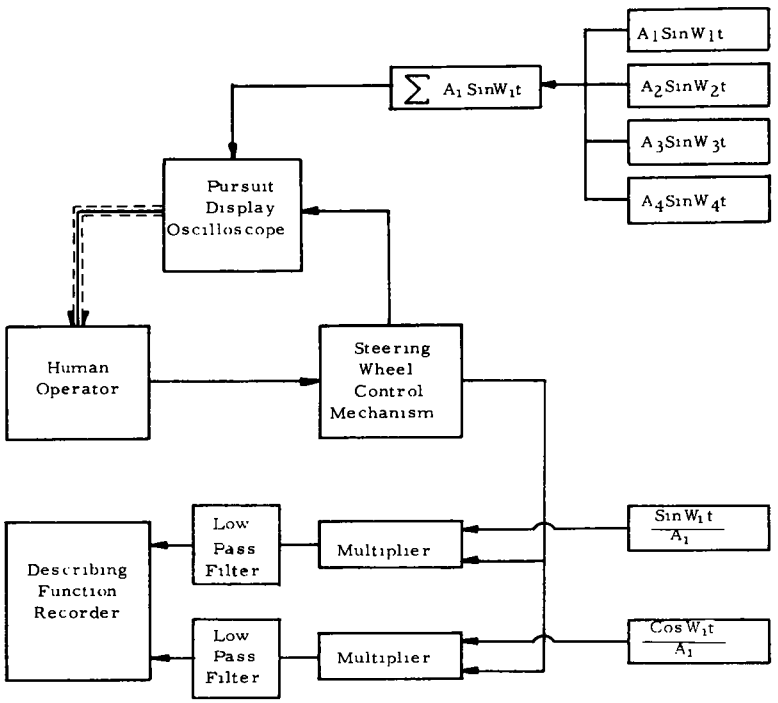

Figure 9. Schematic diagram of computation system for derivation of operator describing function.

A variety of disturbances can be superimposed on the torque motor input to simulate steering wheel shimmy or sudden wheel displacement. The operator can be made to experience kinesthetic stimuli characteristic of adverse road conditions, blowouts, and/or misaligned or unbalanced wheels.

DATA COMPUTATION

The description of human continuous control performance in servomechanism terminology has proven to be a powerful methodological technique. Consequently, time-varying mathematical-describing functions are continuously computed from the tracking data. In addition, conventional "error" scores will be computed. The combination of these performance measures will empirically define the operator's tracking behavior.

The electronic computation system developed for the derivation of operator describing functions is a modification and elaboration of Sheridan's apparatus which utilizes the orthogonal input multiplication method. A detailed description of the theory and techniques associated with this method is available in publications by Sheridan (3) and Briggs (4). Figure 9 shows the electronic system used in the simulator.

In principle, the output signals of the steering shaft potentiometer are multiplied by sine and cosine functions corresponding to the frequency components of the tracking display target. These products are then fed through a low-pass filter. The output of the low-pass filter is comprised of the orthogonal components of a vector which in turn specifies the operator gain and phase characteristics for each frequency. These performance parameters are continuously recorded and may be conveniently represented by a Nyquist or Bode diagram.

Standard statistical techniques are used to compare driver performance among individual subjects and between control and experimental groups under equivalent task complexity. Digital computers are used for the mathematical analyses.

ACCESSORY EQUIPMENT

Additional equipment useful in vehicle operator research projects is included in this section of the report:

Torque-Measuring Steering Apparatus

A second steering wheel and shaft assembly will be mounted on the right side of the operator's cockpit. This assembly will be rigidly anchored at the far end of the shaft on which is affixed a transducer. Thus, torque applied to the wheel can be directly measured by sending the transducer output to a torque meter which can be read directly. This apparatus was constructed because it was felt that an initial estimate of at least maximum, transient, human upper extremity output was necessary as a strength-of-response referent. The torque-measuring steering wheel is to be placed in the cab merely as an experimental convenience.

Enclosure and Shielding

Certain studies will require control over a wide range of environmental factors such as temperature, noise, illumination, interference from stray electrical fields and static, and general movement of personnel in and around the experimental situation. To control these kinds of variables at least partially, the entire mechanical apparatus is encased in detachable plywood panels, in turn shielded with overlapping aluminum screens. These precautions alone extend the range of potential use of the experimental facility.

Research Vehicle

General Motors Corporation has loaned for an indefinite period a Chevrolet station wagon. This has been instrumented to enable measuring responses to the steering wheel, and to brake, clutch, and accelerator pedals. There is a special detachable steering wheel that can be clamped into position that allows measuring torque. All data are recorded with a Mnemotron tape recorder. The tape data are then filtered through channel selectors, amplified, and recorded on continuous graph paper as visible. This equipment permits bridging the gap between laboratory and "real world" studies, at least to a degree.

Auxiliary Equipment

Certain commercial components were donated to the project by Chrysler Corporation, International Harvester Company, and Mack Trucks, Inc. In addition, manufacturers of handicapped driver aids who have donated their equipment for research are as follows:

Brake Center, Inc., Long Island City, N.Y.
Car Hand Controls, Garland, Tex.
Drive Master Corporation, Montclair, N.J.
Gresham Driving Aids, Detroit, Mich.
Holland Porter, North Long Beach, Calif.
Kroepke Manufacturing Company, New York, N.Y.
Leverage Hand-Brake Company, Fargo, N.D.
(donated two models, operating on two different principles)
Oldsmobile, Lansing, Mich.
Simdrico Corporation, Louisville, Ky.
Wells-Engberg Company, Rockford, Ill.

SUMMARY

The simulator may be considered a general human operator control laboratory. With minor modifications the apparatus can be made to accommodate a wide variety of technical human factors research problems. Studies need not be limited to vehicular control research, but may be designed to encompass a large area of the psychomotor and biomechanical behavior of the human operator.

ACKNOWLEDGMENTS

The project engineers who have designed and constructed the simulator are Donald Paterson, Thomas J. Crowley, and Benjamin C. Duggar. The electronic technician was Gervase R. Tinsley.

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