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CONTENTS

FOREWORD

How do drivers under varying stress conditions react to differing roadway and traffic conditions? Answers to this question could have considerable impact on driver improvement programs including development of more realistic driving simulation systems. All the papers in this RECORD deal with studies designed to advance the state of understanding of driver behavior and should be of benefit to educators, researchers, and driver-improvement specialists.

Helander reports on his study of physiological measurements on test drivers in real-world situations where vehicle and traffic variables were also recorded. A computer was used to develop and compare response profiles, which indicated significant covariations between physiological variables and both vehicle variables and road characteristics. A theoretical model for some of the driver-vehicle-environment interactions is proposed.

Different driving maneuvers impose varying amounts of tracking work load on drivers. McDonald and Ellis used several subjects in a specially equipped test car to measure driver work load under various steering maneuvers at varying speeds in a test track setting. The work-load data are expected to be useful in developing a simulation of the driving task.

Sewell and Perratt describe a data acquisition system developed for a test car to study driver performance in real traffic situations in which the driver is under varying stresses. A major goal in developing the data gathering system was to avoid imposition of physical or mental constraints on test drivers to the fullest extent possible. The car has been used successfully in at least four studies on such subjects as night driving and alcohol and drug impairment.

PHYSIOLOGICAL REACTIONS OF DRIVERS AS INDICATORS OF ROAD TRAFFIC DEMAND

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Sixty drivers, all accustomed to a certain make of car, performed test drives along a certain test road. A digital tape recorder was used for real-time recording of the driver's physiological characteristics (electrodermal response, heart rate, and muscle activity), steering, and braking; the vehicle response (accelerations in three directions, velocity, and distance traveled); and traffic events as coded by the experimenter. The characteristics of the test road were measured in the field. Average responses were calculated for the test road, and significant covariations were demonstrated by using the physiological measures as the dependent variable and vehicle behavior on the road as the independent variable. It was also found that the difficulty of a traffic event affects both the driver's brake use and physiological responses. Stress-inducing road characteristics are downhill grades and short sight distances. It is suggested that the driver's capacity to process information varies flexibly as task demand changes. Sudden increases in task demand can be leveled out by modeling the road environment, and this makes the driver more competent at dealing with hazardous situations.

•FEW ergonomic principles are used in highway design. The use of transition curves and consequences of drivers' reaction time in choosing curve radii predominate as rules of thumb, although the validity of these rules has been questioned. This study tries to evaluate the relative influence of different design elements and traffic events on some aspects of driver behavior. Such knowledge is essential for developing more valid principles of road design.

Following is a list of variables and their definitions that are used. An extra A in front of certain abbreviations, e.g., AACCX, indicates that an absolute value of the variable is considered.

- EDR = electrodermal response;
- EDRC = conventional EDR;
- EDRT = normalized EDR;
- HR = heart rate, beats/min;
- EMG = electromyographic measure of muscle tension;
- EMGAS = EMG of the anterior superior muscle, normalized;
- EMGTA = EMG of the tibialis anterior muscle, normalized;
- VEL = velocity, km/h;
- KEYB = keyboard, traffic events description;
- ACCX = longitudinal acceleration;
- ACCY = lateral acceleration;
- ACCZ = vertical acceleration;
- STWA = steering wheel angle;

Publication of this paper sponsored by Committee on Road User Characteristics.

BRAKE = brake pressure;
PPV = psychophysiological variable of the driver;
CRR = connecting roads right side, width, m;
CRL = connecting roads left side, width, m;
PAR = parking area right side, length, m;
PAL = parking area left side, length, m;
SWR = shoulder width right side, m;
SWL = shoulder width left side, m;
RW = road width, m;
SQ = surface quality, scale 1 to 4 (best = 1);
SPL = speed limit, km/h;
SDF = sight distance forward, m;
SDB = sight distance backward, m;
SOR = distance to side obstacle on right, <5 m;
SOL = distance to side obstacle on left, <5 m;
CSOR = distance to continuous side obstacles on right, <5 m;
CSOL = distance to continuous side obstacles on left, <5 m;
HOR = horizontal radius, m;
GRA = gradient, positive when uphill grade, percent;
ACSL = accumulated value of change in slope/100 m;
SEL = superelevation, percent;
SCA = single-car accidents;
OA = other accidents;
SCAF = single-car accidents, forward (in the direction of the test car); and
ACC = accidents, all categories.

DRIVER ACTIVATION LEVEL

One way to find out how drivers process information is to use indirect evidence of the nervous adaptation. Duffy (1) presents the concept of activation level and regards it as a suitable index of behavioral intensity. (A conceptually more narrow synonym is arousal level.) A low activation level implies a low performance level, a moderate level implies a high performance level, and a high activation level because of an overflow of the information processing system implies a collapse of the integrative functions that govern behavior. The level of performance is also influenced by other factors (2, 3). Figure 1 shows that the difficulty of the task affects the relationship.

The average driver strives for optimal conditions, and, if he is not stimulated enough by normal driving, he may seek stimulation by speeding, by listening to the radio, or by engaging in conversation. The left part of the curves (Fig. 1) that corresponds to underarousal is therefore, to a large extent, self-regulating.

From a high level of activation in traffic, we may consequently infer an increased probability that the quality of driving performance will become inadequate.

The level of activation is indicated by fluctuations in the activity of the sympathetic division (SNS) and the parasympathetic division (PNS) of the autonomous nervous system. An increase of activity in SNS causes skin conductivity to increase, pupils of the eyes to dilate, heart rate to accelerate, and so on. The PNS has reversed behavior correlates, e.g., slowing of heart rate and metabolic activity.

We can, therefore, choose a relatively simple psychophysiological correlate as an indicator of activation level. Heart rate, although easy to determine, is unsuitable because neither SNS nor PNS innervation can be easily distinguished. Skin conductivity or electrodermal response (e.g., galvanic skin response, psychogalvanic reaction), however, is also innervated by SNS but does not have the disadvantage of PNS innervation.

PREVIOUS RESEARCH

The EDR has been used in much traffic research. Michaels (4) studied drivers' EDR in urban streets and concluded that the traffic events generating the largest responses involve great differences in speed between the object and the test vehicle. Turning maneuvers and crossing and merging vehicles typically induce more tension than parked vehicles and traffic islands.

Taylor (5) investigated EDR and EDR/time (i.e., EDR rate) where accidents had occurred. He found a significant correlation between EDR and accidents but not between EDR rate and accidents. He formulated a theory in which the EDR rate is a pacing factor or an error signal. "If the pacing factor is raised by larger or more frequent EDRs, the slowing of pace is called for; if there are few hazards, the pace is quickened until they reappear." Taylor considered that pacing is governed primarily by the driver's internal characteristics, whereas external attributes such as road characteristics are of little importance. Other traffic researchers who have used EDR include Hulbert (6), Murtazin (7), and Preston (8).

THEORY

In the proposed system theory shown in Figure 2, the properties of the environment are embodied in a concept called environmental complexity. The perceptual complexity is the driver's interpretation of the environmental complexity and describes the total influence of the environment on the driver. It varies from driver to driver and also depends on the driver's mental and physical conditions. The level of perceptual complexity determines the activation level, which, according to Figure 1, has implications for the performance quality. Decision-making is manifested through control operations influencing the behavior of the vehicle. The homeostatic behavior of the whole system can be estimated by comparing the performance demand of the environment with the performance quality of the driver.

A major feedback loop runs from vehicle behavior to the dynamic environment. Another important feedback loop connects the activation level with the perceptual processes. A highly aroused driver has a narrower width of perception and, therefore, neglects peripheral information. This will affect the selection of responses (9).

Some of the concepts of this system can readily be quantified; the level of activation can be measured by using correlates such as EDR, HR, or EMG. The driver's control operations may be indicated by measurements of brake pressure and the angle of the steering wheel. Indicators of the dynamic environment are traffic events and, from feedback of vehicle behavior, the velocity of the car and its accelerations in three directions: ACCX, ACCY, ACCZ. The static environment is quantified by variables describing various aspects of the road.

OBJECTIVES

The main objective of the study is to provide a validation of the psychophysiological variables, primarily EDR, for use in traffic research. There is also an explicit exploratory interest centered on questions about driver reactions to traffic events and road characteristics. From the theory about the environment's effect on a driver, some hypotheses can be derived: A covariation exists between the dynamic environment and the driver's activation level, the static environment and the driver's activation level, and the driver's activation level and the number of reported accidents along the road.

METHOD

During the test runs, psychophysiological variables from the driver, variables describing the dynamic behavior of the vehicle, and a description of traffic events were registered. All data were stored on a digital tape recorder. The PPV was also registered on a strip chart recorder to monitor and control artifacts. After each test drive, the

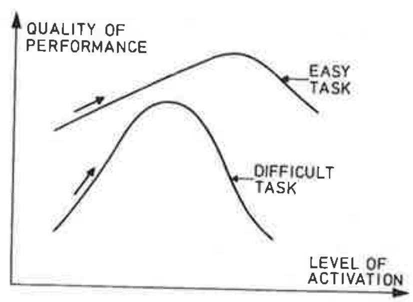


Figure 1. Relationship between level of activation and quality of performance.

Figure 2. Theory on some interactions within the driver/vehicle/environment system.

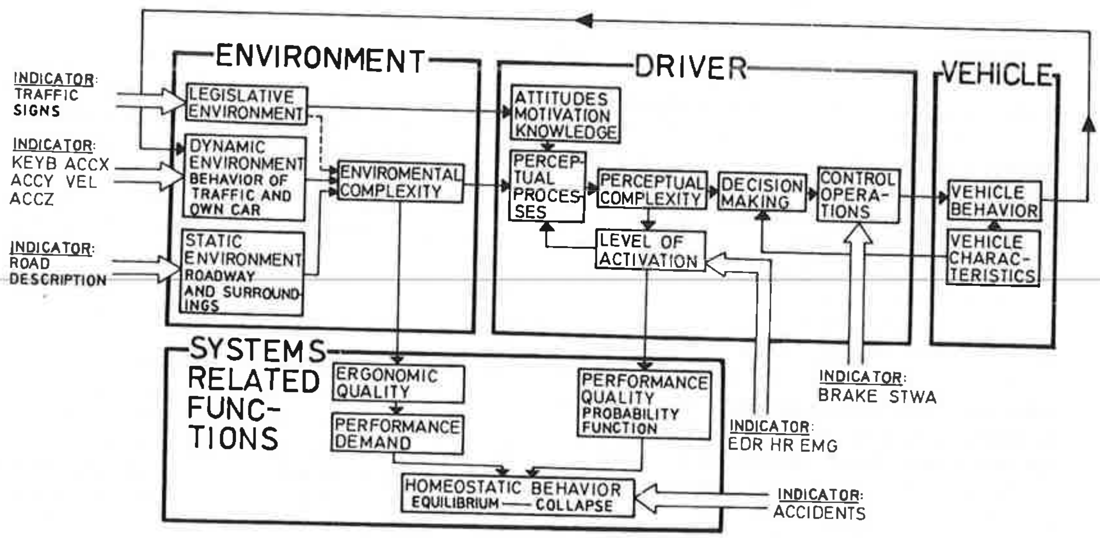
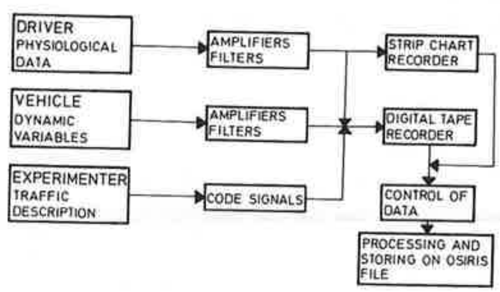


Figure 3. Plan for collecting data.



information obtained was processed in a computer. Figure 3 shows a plan for collecting and processing the data.

Psychophysiological Variables

The driver's activation level was studied by using EDR and HR. As a third measure of activation, muscle potentials from two muscles in the driver's right leg were registered with EMG: the m. tibialis anterior and m. anterior superior. Signals from m. tibialis anterior indicate that the driver releases the pressure on the accelerator, and signals from m. anterior superior indicate that the driver lifts his right leg. Details of the amplifiers, electrodes, and electrode sites (10) and a general description of the methods and research findings (14) are given elsewhere.

EDR was measured from surface electrodes affixed to the thenar parts of the left palm. A constant current with the density of 10 $\mu A/cm^2$ was applied.

Two different EDR measures were obtained. The conventional response (EDRC) was produced by high pass filtering of the EDR signal by using a time constant of $\tau \simeq 10$ s.

$$EDRC = 10 \log\left(\frac{G}{G_M}\right) dB$$

where

G = momentary conductivity, in μmho and
G_M = mean conductivity, in μmho.

This evaluates relative changes in conductivity. A special normalized function (EDRT) was calculated to evaluate the relative magnitude of each EDR amplitude.

$$EDRT = k \cdot \log\left(\frac{G}{G_0}\right) dB$$

where

k = amplification (varying) and
G_0 = conductivity, in μmho, just before the start of a response.

EDRT returns to zero when the maximum amplitude has been reached. Thereby this signal is especially well-suited for computerized analysis. EDRT has been used by Sternbach (20), who found that increases in EDRT accompany decreases in reaction time. The EMG signals were integrated to make output signals directly proportional to muscle tension.

Environmental Variables

The test car was a Volvo 145 with manual gears. The velocity of the car and the distance traveled were measured by a digital counter connected to the left rear wheel. Three accelerometers positioned behind the driver's seat gave information about AACX, AACY, and AACZ. STWA and BRAKE were also recorded. Figure 4 shows the installations in the test car.

The test drives were performed on a 23.7-km stretch of rural road. The road can conveniently be divided into four fairly homogeneous stretches:

1. A coated road that has a low geometrical standard, 5.8 km long;
2. A coated road that has a geometrical standard slightly better than the first

Figure 4. Test car with equipment.

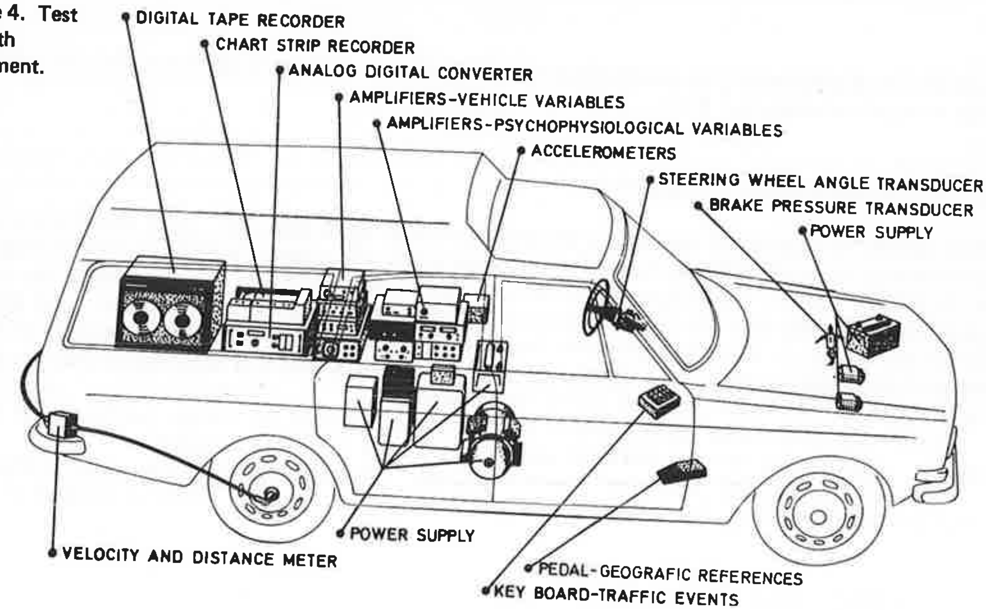
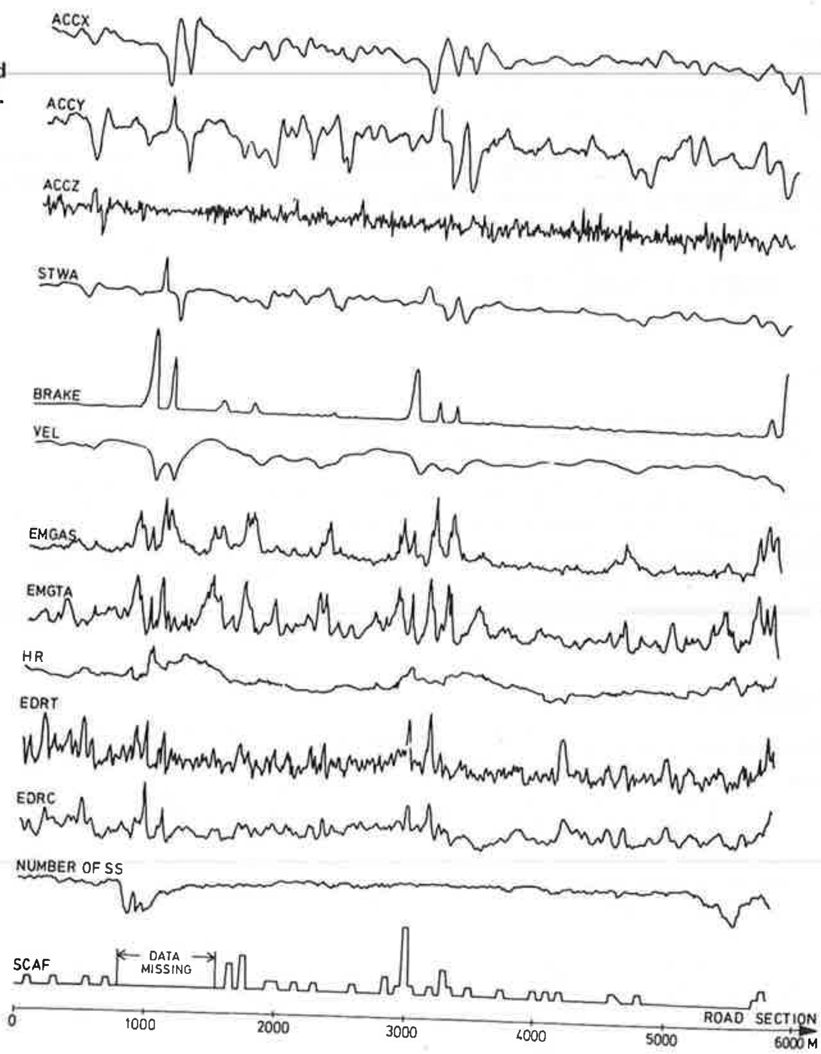


Figure 5. Average response profiles obtained on first road stretch for 60 drivers.



stretch, 8.5 km long;

3. A coated road that has a high geometrical standard, 3.2 km long; and
4. A two-lane highway that has grade separations, 5.7 km long.

Because one objective of the study was to compare the characteristics of the road with the behavior correlates, the properties of the road were measured in the field. The variables were measured at intervals of 25 m along the road; altogether about 10 000 measurement values were obtained.

Police reports on accidents were obtained from 1956 to 1972. The accident sites were localized, and road coordinates calculated. The accidents were then divided into the following categories:

1. Single-car accidents in which the cars had been driving in the same direction as the test car,
2. Single-car accidents in which the cars had been driving in the opposite direction, and
3. Other accidents.

These data and the road description data were transferred to punched cards.

Traffic Description

The traffic was described during the experiments by an observer who used a keyboard to encode different traffic events. Altogether 25 traffic events could be coded, and, of these, 16 were frequent enough to be analyzed. The events considered are given in Table 5. The keyboard was also used to skip certain road sequences during the test drive. Skipping was marked when the experimenter instructed the driver and when there were situations not useful for the test situation.

Test Drivers

A random sample of 150 drivers was selected from Volvo owners in Gothenburg. Approximately 40 percent turned out to be from firms and enterprises and only 65 drivers were used in the tests. This sample was complemented with some nonstratified selections to give a total of 75 test persons. Because of initial difficulties with the test apparatus, 15 of the test drivers were excluded, and, as each subject made one test drive, 60 drivers were obtained. The subjects' ages varied between 19 and 62 (median = 39), and the driving experience between 2000 and 60 000 km/year (median = 20 000). They were paid for their services. The test runs were all performed between 10 a.m. and 3 p.m. when traffic intensity was moderate.

Processing, Storing, and Reducing the Data

Altogether 14 variables were registered 5 times/s on the digital tape recorder. During the tests, a total of 7 million measurement values, corresponding to 120 000 per test, were collected.

Data were processed in a series of computer programs (11), which performed the following transformations:

1. The time measurement for the physiological variables was moved 1.0 s ahead to compensate for a delay.
2. A calibration was made for EMGTA, EMGAS, and EDRT, and the highest value obtained for each driver was given the maximum value of 98. All other values were then scaled accordingly.
3. All variables were ordered according to distance traveled, and values of PPV,

environmental variables, and traffic description were computed (interpolated) for each consecutive 10 m along the road.

After these and other calculations had been performed, the data were stored in OSIRIS format (12) for statistical processing.

Three different data files were constructed. The largest contained individual data from all the test drivers. From this data, a mean drive was calculated by averaging all the responses at 10-m intervals along the road. The third file consisted of averaged responses for each 100-m stretch of road.

RESULTS

Because PPV was to make up the dependent variables in the statistical analyses, some statistical properties were scrutinized. All PPV exhibited distributions that were normal or close to normal. Analyses of variance for η-coefficients were calculated for each pair of variables so that nonlinear relationships between PPV and the environmental variables could be revealed. These calculations and plots obtained for each pair of variables showed no clear trend toward any specific nonlinear relationship, and the transformations of the variables were not justified.

Response Profiles

So that a visual survey over the collected data could be obtained, the average responses for each 10 m were plotted on the computer. The results from the first road stretch are shown in Figure 5.

These plots were first used at the test site to verify apparent connections between the environmental characteristics and the drivers' responses. Peaks in EDR activity were obtained at spots involving an increase in task demand. A simple visual confirmation of this can be obtained when the EDRC curve (Fig. 5) is compared with STWA and BRAKE. In Figure 5, SCAF covaries with EDRC. At the bottom of the figure it is demonstrated that, because of skipped road sequences, the number of subjects varies along the test road. Averaging was performed based on this information.

There was an interesting sequence of responses at the transition between the third and the fourth stretch. Figure 6 shows the average HR, EDRC responses, and the three peaks in the EDRC curve that correspond to

1. An intersection with the highway bridge, just before the driver enters the acceleration lane;
2. The end of the acceleration lane when the driver merges with other traffic;
3. A large bump on the road due to uneven settlement, which produced the largest vertical accelerations during the test runs (approximately half of the drivers were familiar with it, whereas most of the others did not notice it in advance).

Discriminative Power of Electrodermal Response and Heart Rate

t-tests were performed so that a further validation of EDR and HR as correlates of task demand could be provided. Investigating only extreme scores is prevalent in psychological test construction (13), and it was used for this test.

For those road sections where the 27 percent highest and lowest responses in EDR and HR had been obtained, mean values of the environmental variables and accidents were calculated. The differences between the mean values for the cases with high and low scores were then tested for significance by using t-tests. The data from the average response file with 10-m road increments were used. The results are given in Table 1.

Figure 6. Average heart rate and conventional electrodermal response at beginning of highway.

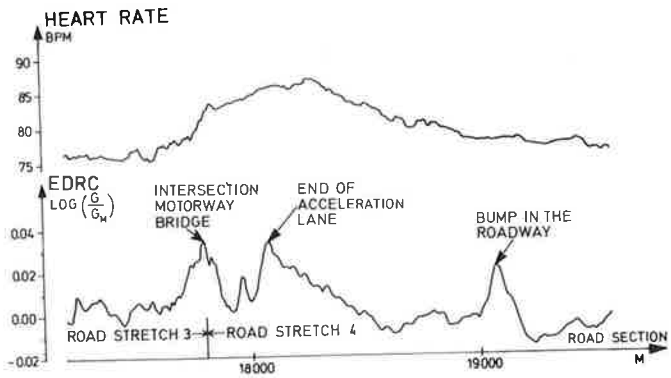


Table 1. t-tests of differences in environmental and accident variables obtained for low-and high-score conventional electrodermal response and heart rate.

Dependent Variable	Mean of Dependent Variable for: EDRC Low-Score	EDRC High-Score	t	p (d.f. = 1275)	Mean of Dependent Variable for: HR Low-Score	HR High-Score	t	p (d.f. = 1247)
CRR	2.40	1.82[a]	1.01	—[b]	0.082	2.87	-3.76	0.001
CRL	2.44	2.43[a]	0.03	—[b]	1.30	3.12	-2.98	0.005
PAR	4.43	4.99	-0.17	—[b]	2.54	11.0	-2.16	0.025
PAL	5.15	3.11[a]	0.77	—[b]	2.04	8.65	-2.08	0.025
SWR	1.52	1.12	6.10	0.001	2.29	1.10	19.4	0.001
SWL	1.03	0.68	8.17	0.001	1.46	0.57	24.3	0.001
RW	7.07	6.56	6.07	0.001	7.61	6.62	12.9	0.001
SQ	1.36	1.59	-5.78	0.001	1.11	1.37	-8.94	0.001
SPL	77.1	74.4	2.42	0.005	93.8	68.2	25.6	0.001
SDF	346	314	2.59	0.005	484	239	21.5	0.001
SDB	331	276	5.13	0.001	439	211	26.1	0.001
SOR	9.07	8.81	1.79	—[b]	9.71	8.55	9.08	0.001
SOL	9.14	8.73	2.91	0.005	9.74	8.36	10.7	0.001
CSOR	7.91	7.29	3.22	0.001	8.62	7.46	6.70	0.001
CSOL	7.29	6.73	2.73	0.005	8.71	5.86	15.6	0.001
AHOR	64666	54041	3.87	0.001	59783	52580	2.58	0.005
GRA	3.32	-5.82	8.47	0.001	-2.60	-3.87	1.27	—[b]
ACSL	2.00	-1.81	3.36	0.001	-0.35	-0.67	0.30	—[b]
ASEL	3.03	3.56	-4.99	0.001	3.09	3.04[a]	0.55	—[b]
VEL	75.1	68.0	6.81	0.001	90.9	59.4	36.9	0.001
KEYB	10.1	8.39[a]	5.11	0.001	12.8	8.53[a]	13.4	0.001
ACCX	3.92	-15.27	8.52	0.001	-7.94	-1.57[a]	-2.71	0.005
AACCY	32.2	53.6	-7.67	0.001	27.2	60.6	-12.3	0.001
AACCZ	9.94	9.94	0.00	—[b]	9.94	9.94	0.00	—[b]
BRAKE	7.41	58.9	-7.27	0.001	3.49	60.8	-7.61	0.001
ASTWA	1.30	3.15	7.85	0.001	9.44	36.3	-11.1	0.001
SCA	0.38	0.64	-3.35	0.001	0.43	0.76	-3.42	0.001
OA	0.71	1.00	-2.07	0.025	0.46	1.53	-6.89	0.001
ACC	1.09	1.63	-3.18	0.001	0.90	2.29	-6.93	0.001

[a]The direction of the change in mean value does not agree with the hypotheses. [b]Not significant.

Multiple Regression Analyses

Stepwise multiple regression analyses were performed with PPV as dependent variables so that a ranking of the influence of the environmental variables and the dynamic variables of the vehicle on PPV could be provided. Each stepwise analysis was interrupted when the F-value for the last included variable was lower than 2.0. The calculations were performed for each road stretch separately and for the whole test road by using average responses for a 100-m road increment. In Table 2, the results are given by using PPV as dependent variables and vehicle variables as independent variables, and in Table 3, the road variables are used as independent variables. In Tables 2 and 3, the first three independent variables included in the stepwise process are numbered indicating the order of inclusion. The sign of the correlation coefficient is also given.

Responses During Traffic Events

Measurement values from individual test drives were used. A total of 133 390 cases was obtained, each corresponding to a 10-m road strip. In the majority of cases (N = 112 630), no traffic event actually occurred. The remaining number of cases was unevenly dispersed among the different events considered. Because the same event could sometimes be coded during consecutive, 10-m strips, the independence of the measurement values within each category was not guaranteed. In view of this consideration and the largest variability in response for the not so frequent events, the exclusion of events with $N < 20$ was justified. The remaining events with corresponding frequencies are given in Table 5. For each category of traffic event, the mean value of each response variable was calculated. The traffic events were then ordered by magnitude for each response variable. Rank correlation coefficients were then calculated for each pair of response variables. The results are given in Table 4. This exploratory analysis was to reveal connections between the response variables; in this paper only the significant correlations are discussed.

For the EDR variables, significant covariations were obtained with EMGAS, ACCX, and BRAKE. It was suspected that the responses in EDR might be due to preparatory muscular activity of muscular response; however, because no EDR was obtained when the brake was applied in a stationary car, the finding was of interest and is further discussed.

In Table 5, the rank orders of the traffic events relating to the magnitude of response in EDRC and brake pressure are given. It can be observed that event 60, own car passes other car, adds most to the differences between the rankings. It was not expected that the driver would apply the brake when passing, and, thus, if this particular event is excluded, the rank correlation coefficient is raised to $r_s = 0.89$.

For EDRT, a significant covariation with ACCY was also obtained. This dependency is, however, less straightforward because it is not retrieved for EDRC and STWA.

Cross Correlations

For illustration of the dynamic dependencies between the different variables, cross correlations were calculated between EDRC and BRAKE, AACCY, and AACCZ by using averaged responses for the first road stretch. The variables were lagged for a maximum of 160 m. The results are shown in Figure 7.

The results in Figure 7 show the problems with response latencies and reaction times encountered when behavior is analyzed on a microlevel.

Considering the response latency in EDR, the left peak ($r_{xy} = 0.40$) obtained for EDRC-BRAKE is synchronous with brake application. Equally interesting, however, are the multiple peaks obtained, indicating feedback information from the drivers' decision-making.

It is generally assumed that skilled drivers function in a more open-loop fashion and are less dependent on feedback information than inexperienced drivers. The multiple

Table 2. Multiple regression for physiological and vehicle variables.

Road Stretch	Dependent Variable	Independent Variable: VEL	KEYB	ACCX	AACCY	AACCZ	ASTWA	BRAKE	r
1	EDRT				+2	-3		+1	0.52
	EDRC				+2		-3[a]	+1	0.59
	HR		-2[a]					+1	0.43
	EMGAS			-2			+1	-3[a]	0.74
	EMGTA		-3[a]	-1				-2	0.76
2	EDRT	-3		-2			+1		0.61
	EDRC			-2			+1		0.70
	HR	-1		+2[a]	-3[a]				0.83
	EMGAS	-1		-2	+3				0.77
	EMGTA	-2		-1				-3	0.83
3	EDRT				+2			+1	0.80
	EDRC		+3		+2			+1	0.85
	HR	-1					-3[a]	-2[a]	0.92
	EMGAS	-2		-3				+1	0.93
	EMGTA	-2	-3[a]	-1					0.80
4	EDRT	-1	+3			+2			0.73
	EDRC	-1	+2						0.67
	HR	-1		+2[a]	-3[a]				0.87
	EMGAS	-1			-3[a]			+2	0.91
	EMGTA	-2		-1				-3	0.96
5	EDRT				+2	+3		+1	0.53
	EDRC				+2	+3		+1	0.45
	HR	-1		+2[a]				+3	0.65
	EMGAS	-3		-2			+1		0.74
	EMGTA	-2		-1				-3	0.84

Note: $p < 0.01$. [a]Sign of correlation coefficient does not agree with the hypotheses.

Table 3. Multiple regression for physiological and road variables.

Road Stretch	Dependent Variable	Independent Variable: CRR	CRL	PAR	PAL	SWR	SWL	RW	SQ	SPL	SDF	SDB	SOR	SOL	CSOR	CSOL	AHOR	GRA	ACSL	ASEL	r
1	EDRT										-1							-2		+3	0.42
	EDRC															-1					0.23[a]
	HR				+3	+2[b]			-1												0.75
	EMGAS										-1						-3	-2			0.65
	EMGTA							+1[b]			-2							-3			0.63
2	EDRT								+2	-1								-3			0.43
	EDRC		-3[b]							-1								-2			0.38
	HR									-1		-3	-2								0.78
	EMGAS								+1		-2							-3			0.51
	EMGTA										-2	+3[b]						-1			0.63
3	EDRT														-2		-3			+1	0.64
	EDRC														-3		-1			+2	0.56
	HR						+3	+3[b]		-1				-2							0.84
	EMGAS													-2	-1						0.54
	EMGTA		-2[b]								-3						-1				0.53[a]
4	EDRT						-1														0.54
	EDRC						-1											-2	-3		0.66
	HR						-3				-2							-1			0.72
	EMGAS						-2			-1			-3								0.81
	EMGTA									-3			-1			+2[b]					0.76
5	EDRT						-2	+3[b]										-1			0.33
	EDRC						-1								-3			-2			0.32
	HR								-3			-1	-2					-2			0.50
	EMGAS										-1						-3	-2			0.54
	EMGTA										-1								-3		0.61

Note: $p < 0.01$ except as indicated in footnote a. [a]$p < 0.05$. [b]Sign of correlation coefficient does not agree with the hypotheses.

Table 4. Spearman rank correlation coefficients for means of responses during 16 types of traffic events.

Variable	VEL	EDRT	EDRC	HR	EMGAS	EMGTA	ACCX	ACCY	ACCZ	BRAKE	STWA
VEL	1.00										
EDRT	-0.11	1.00									
EDRC	-0.02	0.67[b]	1.00								
HR	-0.26	0.07	0.14	1.00							
EMGAS	-0.04	0.32	0.57[a]	0.30	1.00						
EMGTA	-0.47[a]	0.12	0.40	0.26	0.62[b]	1.00					
ACCX	0.34	-0.62[b]	-0.71[b]	-0.05	-0.44[a]	-0.56[a]	1.00				
ACCY	-0.28	-0.62[b]	-0.36	-0.38	-0.16	0.21	0.13	1.00			
ACCZ	-0.23	0.33	0.54[a]	-0.02	0.30	0.10	-0.46[a]	0.09	1.00		
BRAKE	-0.43[a]	0.61[b]	0.71[b]	0.25	0.53[a]	0.67[b]	-0.94[b]	-0.12	0.40	1.00	
STWA	-0.05	-0.32	-0.07	-0.54	-0.01	0.16	-0.20	0.70[b]	0.02	0.14	1.00

[a]$p < 0.05$. [b]$p < 0.01$.

Table 5. Rank orders of traffic events based on magnitude of response in conventional electrodermal response and brake pressure.

	EDRC			BRAKE
Rank Order	Traffic Event	Traffic Event Code	Number of Events	Traffic Event Code
1	Cyclist or pedestrian + meeting other car	23	28	23
2	Other car merges in front of own car	40	47	40
3	Multiple events	2	163	2
4	Own car passes other car	60	3 590	30
5	Leading car diverges	30	207	20
6	Own car passes other car + car-following	61	126	61
7	Cyclist or pedestrian	20	839	21
8	Other car passes own car	50	157	11
9	Meeting other car	3	1 535	3
10	Cyclist or pedestrian + car-following	21	65	1
11	Car-following	1	13 049	70
12	Car-following + meeting other car	11	353	0
13	No event	0	112 630	50
14	Parked car + car-following	71	64	71
15	Parked car	70	742	10
16	Meeting other car	10	50	60

Note: $r_s = 0.71$; $p < 0.001$.

Figure 7. Cross-correlation coefficients for average responses on first road stretch.

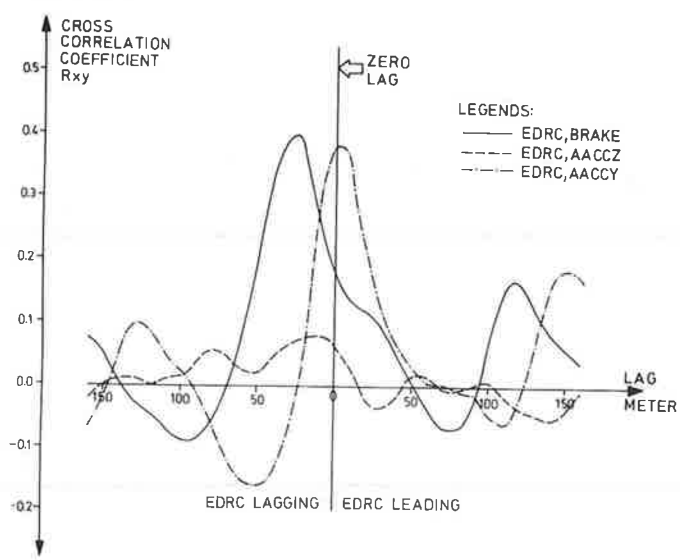
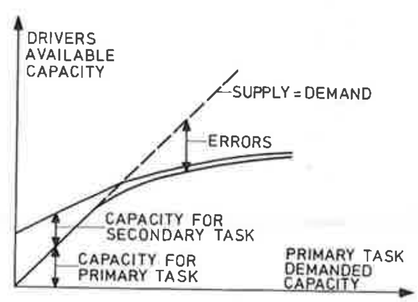


Figure 8. Driver's available capacity as function of primary task demand.



peaks might, therefore, reflect interindividual discrepancies contained in the average responses.

DISCUSSION OF FINDINGS

Response Profiles

In the averaged responses (Fig. 5), the influence of the traffic is of minor importance because the average number of traffic events was approximately constant along each road stretch. The responses obtained therefore mainly reflect the demands imposed by the road environment.

The arousal level as quantified with EDR varies flexibly, whereas changes in HR are not as easily triggered as EDR. However, peaks in HR generally occurred only when the EDR activity was high, although EDRs were obtained irrespective of HR. Figure 6 shows the bump in the roadway that produced an increase in EDR but not in HR. This event, however, was specific because it required no action, and the evoked response pattern is in agreement with what was originally called a P-pattern (15). In stages of attentive, passive acceptance of stimuli when no motor response is required, the arousal pattern is characterized by a directional fractionation: HR slows down even as other indexes suggest an increase of arousal level.

t-Tests

t-tests were performed to obtain a discrimination between the road variables and their influence on activation level correlates. As given in Table 2, the change in mean values of the dependent variables is, except for a few cases, in the expected direction according to the hypotheses. This implies that high-score responses are associated with increases in task demand.

The expected changes are retrieved also for the accident variables (SCA, OA, ACC) although the accident statistics provide a satisfactory resolution only on the first road stretch. For this stretch, Spearman rank correlation coefficients have been calculated separately (10) and significant correlations were obtained for EDRT; SCAF ($r_s = 0.22$, $p = 0.05$); $\overline{HR}$; and ACC ($r_s = 0.32$, $p = 0.01$).

Multiple Regression Analyses

For these analyses, 100-m road increments were used. The influence of fast feedback processes and response lags was thereby reduced, and the variability in data decreased. As a result, the magnitude of the correlation coefficients increased markedly. It can be argued that such measures make the data better suited for analysis with common statistical procedures (at this stage it seems hard to defend the use of complex dynamic models); however, the road increment chosen must not be too long. It seems that Taylor's failure to find connections between road variables and EDR (5) derived from his choice of 1000-m increments. Averaging over such long distances would also reduce gross differences in the data.

Based on the dispersion of independent variables in Tables 2 and 3, the analyses yielded no clear picture. Some explanations for this can readily be offered: Multiple regression is a rather inefficient method for a small number of cases, and intercorrelations between the independent variables make the order of inclusion to some extent arbitrary. However, despite a rather moderate correlation coefficient between EDRC and EDRT ($r = 0.65$), the results for these variables were consistent for each road stretch. This suggests that the obtained incongruity actually depends on gross differences between the road stretches. Therefore, the magnitudes of isolated environmental variables are less important than the total environmental context.

As given in Table 2, variables associated with the longitudinal control of the vehicle

(VEL, ACCX, and BRAKE) are of higher significance than those involved in the lateral control (AACCY and ASTWA). The negative correlation coefficients obtained for VEL on the fourth road stretch suggest particularly, however, that a good road quality is reflected both in high-velocity and low-response values.

In Table 3, the road variables that seem to explain most of the variance are GRA and SDF. Similar results for gradients have been obtained by Wyss (16). Inasmuch as driving on downhill grades requires a frequent longitudinal control, the result actually agrees with the other findings.

The correlations found with SWL are trivial and, if anything, illustrate the common Swedish road construction policy of providing narrow shoulders.

Traffic Events

Greenshields (17) showed that traffic events described with a keyboard will produce as reliable a result as one obtained from evaluating a film recorded during the test session. Such reliability problems are of little significance in this study because there was generally enough time to describe the traffic. More important is that traffic events are not discrete but develop gradually. This leaves the experimenter with the difficult choice of determining when the driver's behavior is influenced, e.g., judging when a car-following situation has developed or dissolved.

The rank correlation, $r_s = 0.89$, obtained for BRAKE and EDRC fully agrees with the other results. The rankings of traffic events in Table 5 furthermore hold a high face validity because the complexity of the separate events is reflected in both BRAKE and EDR; however, despite the consistency in these findings, the variability in response within each event is large.

Theoretical Implications

The theory proposed in Figure 2 is far from complete, but it served as a tool for systematizing. Except for the activation level and its implications, the theory was regarded as uncontroversial. The hypotheses stated are considered verified even if the evidence for the accident data is meager. The distinction between the environmental complexity and its cognitive counterpart (perceptual complexity) is essential, and the results obtained show that the environmental context is more important than actual changes in some of the road variables.

The concept of the varying capacity of a driver (18) can possibly be used in a model primarily intended for measuring task demand by imposing a secondary task (2, 3, 19). Figure 8 shows that the driver's available capacity is determined by the primary task demand of driving.

If task demands increase above a certain limit, the driver's available capacity will be insufficient, and errors will appear. These occurrences are capable of different interpretations and signify deviations from an ideal path.

The available capacity thus varies dynamically because of changes in task demand. For instance, when a driver turns a corner after driving along a straight road, primary task demand suddenly increases, capacity for a secondary task decreases, and conversation temporarily ceases.

The findings suggest that the EDR profiles display transient, mental adaptational processes in the driver (2). EDRs seem to be obtained when the relative increase in task demand exceeds some value, irrespective of the initial level of task demand. This implies, for example, a sensitivity to minor changes only when the ergonomic quality of the road is good. Evidence for this is found by comparing response profiles on the first and the second road stretches (10); EDR amplitudes were of the same order, whereas the quality of the second stretch was better throughout. Furthermore, when a driver encounters two curves in succession, the largest response is obtained in the first curve. This is shown in Figure 5 for EDRC and the 1000- and 3000-m road sections.

The average HR presents a smoother course than EDR. It is less responsive to swift changes in the environment, but, considering the correlation coefficients obtained in Tables 2 and 3, HR seems to be a good indicator of gross environmental characteristics; however, in relation to the P-pattern, it is a less effective indicator of mental effort than EDR (2).

The EMG variables, as opposed to HR and EDR, quantify physical work-load aspects. Although recordings of muscle potentials have frequently been used as correlates of activation level (1, 14), the common procedure has been to record the activity in muscles not primarily engaged in the task. The theoretical implications for this study are therefore elusive, although, in light of the connections found between EDR and longitudinal control variables, EMG recordings might be more interesting than first believed because the muscles are those involved in exercising longitudinal control.

Measurement of Electrodermal Response

Measurement of EDR demands that some technical problems be solved: the choice of amplifier, electrodes, and electrode sites. More troublesome is the extreme sensitivity of the method of moving artifacts; therefore, the utmost care must be taken to obtain proper recordings. It seems likely that some earlier studies did not give these factors proper attention, and sometimes (i.e., for method validity) rather pessimistic findings resulted. The method is problematic in urban areas where controls must frequently be moved, making artifact movement more likely.

Psychophysiological recordings reveal a large interindividual variability. This is due to both spontaneous activities, i.e., responses that cannot be explained by external stimuli, and interindividual differences in responsiveness. Therefore, the technique to calculate average responses, though new in this context, is crucial for investigations like the present one.

CONCLUSIONS

Engineering Implications

The primary objective of the study was an explorative evaluation of the psychophysiological variables used. The chosen approach was rewarding, and some practical implications can be suggested although much still remains to be confirmed in more controlled studies.

The vehicle variables provided a better explanation of the physiological variables than did the road description. This illustrates the importance of dynamic factors, which a static road description does not account for. For the purpose of highway sufficiency ratings it is generally considered that human aspects (comfort, convenience, and safety) should be taken into consideration. Obviously this purpose is better attained when correlates of vehicle behavior rather than measures of road characteristics currently used by highway engineers are employed.

As the responsiveness in PPV varies between individuals, sufficiency ratings derived from such variables will not be useful unless a number of individuals are tested.

For convenience and comfort, continuity in road quality is more important than the actual level of quality. Sudden increases in task demand also adversely affect road safety because the activation level is raised with concomitant perceptual narrowing and increases in reaction time. Therefore, whenever possible, increases in task demand should be leveled out.

This can be achieved by certain changes in the road environment, which would provide physical guidance that would manipulate the driver's arousal level. Rumble strips, for example, are probably effective if they are encountered before a curve. This method is, however, less efficient in urban areas where the activation level is consistently higher and, accordingly, little remains to be manipulated.

Those specific road elements demanding brake use are stressful and should be avoided in road design, e.g., downhill grades and short sight distances.

Suggestions for Future Studies

To further the findings of this paper, one would include a controlled study to identify more accurately those design elements that actually increase task demands. Conversely, the effects of alternative design elements could be evaluated.

Drivers' information processing by day and at night could be compared. Response profiles obtained during the day would represent a behavioral frame of reference because all cues of information would actually be present.

It would be interesting if future studies were to combine eye-marker data with EDR recordings. Eye marks have high accuracy in sorting out relevant stimuli, but they largely represent fundamental behavior at a preattentive level. By contrast EDRs are of low precision in indicating the stimuli, but they represent a later, more attentive stage in information processing.

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DRIVER WORK LOAD FOR VARIOUS TURN RADII AND SPEEDS

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The need exists for a method by which a highway designer can determine, during the design stage, whether a highway design will demand so much of a driver's attention that there is insufficient time to look for and avoid accidents. One aspect of attentional demand is tracking the lane in curves and tangent sections. A study was done to determine (by use of a secondary task) what percentage of a driver's attention is required to track a lane while various curves are negotiated at various speeds. In addition, data were gathered about how drivers control their lane position. Results indicated that lane tracking in a 17-deg turn demanded 26 percent of the subject's attention at 20 mph (32 km/h) and 42 percent at 40 mph (64 km/h) and that attentional demand in the straightaway remained around 23 percent for speeds from 40 to 80 mph (64 to 129 km/h). Lane-tracking data indicated that the median location was 5 in. (13 cm) to the left of the lane center in straightaways, 7 in. (18 cm) to the left in left turns, and 6 in. (15 cm) to the right in right turns. Distributions of drift distances from these three median locations were also determined.

•AS freeway interchanges and other highway design features increase in complexity and sophistication, the limit of one's ability to perceive and process information is approached. Current freeway speed zones, requirements for sign information processing, and planned changes in each of these areas suggest that the driver may not be left with sufficient spare time to look for and avoid accidents. Drivers today need that extra margin of safety, and it can frequently be provided by highway design. This research is concerned with one phase of the development of a driver-work-load model (6). The essential purpose of the model is to predict how busy a driver will be while driving on highways of varying designs. The model may be used to assist a designer in evaluating a proposed roadway design for identifying and alleviating unacceptable work loads imposed on the driver by the roadway.

The primary objective of this study was to determine the work load forced on the driver while a lane was tracked at various speeds in turns of various radii. A secondary objective was to gather data on how drivers control their lane position.

BACKGROUND

Work load has many different connotations. It may refer to a subjective feeling of the difficulty of a task or to the physical exertion required. Senders (10) defined work load as "a measure of the 'effort' expended by a human operator while performing a task, independently of the performance of the task itself." Knowles (5) defined work load, in part, as the answer to the following two questions: How much attention is required? and How well will the operator be able to perform additional tasks?

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The definition of work load to be used here will be similar to that suggested by Knowles: the attention demanded by the task under consideration and its subsequent reduction in the attention available for other tasks.

Of the three major approaches to work-load theory (5, 10, 12), the most extensive work is by Siegel and Wolf (12). The primary purpose of their model is to predict the effectiveness with which operators will be able to carry out their tasks under specified conditions.

Siegel and Wolf began with a list of tasks that the operator must perform. Empirical data had been previously gathered concerning the time required and the time available for completing each of these tasks. The authors used a concept, "stress," which is defined as the time required to execute a series of tasks at average speed divided by the time available for execution of these tasks. A stress value of less than 1 would indicate that the operator has more time available than is required for executing the task. A stress value of more than 1 would indicate that the operator has less time available than is normally required for executing the task and that he must, therefore, work at greater than average speed to complete the tasks in the allotted time.

Siegel, Wolf, and Sorenson (13) indicated that as long as stress value was less than 1, the average task execution time remained unchanged. However, mild stress (ratios from 1 to 2.3) acted as an organizing agent and led to shorter execution times. But at a stress value of 2.3 (stress threshold), the operator became disorganized, and execution time returned to the original average length. Above 2.3, execution time increased until at 3.3 execution time was double the value at a stress value of 1 or less. Therefore, an operator may work at up to 2.3 times his average speed without falling behind. When required to operate 2.3 times faster than one's average speed, a driver will tend to fall behind and not complete all of the tasks in the allotted time. These statements hold true for physical tasks performed over short time frames because of fatigue. In nonphysical (monitoring) tasks, the operator may operate at above average speed over longer time frames. Because we believe that most of the work done by a driver is visual monitoring, driving will be considered a nonphysical task.

Knowles' (5) approach to work load was quite different from that of Siegel and Wolf (12). Knowles used a secondary task to directly measure the attention demanded by a primary task. An example of a primary task could be steering an automobile. The secondary task could be monitoring a display on which numbers appear and in which a subject is required to repeat the numbers as they appear. In estimating work load, the procedure is as follows:

1. The subject is asked to perform the secondary task independent of the primary task.
2. The subject's performance on the secondary task is scored, and the score is designated as a 100 percent performance.
3. The subject is asked to perform the primary task and to devote all spare attention to the secondary task.
4. The subject's performance on the secondary task is again scored, and the performance is compared to the 100 percent performance score.
5. The percentage of reduction in performance on the secondary task is assumed to be the percentage of the subject's attention required to carry out the primary task and to shift eyes from one task to the other.

Senders (10) outlined the requirements for a model that would predict the operator work load of a system still in the design stage. The model was designed to be used on control panels of aerospace vehicles. The assumption was that almost all information was derived from instruments instead of from direct observation of the environment. The steps in developing the model are as follows:

1. Describe the physical system by a set of differential equations;
2. Calculate, from the equations of the system, the frequency characteristics of the signals that will flow in the control loops;

3. Determine, from the mission specifications and the stability requirements of the system, the required accuracy for each signal;

4. Calculate, from frequency and accuracy requirements, on the basis of the model chosen the frequencies and durations of observations;

5. Give the percentage of the total time available that must be spent observing that signal as the product of mean frequency and mean duration of observation for each signal; and

6. Estimate by the sum of these products the mean loading placed by the system on the human operator.

Another model of operator work load gives us insight into how drivers respond to overload conditions. The model developed by King and Lunenfeld (4) divides driving into three major levels of performance: microperformance, situational, and macroperformance. The microperformance level consists of steering and speed control. Both of these tasks are highly overlearned reflex actions. The situational level consists of monitoring and responding to elements of the road, traffic, and external environment. Tasks in the situational level are more cognitive than those in the microperformance level. The macroperformance level consists mainly of trip preparation and direction finding—the most highly cognitive tasks of driving.

King and Lunenfeld also order the levels in terms of primacy. They believe that drivers satisfy their driving information needs by placing highest priority on obtaining microperformance information; therefore, full attention is devoted to the microperformance level until they feel they have sufficient information to successfully carry out the microperformance duties of driving. When these microperformance needs are satisfied, attention is shifted to the situational level until situational level information needs are satisfied. When the two higher priority levels are satisfied, drivers shift attention to the macroperformance level. The primary result of this primacy system appears when drivers are presented with more information than can possibly be processed. When this situation occurs, drivers will be forced to ignore some of the information. The primacy concept states that the first group of information to be ignored is associated with the macroperformance level. If there is still too much information, drivers will ignore the situational information. The primacy concept will be useful for predicting driver response to unacceptably high work loads. For example, as work loads on drivers become too high, the first omitted task should be reading of directional signs.

Other contributions to the area of work-load theory have been made. Michaels (7) measured the galvanic skin response (GSR) of subjects driving on arterial routes and alternate routes. He found a significantly higher GSR on the arterial routes, but the technique was not sensitive to design factors along the roadway.

One study has been done that relates directly to driver work load. Senders et al. (11) used a translucent visor to occlude the view of the driver. The visor was raised and lowered by the experimenters in some cases and by the subjects in others. When the drivers were allowed less frequent and shorter observations, they tended to drive at lower speeds. When drivers had control of the visor, they tended to make longer and more frequent observations as the speed at which they were instructed to drive increased. Senders et al. (11) theorized that a driver is capable of processing information at a certain maximum rate. In addition, a given roadway contains a certain amount of information per mile that the driver must process. The faster the driver passes through the roadway, the faster he must process the information. Therefore, a driver will not exceed a certain speed on a roadway (11) because

> . . . drivers tend to drive to a limit. We suggest that the limit is determined by that point when the driver's information processing capacity, either real or imagined, is matched by the information generation rate of the road, either real or estimated.

Farber and Gallagher (1) used the occluding visor technique to detect the effect of visibility conditions on driving task difficulty in a slalom course. The standard measures of driving performance (maneuver smoothness and cones knocked down) were insensitive to task difficulty, but attentional demand was sensitive.

Several studies have been carried out concerning the design of vehicle controls. Hoffman and Joubert (2) found that the optimum response time for a turning vehicle is 0.2 s. Changes in steering ratio and steering wheel torque had no effect on driver performance, but sight distance (controlled by a shield on the front of the vehicle) did have a significant effect. Olson and Thompson (8) found that steering ratio had a significant effect on driver preference, but performance was not significantly affected. These findings agree with those of Segel (9), which state that pilot ratings are the only methods sensitive to changes in control characteristics. Kidd and Harper (3) have also demonstrated that objective performance measures are insensitive to control situations. Knowles (5) agrees with Kidd and Harper (3) about the inability of objective measures to detect differences in two control systems. He further states that his secondary loading task approach is an objective method of detecting this difference. Therefore, there is a consensus that objective performance measures are insensitive to reasonable changes in vehicle control characteristics. Two methods are sensitive to this difference: driver opinion, which is subject to the biases and preconceptions inherent in human beings, and driver work load, as measured by a secondary loading task.

Even an approximate index of driver work load for various driving maneuvers would be useful to the highway designer. Knowledge of what percentage of the driver's attention is required for driving and, therefore, how much is left over for sign reading would be helpful. Designers know that drivers are busier in turns than in tangent sections, but they do not know how much busier. This study does not provide the full answer to the questions, but it does represent a first step toward it.

METHOD

The primary objective of the study was to determine how much tracking work load is imposed on the driver by various driving maneuvers. A secondary objective of the study was to gather information on how the average driver steers a vehicle.

The study was accomplished in two parts executed simultaneously: (a) Driver work load was measured in a series of maneuvers at varying speeds, and (b) data were gathered on how the average driver steers a vehicle in a highway lane.

Driver work load was measured by the Knowles technique. A number display (secondary task) was mounted on the hood of the vehicle. This display consisted of a motion picture projector that showed two or three numbers per second on a small screen. Subjects would, first, repeat as many numbers as possible while the vehicle was stationary. This number was the 100 percent attention score. Then they would execute the driving maneuver and devote all of their spare attention to the number display. The percentage of reduction in numbers repeated was assumed to be the percentage of the driver's attention required to execute the maneuver.

The secondary task method of work-load measurement was chosen over the occluding visor method because it more closely approximated the sign-reading task of the driver. In addition, the driver is able to pick up some driving cues with his peripheral vision while reading signs and fixating on the secondary task. This is not true with the occluding visor.

Subjects

Subjects were drawn from the office staff at the Texas Transportation Institute Research Annex. Table 1 gives pertinent information about the subjects, all of whom had valid driver licenses.

Apparatus and Procedure

A 1968 Plymouth Fury (Fig. 1) was used as the study vehicle. The steering linkage of the vehicle and front-end alignment were inspected by the chief mechanic at the Texas Transportation Institute Research Annex. Based on the physical condition and adjustment of the system, the vehicle was classified as representative of the average full-sized sedan on the road. The secondary task, i.e., number display, was mounted on the hood above and to the right of the driver's line of sight (Fig. 2). Figure 2 was photographed at the beginning of the sharpest right turn in the study. Note that the view is more than sufficient for tracking the lane, but the sight distance around the turn is restricted. This was considered acceptable because the objective of the study was to measure the microperformance, tracking work load (4), and not the situational work load.

Instrumentation recorded steering wheel position and velocity on a Vetter FM tape recorder. A time-lapse Super 8 motion picture camera mounted on the right side of the vehicle was aimed at the road surface beside the right front tire (Fig. 3) to monitor lane position. A target was mounted 3 in. (7.6 cm) to the right of the fender and in the view of the camera. At the beginning of each series of runs, a calibration bar marked in inches was placed on the road surface below the target, and the 3-in. (7.6-cm) mark on the bar was aligned with the target by use of a plum bob. Several pictures of the target and bar were filmed for later data analysis. Power for the projector and camera was supplied by a portable generator mounted in the vehicle trunk.

The study took place at the Texas Transportation Institute Research Annex, which is a former Air Force base. A lane, 12.5 ft (3.8 m) wide, was delineated by standard 4-in. (10-cm) white striping on the runways and taxiways.

The maneuver types, speeds, and direction of turns were administered to the subjects in a counterbalanced order based on a Latin square design. There were three maneuver types: sharp turn, wide turn, and straightaway. There were two different sharp turns, and, because they were close together, the subjects drove through both turns in one data run. The degree of curvature of the turns is given in Table 2. Sharp-turn speeds were 20, 30, and 40 mph (32, 48, and 64 km/h); wide-turn speeds were 20, 40, and 60 mph (32, 64, and 97 km/h); and straightaway speeds were 40, 60, and 80 mph (64, 97, and 129 km/h).

Instructions were given to subjects by a tape recorder. Subjects were instructed to drive normally and to repeat as many numbers as possible without neglecting their primary task of driving the vehicle. In addition, they were instructed to establish their speed before entering the maneuver and to ignore the speedometer during the maneuver. This was done to eliminate speed control work load and to measure work load caused solely by tracking.

Subjects were first familiarized with the equipment and maneuver by executing the task in alternate directions at increasing speeds. During the four practice runs, subjects repeated the numbers, but the responses were not recorded. After the practice runs, when the vehicle stopped, 100 percent attention was obtained. The maneuvers were then executed, and responses of subjects were recorded on a tape recorder. Another measurement of 100 percent attention was obtained at the end of the data runs. The procedure was essentially the same for all maneuvers.

In the original study plan, the driver work load was to be measured on 18 subjects. Data for lane position, steering input, and work load were to be gathered simultaneously on six subjects. Equipment failure forced termination of the study after 11 subjects. Both sets of data were obtained on subjects 9, 10, and 11. A decision was made to rerun the 11 subjects and to gather lane position and steering input data when the secondary task was removed from the hood of the vehicle. Subjects were instructed by tape-recorded instructions to drive normally.

Before each phase of the study to gather lane position and steering input, a calibration bar was placed on the road surface within the view of the motion picture camera, and several frames of film were exposed. During each data run, the camera was activated before each maneuver. The camera photographed the lane stripe and

Table 1. Analysis of drivers in study.

Testing Order	Sex	Age	Miles per Year	Years Formal Education
1	M	24	25,000	17
2	F	23	15,000	16
3	M	23	28,000	15
4	F	21	5,000	15
5	M	22	10,000	15
6	F	39	5,000	12
7	M	18	23,000	13
8	F	20	10,000	12
9	M	21	20,000	16
10	F	20	18,000	12
11	M	24	25,000	17

Note: 1 mile = 1.6 km.

Figure 1. Research vehicle.

Figure 2. Driver view of secondary loading task.

Figure 3. View from lane-monitoring motion picture camera.

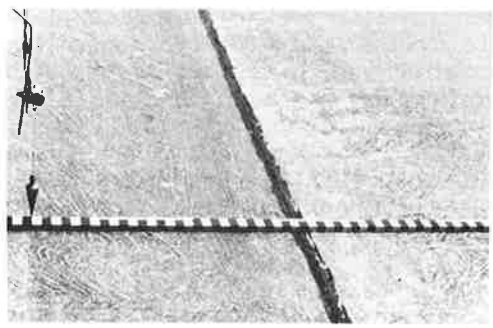
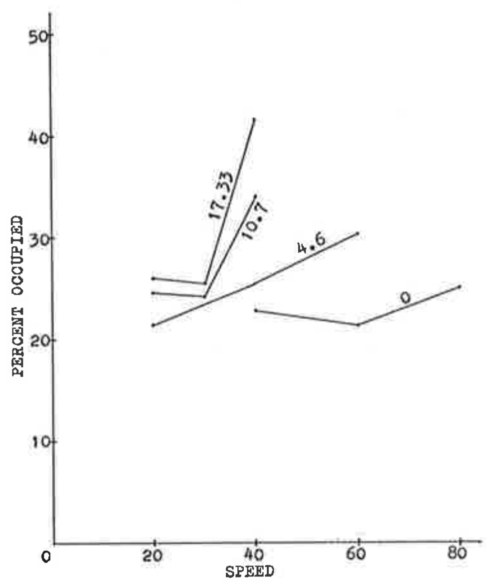


Table 2. Degree of curvature of turns.

Turn	Curvature (deg)	Radius (ft)
A	17.33	330
B	10.70	530
C	4.60	1,273

Note: 1 ft = 0.3 m.

Figure 4. Work load at various speeds and curvatures for right turns.



target at a rate of 2 frames/s throughout the data run. The target contained a light that could be activated by the experimenter. When the event marker switch was depressed, the target light and an event channel on the FM data recorder were activated. The target light, the event marker, and the steering and velocity data were recorded simultaneously, and this served to synchronize the information gathered by the two methods. At the end of each session, the experimenter had obtained a data tape containing steering wheel position, velocity, and event marks and a film with photographs of the calibration bar, the lane stripe position, and event marks during the data runs.

RESULTS

The data were analyzed in two parts. In the first part, work-load data were analyzed to determine the work load associated with each maneuver at each speed. In the second part, control data were analyzed to determine how a driver steers a vehicle in a lane.

Work-Load Data

Tape recordings of subject responses (repeating numbers) were scored for the percentage correct. Driver work load was calculated for each subject on each speed, direction, and maneuver. Because the study was terminated with 11 subjects, there were not an equal number of data points under each of the 3 orders of maneuver presentation. Therefore, an analysis of variance was done on the work-load data to check for an order effect that was at the 0.05 level of significance. This finding required that the data be balanced according to order effect; therefore, a dummy twelfth subject was added and given the average work-load score of the other three subjects in the third order of presentation.

Figures 4 and 5 show the average visual work load (in percentage occupied) for the 12 subjects at each speed used. Each line connecting the points in the figures is labeled with the degree of curvature of the turn in which the data were gathered. Note that the work load generally increased both with degree of curvature and speed. This finding is, of course, expected and lends support for data validity. A polynomial regression was applied to the data points in each of the seven curves shown in Figures 4 and 5, and the results are given in Table 3. The effect of speed was found to be significant beyond the 0.01 level of significance for all curves except the 10.7-deg curve turning left. This result may be explained by noting that drivers had to negotiate a sharp turn (not used in the study) just before they entered the 10.7-deg left turn. Apparently the short, 50-ft (15.2-m), straight section between the two turns was not sufficient to allow the drivers to enter the turn without some aftereffects from the previous turn. There was no approach problem from the other direction, and the data fit the expectations better. In that the data for the 10.7-deg left turn were considered invalid, they were replaced by another curve for predicting driver work load. The substitute data exhibit the same relationship to the other left-turn data as that in the right-turn data.

Figures 6 and 7 show the relationship between degree of curvature and percentage occupied. Each line connecting the points is labeled with the speed at which the data were gathered. Results of a polynomial regression applied to the data (Figs. 6 and 7) are given in Table 4. The effect of curvature was significant beyond the 0.01 level for all but the 20-mph (32-km/h) left curve, which was significant beyond the 0.05 level. Again this finding supports the validity of the study data. It was anticipated that degree of curvature would have a stronger effect on driver work load than speed. Observation of the F-ratios confirms this expectation.

Figure 5. Work load at various speeds and curvatures for left turns.

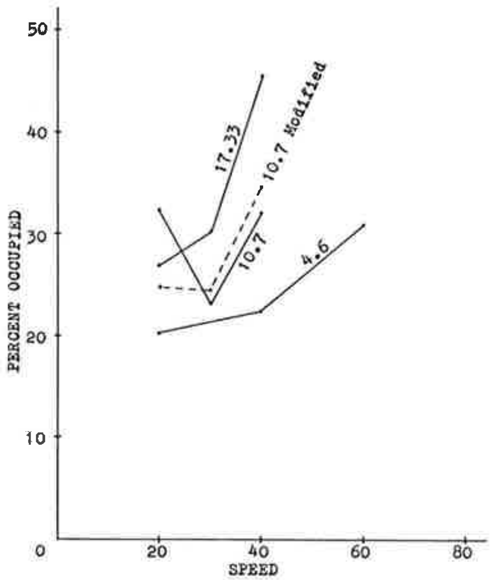


Table 3. Analysis of variance data for curves in Figures 4 and 5.

Curvature (deg)	Regression Equation	Correlation Coefficient	F-Value
17.33[a]	Y = 7.90 + 0.77 X	0.84	23.03
10.70[a]	Y = 14.24 + 0.44 X	0.83	22.56
4.60[a]	Y = 17.03 + 0.14 X	0.98	194.51
0.00	Y = 18.93 + 0.06 X	0.68	8.49
17.33[b]	Y = 6.47 + 0.91 X	0.94	79.38
10.70[b]	Y = 30.21 + 0.05 X	0.09	0.09
4.60[b]	Y = 13.47 + 0.18 X	0.87	31.53

Note: $F_{0.99}(2,20) = 5.85$.

[a]To the right. [b]To the left.

Figure 6. Work load at various curvatures and speeds for right turns.

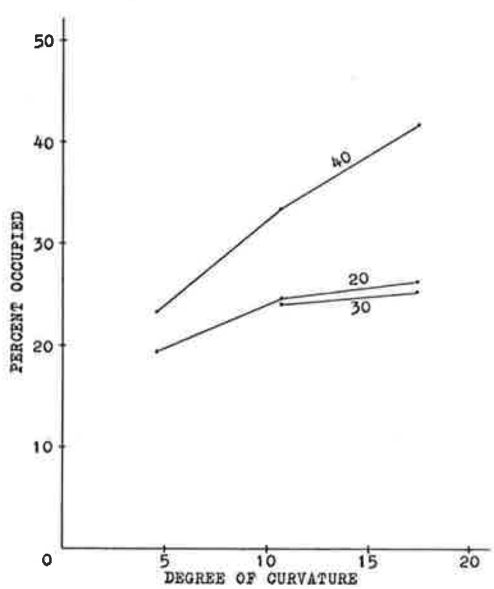


Figure 7. Work load at various curvatures and speeds for left turns.

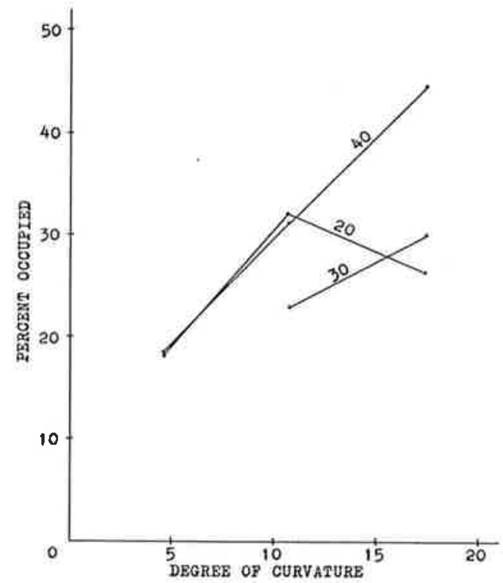


Table 4. Analysis of variance data for curves in Figures 6 and 7.

Speed (mph)	Regression Equation	Correlation Coefficient	F-Value
20[a]	Y = 17.65 + 0.54 X	0.95	88.93
40[a]	Y = 17.05 + 1.45 X	0.99	1450.73
20[b]	Y = 18.90 + 0.62 X	0.57	4.74
40[b]	Y = 17.53 + 0.15 X	0.98	217.66

Note: 1 mile = 1.6 km.
$F_{0.99}(2,20) = 5.85$; $F_{0.95}(2,20) = 3.49$.
[a]To the right. [b]To the left.

Figure 8. Frequency of occurrence of median locations in straightaway maneuvers.

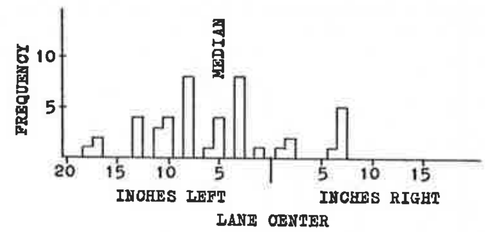


Figure 9. Frequency of occurrence of median locations for left turns.

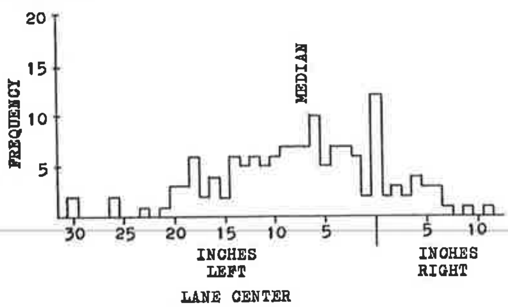


Figure 10. Frequency of occurrence of median locations for right turns.

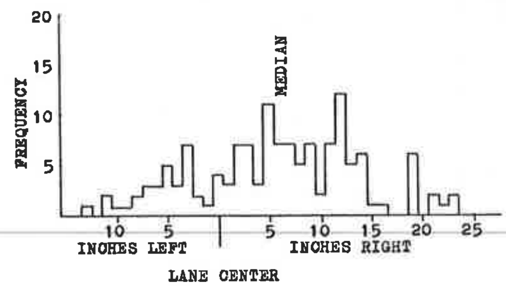
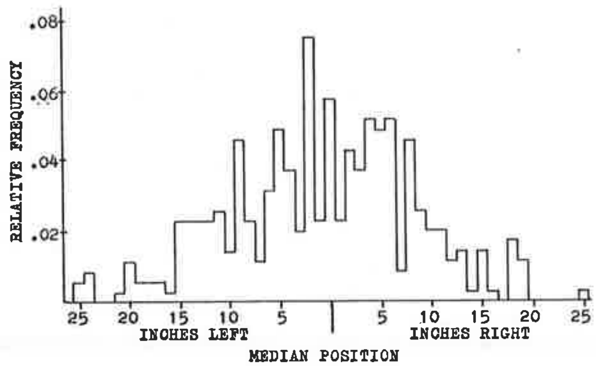


Figure 11. Frequency of drift distances—straightaway.



Control Data

During this study, films were made that contained photographs of the calibration bar and the right-lane stripe during the maneuvers. The films were later analyzed to determine how a driver steers a vehicle in a lane.

When the films were analyzed, the photograph of the calibration bar and target was projected onto a screen with a plastic overlay. The scale on the calibration bar was copied onto the plastic overlay, and the target was circled. Frames of film were then advanced one at a time, and the location of the stripe on the scale was read and recorded. As each frame was advanced, a check was made to determine whether or not the target was inside the circle on the screen. This was done to guard against improper framing by the projector or inadvertent movement of it.

At the end of the film reading, a sequential list was obtained that indicated the number of inches apart the stripe and right edge of the vehicle were at each 0.5 s during the data run. Data were analyzed to determine the median location of the vehicle in the lane for each data run. The median value was chosen because of its relative insensitivity to skewed distributions.

Figure 8 shows the frequency with which each median location occurred for all subjects while they were driving straight ahead. The median score is 5 in. (12.7 cm) to the left of lane center, which may be because drivers are better able to judge clearance on the left side of the vehicle and, consequently, leave more room for error on the right side.

Figures 9 and 10 show the frequency of each median location while drivers were turning left and right. Note that the data agree with the commonly observed tendency for drivers to move to the inside of a turn. The median location of the vehicle was assumed as the position to which subjects were continually steering the vehicle.

After the original data for vehicle location were reexamined, another analysis was performed. Steering wheel and lane position data were compared to determine the location of the vehicle in the lane at the time of each steering wheel input. These corrections were compared to the median location of the vehicle during that data run to determine how far drivers allowed the vehicle to drift from the median location before correcting its path.

Figure 11 shows the number of times each drift distance occurred for all subjects driving on the straightaway. Figures 12 and 13 show the number of times each drift distance occurred while the drivers were turning left and right respectively.

Table 5 gives the average lateral motion in in./s, which was induced by steering corrections at each speed used in the study. These data will be required when one attempts to simulate the steering inputs of a driver for computing the predicted stress.

Lane position and steering input data were gathered for three subjects under two conditions—repeating numbers and driving normally. Observations of the lane position data under these conditions revealed no significant differences; therefore, based on a sample of three subjects, it is assumed that the 11 subjects in the study were driving normally while their driver work loads were measured.

This study produced two sets of results. From the work-load data, the degree of tracking work load imposed on the driver by different maneuvers and speeds is now known. Further research will be required to determine the driver work load generated by higher level driving tasks. The control data results will be useful in simulating driver control inputs for calculating work load by use of the Senders method.

DISCUSSION OF RESULTS

The results represent a first step toward filling the gaps in knowledge in highway design so that driver work load can be predicted. The literature contains data on the time required to read signs of various designs and methods that exist by which the work load imposed on a driver by monitoring other vehicles on the roadway can be calculated. However, no data have previously existed on the attentional demand of lane tracking. Now that these data are available, the highway designer can calculate

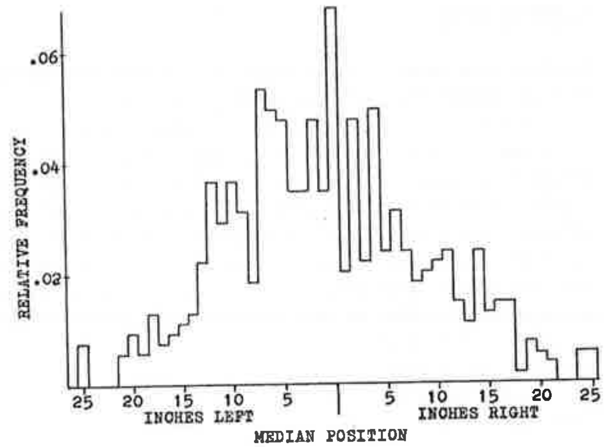


Figure 12. Frequency of drift distances for left turns.

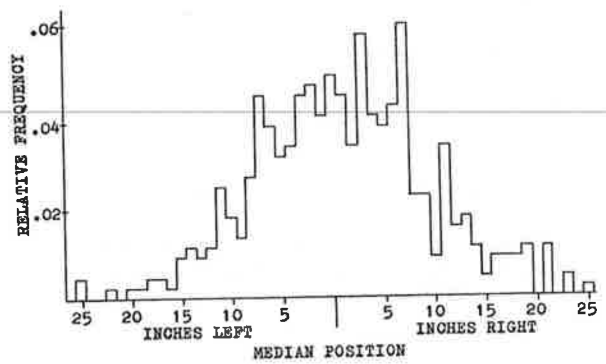


Figure 13. Frequency of drift distances for right turns.

Table 5. Average lateral speed induced by steering inputs.

Maneuver	Speed (mph)	Lateral Speed (in./s)
Sharp turn	20	3.88
	30	5.59
	40	4.23
Wide turn	20	3.21
	40	3.75
	60	3.65
Straightaway	40	2.21
	60	3.47
	80	3.36

Note: 1 mile = 1.6 km. 1 in. = 2.54 cm.

the work load of the total driving task.

Admittedly, the highway design features used in the study did not cover the full range of possible design features. Further research will be required to determine the attentional demand of highway designs outside this range. One obvious option is to directly measure driver work load on other highway design features to expand the data base. Another option is to calculate the driver work load by simulating the driving task by using the Calspan vehicle dynamics model and data for lane tracking.

The vehicle dynamics model is a computer simulation of a complete automobile including its steering and suspension systems. By defining the path and surface properties of a roadway, one can simulate the reactions of the vehicle to that roadway. However, the model currently steers itself as if it were driven by an autopilot. The model could be reprogrammed to steer itself in the way that a driver steers a vehicle. By use of a Monte Carlo technique, the vehicle could be allowed to drift from the lane center, and steering corrections would be input at various drift distances in keeping with the probabilities found for drivers in this study. The steering inputs would be those required to produce the lateral speeds also found in the study. When the vehicle dynamics model has been reprogrammed to steer itself as a driver would steer an automobile, the simulated steering corrections could be input to the Senders workload model to calculate driver work load for the specific highway design.

In conclusion, a method for calculating driver work load based on highway design has been delayed because driver work load from lane tracking was unknown. A work load based on lane tracking has been determined on a limited range of highway characteristics, and a method for calculating work load for characteristics outside this range has been formulated.

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DATA ACQUISITION SYSTEM FOR STUDIES OF DRIVER PERFORMANCE IN REAL TRAFFIC

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This paper describes a real-time data acquisition system installed in a full-sized North American automobile for the study of driver performance in real traffic and under various conditions of driver stress. The basic parameters recorded are distance traveled and three primary control movements: steering wheel, accelerator, and brake. Provision is also made for vehicle yaw measurement, driver's pulse rate, and perceived illumination level in night-driving tasks. Other parameters may be recorded as dictated by project requirements. Test conditions and principal findings of the various projects carried out at the National Research Council of Canada during the past 3 years are discussed. In these projects, the frequency and magnitude of steering wheel movements have formed the basis for assessment of driver performance and task difficulty. The application of power spectral analysis techniques appears most promising, and it is in this context that the advantages of a system for highly flexible, real-time data acquisition are most apparent.

•DURING the last 11 years, several researchers (3, 4, 5) have used instrumented vehicles to assess a driver's performance in traffic. Some work has also been done (6, 7, 8) on the stimuli that cause particular patterns of control movements. A consensus based on their results indicates that the relative skill of a driver can be assessed by an analytical study of the frequency and correlation of the three primary control movements: steering wheel, accelerator, and brake. Of these three, it appears that the frequency and magnitude of steering wheel movement may have the greatest significance.

In normal circumstances, the changing heading rate of a vehicle stimulates steering wheel movements. Lateral movement in more difficult circumstances in which constraints are imposed on the driver by external factors such as lane width and traffic density may also influence steering wheel movement. Wind speed and pavement surface characteristics will affect assessment of a driver's performance based on control movements. All external stimuli may be considered as independent random variables, and the separation of their individual contribution to the overall pattern of control movements is extremely difficult.

By using the same route for a given experiment in normal traffic situations, starting each test run at the same time of day, and acquiring sufficient data from each subject to form a statistically significant sample size, one can minimize the effect of these random variables.

This paper describes a real-time data acquisition system installed in a full-sized North American automobile for the study of driver performance in traffic. Application of this system in specific tests conducted by the National Research Council of Canada and findings from these tests are also reviewed. Following is a discussion of the test vehicle and the instrumentation used.

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TEST VEHICLE

The test vehicle is a standard North American four-door hardtop with a 429-in.^{3} (7-liter), V-8 engine, three-speed automatic transmission, numerous power options, and air conditioning. The air conditioning was mandatory so that cooled air could be provided for the data acquisition system.

The data acquisition system is housed entirely within the car trunk. The 110-Vac, 60-Hz electrical power requirements for the system are provided by an engine-driven 28-V alternator, a 24-Vdc battery system in the engine compartment, and two static inverters in the trunk. The maximum power output is 500 V-A.

Power for the signal transducers is obtained from a small rechargeable nickel-cadmium battery pack.

Preliminary investigations, confirmed by Blais (15), showed that the Vdc measured directly at the headlamps varied within wide limits, and consequent variations resulted in seeing distance. In night-driving tasks, headlamp voltage had to be controlled within precise limits. This was achieved by boosting the nominal voltage to 18 Vdc, which was then regulated to 12.8 Vdc (±0.10 percent). This did not affect any other part of the basic 12-V electrical system of the vehicle.

The trunk also houses a two-way, 35-W mobile radio transceiver for voice and data communications.

A low-pressure, pneumatic booster system with rear suspension has been added to prevent rear-end sag due to the increased weight in the trunk.

Principal dimensions of the vehicle are (1 in. = 0.03 m)

Item	Dimension (in.)
Overall length	222
Overall width	78
Overall height	57
Wheelbase	123
Track, front	63
Track, rear	64

The gross weight of the vehicle with zero fuel and no occupants is 4,950 lbm (2246 kg), and the weight distribution is 53 percent in the front and 47 percent in the rear.

Figure 1 shows the vehicle.

DATA ACQUISITION SYSTEM

The principal component of the data acquisition system is a third-generation, 16-bit minicomputer consisting of a central processor and a core memory that has a total capacity of 16-K bytes. The following external peripheral devices are interfaced with the central processor:

1. A 16-channel analogue-to-digital (A-D) converter with either random or sequential channel selection under program control. Each channel may be used with any one of five program-controlled gain settings. When there is a gain of unity, the maximum input voltage before conversion is ±10 V. The resolution after conversion corresponds to an output voltage change of approximately ±5 mV.
2. A 7-track reel-to-reel magnetic tape unit for bulk data storage and subsequent recovery. The recording density is 556 bpi, and the maximum tape capacity is 600 ft (183 m). When allowances for writing interrecord gaps and end-of-file gaps are made, the maximum effective data transfer rate from core to tape is approximately 350 eight-bit data bytes/second. At this maximum rate, the duration of a single test run before it is necessary to mount a new tape reel is approximately 45 min.

Figure 1. Test vehicle.

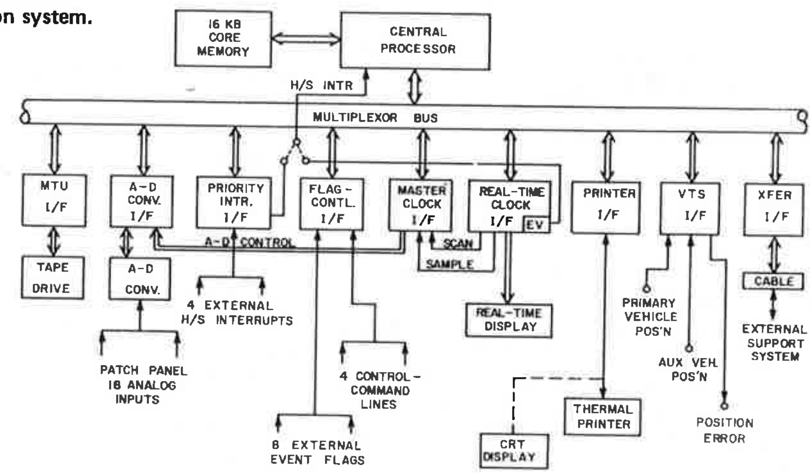


Figure 2. Data acquisition system.

Figure 3. Installation of system in vehicle trunk.

3. An 80-column thermal printer (300-baud rate). This provides direct access to and control of all data acquisition functions by commands entered from the keyboard by the operator. It also serves as an output device for logging system messages, and under certain circumstances, may be used for on-line printing of preselected data parameters during a test run.

The printer may be replaced by an optional cathode ray tube (CRT) display device (2,400-baud rate), which has the same input/output (I/O) functions as the printer but does not provide a hard copy. The CRT device may also be used to provide a graphical display of one or more data parameters, but as such it can only be used as a stand-alone device not under control of the real-time basic operating system.

There are five additional system components or interfaces, but, for the purposes of this paper, they may be considered peripherals because they function as I/O devices. These components are

1. A timing control system, which uses a 6-MHz crystal oscillator as a reference. The output is fed through a divider network and has two functions. It acts as a programmable master clock, which is used to control the time intervals at which data are read from the A-D converter. It also provides the reference for a programmable digital clock, which may be set to real time by an operator entry from the printer keyboard and read under program or operator control with a resolution of 1 ms. Real time may also be read and recorded simultaneously with data to verify data continuity during recovery from tape and to record occurrence time of specific events.
2. A high-speed interrupt device, which accepts up to four interrupts from external stimuli. These interrupts are acknowledged and serviced on a priority basis and take precedence over all normal system I/O interrupts, which are queued on the multiplexor bus.
3. A flag-control device, which has two functions. The flag section accepts up to eight interrupts from external stimuli, which are used simply as on and off indicators (event markers). The control section can control up to four external devices, which are not directly interfaced with the central processor. For example, a control line may be used to switch a chart recorder on and off at specified time intervals.
4. A vehicle-tracking device by which the relative position of the test vehicle and an auxiliary vehicle may be determined at any time. It also acts as a distance-traveled accumulator for the test vehicle.
5. A slave-transfer (I/O) device, which is not part of the data acquisition system proper. It is used with the laboratory support system for loading programs into the vehicle computer and for data transfer from the computer (or magnetic tape unit) to the support system devices for further processing.

Figure 2 shows a functional block diagram of the complete system.

The complete data acquisition system except the printer is rack mounted in a steel frame, which normally lies flat in the trunk (Fig. 3). The lower front edge of the frame is hinged, which allows the complete system to be swung up 90 deg for access to and servicing of the components.

The thermal printer (or CRT device) is installed in the rear-seat space of the vehicle on a board resting on the center portion of the bench seat.

SYSTEM CONTROL AND OPERATION

The data acquisition and control software interfaces with a basic operating system. These two programs together form a real-time system that occupies approximately 12,000 bytes of core memory and that gives the operator complete control of all data acquisition functions by commands entered from the printer keyboard.

The structure and operating principles of the data acquisition and operating system software packages are described by Sewell and Perratt (1).

Note that an equal-capacity, two-buffer system is used that permits incoming data to be stored in one buffer while, at the same time, the contents of the alternate buffer are being written on tape.

VEHICLE INSTRUMENTATION

Vehicle Tracking

The vehicle-tracking system (VTS) was designed primarily for use in night-driving tasks in which the driver of the test vehicle is subjected to headlamp glare from an approaching vehicle. In analysis of the data, one must be able to determine the relative position and velocity of the two vehicles at any given time.

In brief, the VTS accepts wheel revolution counts (equivalent to distance traveled) generated by the test and glare vehicles and, in combination with software, computes the positional error, which is then displayed to the driver of the glare vehicle. The display is a meter needle moving over a graduated scale; the displacement of the needle from the center-zero position indicates to the driver of the glare vehicle whether acceleration or deceleration is necessary to maintain position with the test vehicle.

Wheel revolution counts are generated by the test vehicle in the following manner. A system consisting of a two-lobe shutter and two photocell circuits is built into the left rear wheel hub. The shutter is coupled directly to the rear axle hub assembly, and, as it rotates, it sequentially interrupts the transmission of light between the emitter and receptor of each photocell circuit. Two symmetrical square-wave pulse trains are thus generated with a 90-deg phase shift and with 4 cycles per wheel revolution.

The pulse trains are fed to a sorting and decoding logic circuit designed to discriminate between forward and reverse vehicle motion. The end result is the generation of a single train in which there are eight pulses (counts) per wheel revolution.

Wheel revolution counts are generated by the glare vehicle similarly, except that the shutter is driven from the speedometer drive shaft. The sorting and decoding logic is less sophisticated, and the final train contains only four pulses per wheel revolution. Equating glare vehicle counts with those of the test vehicle is carried out by the data acquisition program.

The pulse train generated by the test vehicle is fed to a 16-bit, up-down counter that is software extended to 28 bits for forward motion only. In normal use, this counter is simply read on command to determine the total distance traveled in terms of the total accumulated wheel counts.

The pulse train generated by the glare vehicle is fed to a 12-bit counter whose contents are modulated and transmitted to the test vehicle every 100 ms by a mobile radio transceiver similar to that installed in the test vehicle. The received signal is fed to a demodulator that converts it back to binary form. The serial binary information is operated on by both hardware and software and is compared with the information in the test vehicle counter. The final result of the comparison represents the positional error of the glare vehicle, which appears as a 6-bit (sign plus 5 bits of magnitude) serial sequence preceded and followed by 1 synchronizing bit. This sequence is modulated and transmitted back to the glare vehicle. The position error signal is then demodulated and used to update a position error storage register, the contents of which are fed to a digital-to-analogue converter. The voltage output from the converter is then used to provide an analogue error signal on the visual display meter of the glare vehicle. The complete system, designed by Perratt, is described in detail and includes all logic circuits and software notes (2).

Digital Inputs

All serial digital inputs occur as step functions that are recorded as a change of state of a control flag. The flag states are set (high) or reset (low). Six serial digital inputs are currently available.

Turn Signals

Operation of the turn signal lever causes either the left- or right-turn flag to be set. A capacitive-discharge circuit ensures that the flag remains set as long as the signal light is flashing. A lockout feature is provided, which ensures that both flags remain reset when the emergency warning flashers are used.

Driver-Controlled Event Marker

The standard turn signal lever has been replaced by a specially designed lever having the same weight and center-of-gravity position. A spring-return microswitch is built into the lever, and the operating button projects from the stalk. The button is operated by light finger pressure and causes the flag to be set whenever it is pushed in.

The button may be used to signal an event of special significance while a test run is in progress. Alternatively, with suitable software, it may be used for data acquisition program control when, for psychological reasons, the presence of an operator in the vehicle is to be avoided.

Operator-Controlled Event Marker

This is a simple on-off switch and has the same functions as the driver-controlled event marker. It may also be used to convey a visual or audible signal to the driver.

High-Beam Indicator

The flag is set whenever the headlamps are switched to high beam and is not reset until low beam is returned to. The time on high beam is determined from the difference between the set and reset times.

Brake Applications

The flag is set whenever the brake pedal travel equals or exceeds 0.50 in. (1.27 cm) from the brakes-off position.

In this context, consideration has been given to measurement of hydraulic pressure directly at the brake cylinders as an analogue signal; however, this creates a number of currently unresolved problems in maintaining integrity of the braking system.

Analogue Inputs

For achieving maximum resolution, all analogue inputs generated by the signal transducers are preconditioned so that the voltage presented to the digitizer of the A-D converter has a maximum range of ±10 V after application of the program-specified gain factors.

Following are the analogue inputs currently available.

Steering Wheel Position

A 10-turn potentiometer is driven from a split pulley clamped to the lower end of the steering column, which is immediately forward of the firewall. The maximum steering wheel rotation is $4\frac{1}{4}$ turns lock-to-lock, and the angular resolution is approximately ±0.25 deg.

Accelerator Pedal Position

A single-turn potentiometer is driven from the throttle shaft linkage to the carburetor. The relationship between output voltage and pedal position is not absolutely linear, but the errors are not sufficiently significant.

The maximum pedal travel is 2.5 in. (6.35 cm), and the positional resolution is approximately ±0.001 in. (±0.025 mm).

Illumination Level

A photovoltaic cell with a cosine receptor is mounted immediately in front of the rear-view mirror at the top center of the windshield. The maximum output voltage is adjusted to suit the maximum opposing glare conditions to be expected. Typically, standard Society of Automotive Engineers (quad) headlamps on high beam result in a perceived illumination level of 1.0 ft-c (10.764 lx).

Yaw Measurement

Two servoaccelerometers are mounted on the vehicle. One is on the front bumper, and one on the rear, and their sensitive axes are perpendicular to the longitudinal center-line of the vehicle in the horizontal plane.

By appropriate combination of the two outputs, the resultant signal represents acceleration in yaw. Vertical and horizontal accelerations, either separately or combined, are almost eliminated by the low cross-axis sensitivity. Lateral- and roll-motion sensitivity are minimized by suitably matching the individual accelerometer sensitivities before the outputs are summed.

Driver's Pulse Rate

Three silver/silver chloride electrodes are attached to the driver's body with a non-irritant electrolyte gel, which completes the circuit between the skin and the electrodes.

The electrodes are placed as follows: (a) on the sternum approximately 2 in. (5.08 cm) below the larynx, (b) immediately over the heart, and (c) over the fifth intercostal space on the right side.

After signal conditioning and amplification are done, the voltage is supplied to a triggering circuit so that a rectangular pulse is generated at approximately 75 percent of the maximum systolic peak voltage.

The wave train thus generated may be used either to determine (a) the average pulse rate over a specified time period or (b) the actual time interval between each systolic peak. In the experiments carried out to date, the latter method has been used because it detects instantaneous changes resulting from transient stress conditions.

SUPPORT SYSTEM

A comprehensive support system is provided in the laboratory so that programs may be loaded into the on-board vehicle computer and recorded data may be extracted from core memory or tape.

The principal component of the support system is an advanced version of the computer installed in the vehicle, with 24-K bytes of core memory.

The following peripheral devices are interfaced with this computer:

1. A standard teletype (110 baud rate);
2. A high-speed card reader (400 cards/min);
3. A 132-column, high-speed line printer (300 lines/min);

4. A high-speed, paper tape reader-punch (read at 400 characters/s, punch at 75 characters/s); and
5. A 9-track, 25-in./s, 800-bpi read/write tape drive and controller for editing and rerecording raw data.

Support system facilities are interfaced with the vehicle computer by using the slave-transfer interface of the latter and a master-transfer interface, which is part of the support system facilities.

The complete support system facilities are also interfaced by a dataset adapter and modem (2,400 baud rate) with the central computational facilities (IBM 360/67 time-sharing system) of the National Research Council of Canada (NRCC).

The laboratory-based support system thus becomes a complete programmable remote-job entry terminal. By this, raw data may be preprocessed for transmission by the datalink to the central computer and may be stored there for further processing and analysis.

RESEARCH STUDIES AT NRCC

Research work carried out at NRCC for assessing driver performance can be classified under four main headings:

1. Experiments on a multilane, limited-access divided highway with a vehicle moving at a nominally constant speed (free-situation driving task);
2. Experiments on a route in which both the number of lanes (divided or otherwise) and the posted speed limit vary (controlled-situation driving task);
3. Night-driving tasks in which the driver of the test vehicle is subjected to head-lamp glare from approaching vehicles; and
4. Experiments to determine the effects of alcohol and drugs on driver performance.

The real-time data acquisition system described is a recent development and has been used operationally only in alcohol and drug experiments. All previous work was carried out by using a non-real-time system of considerably less complexity. In addition to the lack of a continuous real-time reference, high-speed interrupt, and external device control features, it did not possess the double-buffer system, which permits simultaneous data storage in the core and data transfer to tape.

Because of the lack of the double-buffer system, the core space available for data storage was restricted to that remaining after the basic control programs had been loaded. When this core space was filled, further data acquisition was suspended until the data in core had been transferred to tape. This gave the researcher two options: (a) acquiring data at relatively infrequent intervals from 30 min to 2 hours or (b) acquiring data at a high rate for as short a time as 1 min.

If the first option were exercised, the number, sign, and magnitude of steering wheel and accelerator pedal movements were determined as control reversals by the data acquisition software by using a logic method developed by Sewell (9). In exercising the second option, control positional information was stored directly in core.

Free-Situation Driving Task

The route chosen was a 35-mile (56-km) section of limited-access divided highway with six lanes on 5 miles (8 km) and four lanes on 30 miles (48 km). The posted speed limit throughout is 60 mph (96 km/h).

Sixteen volunteers were used (11 men and 5 women). Their ages ranged from 25 to 53, and they had from 9 to 30 years of driving experience. All subjects except one had accident-free records.

During the 11 months of the project, a total of about 6,000 miles (9600 km) were driven. For the first 2 months, an observer was carried in the vehicle, whose function was to make subjective estimates of traffic density at selected points along the route. For the remainder of the test period, the driver was the sole occupant.

Data were acquired at intervals of 7.5 s. Each 7.5-s time slice contained the following noncumulative information: wheel counts (distance traveled), number of steering reversals, number of accelerator pedal reversals, and number of brake applications.

For the first 2 months, steering wheel reversals were recorded at only one level of magnitude (2 deg). Preliminary analysis showed that this was insufficient and the number of levels was increased: from two (2 and 10 deg) to seven (from 1 to 30 deg). Accelerator pedal reversals were recorded at one level only [0.10 in. (2.5 mm)], and the number was not increased because of core space restrictions.

By a plot of steering reversal rate against magnitude for three vehicle speed ranges, Figure 4 shows the reasons for increasing the number of steering reversal levels. In Figure 5, essentially the same information is shown, but steering reversal rate is plotted against vehicle speed for seven levels of magnitude.

If the experimenter had selected steering reversal magnitudes from 8 to 12 deg as a criterion for assessment of driver performance, analysis would probably not have indicated any significant differences between subjects, nor would the effect of changes in vehicle speed have been apparent.

Except for one female subject who had driven professionally in sports car and formula A races, no significant correlations were established between steering and accelerator reversal rates. However, for her, correlation patterns were more consistent and were significant at the 5 percent level in 75 percent of the runs made.

The relationship between steering reversal rate and magnitude suggests that the performance of an individual driver may be associated with a unique pattern. Certainly, the more experienced (and less aggressive) drivers exhibited greater consistency in their control movement patterns.

The route was divided into nine sections according to observed average traffic densities. These observations, although highly subjective, were sufficiently informative to indicate that the frequency of steering reversals associated with vehicle tracking (5 deg of magnitude or less) depends on traffic density. Figure 6 shows the percentage of mean variation in steering reversal rate for each section. The highest traffic densities were observed in sections D to F and correspond to the six-lane section in which there are five interchanges.

The data were also analyzed to determine the effect of wind speed on steering reversal rates. Two reversal magnitudes were selected: 2 and 10 deg, the tracking and maneuver reversals respectively. The wind speed ranged from 0 to 20 mph (0 to 32 km/h) and was divided into subranges of 5 mph (8 km/h) each. The actual steering reversal rates obtained were normalized by dividing by the vehicle speed so that effects of changes in vehicle speed could be minimized.

The ratios of tracking and maneuver steering reversal rates to vehicle speed were plotted against wind speed, as shown in Figure 7. Both tracking and maneuver reversal ratios are linear functions of wind speed, and the proportion of tracking to maneuver reversals decreases exponentially with increasing wind speed.

Four experimental test runs were made with four male subjects to determine pulse interval. Each subject was instructed to use the event marker to signal the decision-making point in what he considered to be a difficult overtaking situation. Although the data obtained were insufficient for statistical purposes, some interesting general trends were apparent.

Each subject's pulse rate was first determined in an inactive, at-rest state. The average rate was 68 beats/min. Sitting in the stationary vehicle before starting a run increased the rate to 78, and moving on the highway at 60 mph (96 km/h) increased the average pulse rate further to 84 beats/min in a completely normal situation.

However, when the decision point had been reached in a difficult situation, the systolic interval initially increased from an average, normal situation value of 0.71 s to as much as 1 s and remained at that level for 3 or 4 beats. This was immediately followed by a sharp decrease in the systolic interval to 0.5 s or less, which corresponds to a pulse rate of 120 to 150 beats/min. The high pulse rate was maintained until normal driving conditions had been reestablished. Results of the free-situation driving

Figure 4. Steering reversal rate versus magnitude as function of vehicle speed.

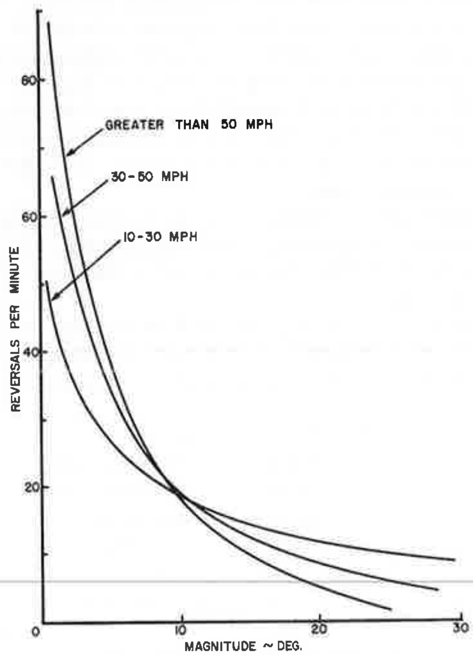


Figure 5. Steering reversal rate versus vehicle speed as function of magnitude.

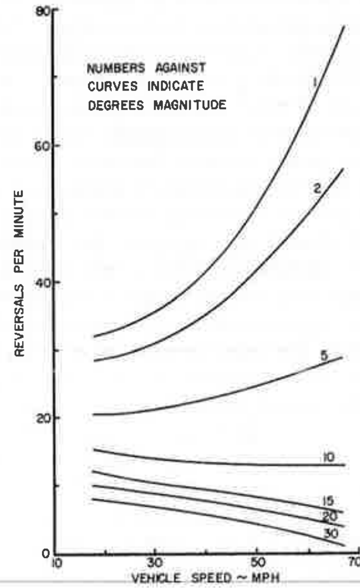


Figure 6. Percentage of mean variation in steering reversal rate by highway section.

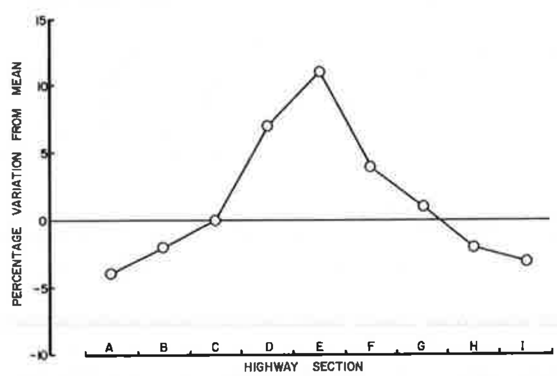
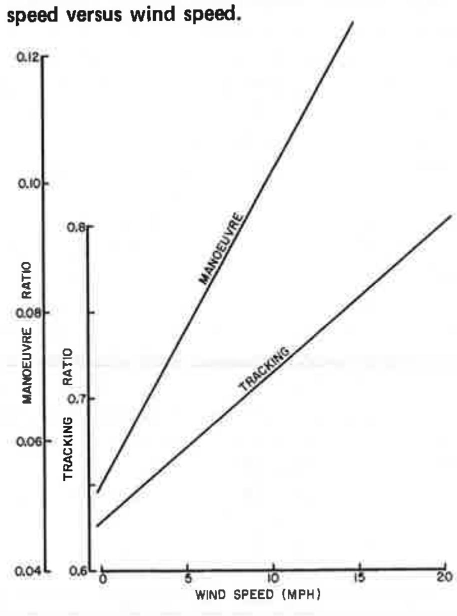


Figure 7. Ratios of steering reversal to vehicle speed versus wind speed.



task experiments will be published by Sewell (14).

Controlled-Situation Driving Task

The route chosen was 18.9 miles (30.2 km) long and was divided as given in Table 1.

Twelve volunteer subjects were divided into two groups according to age and experience. Each group had four men and two women; all had accident-free records.

Each subject was asked to drive over the route nine times and make three runs at each of three specified times of day. In all runs, an observer who was to keep a precise count of the number of approaching vehicles and to record the type of passing maneuver made by the subject was carried in the rear seat.

Data were recorded in the same manner as in the free-situation driving tasks, except that the number of steering reversal levels was increased to eight, and the number of accelerator pedal reversal levels was increased to five.

In general, each subject appeared to have a unique pattern of control movements that remained fairly constant throughout. The relationships between steering reversal rate and vehicle speed and between steering reversal rate and traffic density in the free-situation driving tasks were confirmed.

Statistical differences between the two groups (whose average driving experience was 7.3 years and 26.2 years respectively) were expected to be less than that reported by Greenshields and Platt (4), whose driving experience comparison groups were 10 weeks and 20 years. Although this expectation was found to be true, there were no significant differences in the means of each measure examined. This may reflect a greater similarity in driving ability as distinct from experience.

The less experienced group made significantly more fine-steering reversals (1 deg), which would suggest more accurate tracking performance. This would appear to be a somewhat paradoxical situation because tracking performance may be directly related to driving skill; however, tracking performance should be considered as follows (7):

> Steering is a loosely constrained tracking task requiring that errors be kept within acceptable limits rather than continuously minimized. The ability to assess an acceptable tolerance on steering errors is one of the skills of driving. Excessively accurate steering reduces the driver's capacity for handling other facets of the driving task.

The less experienced group made fewer accelerator reversals and more brake applications. This suggests that the driver with less experience is more inclined to use the brakes as a means of controlling vehicle speed. Results of these experiments have been reported by Smiley (10).

Night-Driving Tasks

Night-driving experiments were conducted on a section of highway not yet opened to the public. The objective was to obtain data for steering wheel position and related illumination levels for typical two-lane passing situations in which the driver of the test vehicle was subjected to glare from approaching vehicles.

Analysis of data in previous work and studies by McLean and Hoffman (6, 7, 11) have indicated that power spectral analysis methods applied to data for steering wheel position would prove most informative.

The successful application of power spectral analysis methods to discrete raw data requires that data samples be obtained at a frequency not less than five times the maximum expected frequency of occurrence. So that this requirement could be satisfied, data were acquired at a rate of approximately 17 samples/s. Core space restrictions limited the duration of a single run to approximately 1 min.

Table 1. Section description of route for controlled-situation driving tasks.

Type of Road	Number of Lanes	Divided	Length (miles)	Traffic Density	Speed Limit (mph)
Suburban	2	No	3.5	Low	30
Limited-access	4	Yes	5.2	Medium-to-high	60
Suburban	4	No	6.8	Medium	30
Suburban	4	Yes	3.4	High	40

Note: 1 mile = 1.6 km.

Table 2. Headlamp conditions.

Condition	Test Vehicle	Glare Vehicle
A	Low beam	None
B	High beam	None
C	Low beam	Low beam
D	Low beam	High beam

Figure 8. Normalized power spectra of steering wheel movement with no opposing glare.

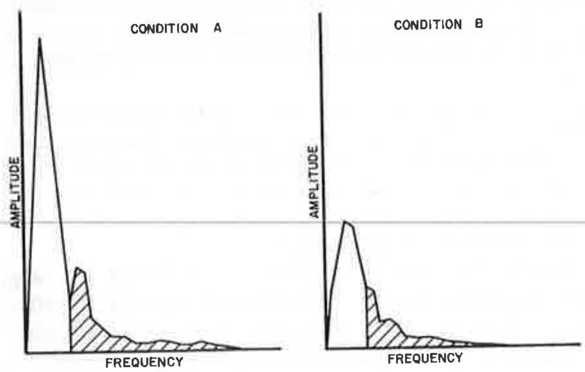
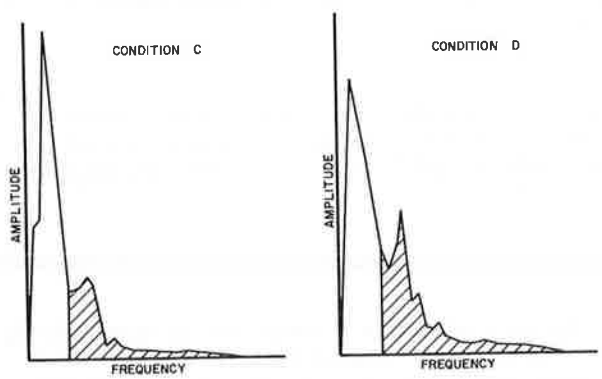


Figure 9. Normalized power spectra of steering wheel movement with opposing glare.



Six subjects were used: Three were between 26 and 30, and three were over 50. The older age group was chosen on the assumption that the eyes of those over 40 are more affected by glare.

All test runs were made at vehicle speeds of 60 mph (96 km/h) under the headlamp conditions given in Table 2.

For conditions C and D, two glare vehicles followed each other so that the driver of the test vehicle would be subjected to glare from the second vehicle 10 to 15 s after the first had passed. The first vehicle or glare vehicle was equipped with a headlamp voltage control system identical to that in the test vehicle. All vehicles were fitted with standard SAE (quad) headlamps. All subjects completed 12 runs for each no-glare condition and 18 runs for each glare condition.

The power spectral analysis of the density function of steering wheel movement frequency was calculated for each run by using the methods given by Bendat and Piersol (12).

For the no-glare conditions, the spectra were calculated for four consecutive 15-s periods and then averaged. For the glare conditions, the spectra were calculated for the 15-s period before each meeting point and 2 s after the second meeting.

According to McLean and Hoffman, the proportion of the area of the spectrum above 0.4 Hz increases with increasing task difficulty. Figures 8 and 9 show four typical normalized spectra, one for each headlamp condition (high-frequency area is indicated by hatching). For the condition given, the increasing order of task difficulty according to the McLean-Hoffman criterion is B, A, C, and D.

The average number of steering reversals between 2 and 8 deg of magnitude was greater for opposing glare conditions, whereas for steering reversal magnitudes equal to or greater than 15 deg, the average number was greater for no-glare conditions.

Any effects of glare on steering wheel movements as a function of the age of the subject were not apparent. The work involved in this project is discussed in detail by Smiley (13).

Effects of Alcohol and Drugs

These experiments were conducted on an easterly extension of the same highway (not open to the public) used for the night-driving tasks. The project was sponsored by the Insurance Bureau of Canada and carried out under medical supervision.

Vodka was administered diluted with orange juice, or it was given with either marijuana, an antihistamine (diphenhydramine), or a sedative (diazepam). Orange juice alone or with sugar capsules or marijuana cigarettes from which the active chemical ingredient (THC) had been extracted were administered as placebos.

Alcohol was administered in sufficient quantity to raise the blood alcohol level to 0.06 percent (the legal limit in Canada is 0.08 percent), and the drugs were given in proportion to body weight.

Eight volunteer subjects were used (6 men and 2 women), aged 19 to 27. All had not less than 2 years of driving experience, and all had used both alcohol and marijuana previously.

This was the first series of experiments in which the complete real-time data acquisition system was used. Steering wheel position and interval wheel counts were recorded at intervals of 50 ms. Total accumulated wheel counts and real time were recorded synchronously with these parameters at intervals of 3 s.

A special feature was introduced to determine the driver's reaction times and ability to cope with a secondary task. A red signal light was switched on at programmed random intervals, and when the driver became aware that the light was on, he or she was to switch it off by depressing a foot-operated switch. Each on-off sequence generated a priority interrupt and the event times were stored in the memory.

The test section was 8.5 miles (13.6 km) long. At the approximate center, a 2,000-ft (610-m) slalom course containing a number of sine-curve bends of varying amplitude was set up by using fluorescent cones to define a path varying in width from 8 to 10 ft (2.4 to 3.0 m). A group of three vehicle-activated traffic signals was set up at the end of the test section.

Each subject was instructed to accelerate to 60 mph (96 km/h) from the start, decelerate to 25 mph (40 km/h) on approaching the slalom, and take the vehicle through the course at that speed. The subject then accelerated to 60 mph (96 km/h) again and, at 300 yd (274 m) from the traffic signals, reduced speed to 30 mph (48 km/h) and stopped at whichever signal showed red. The front wheels were to touch a white line painted across the highway opposite the signal. The stopping error distance was then recorded.

Additional control tasks were introduced in the 60-mph (96-km/h) sections by using approaching vehicles [also traveling at 60 mph (96 km/h)] in the adjacent lane.

After the control runs for familiarization, each subject made one run 1 hour after administration of alcohol alone, the alcohol-drug combination, and the placebo to establish normal patterns. Although a complete report is not yet available, preliminary analyses have indicated the advantages of the real-time system. Power spectra of steering wheel movement show marked differences between all alcohol-drug combinations.

The subjects' approach and traverse through the slalom course varied from recklessness to extreme timidity. Vehicle control in the course was highly erratic, and in some cases, the subject came to a halt in the middle of the course. In some cases, the secondary task reaction times of the impaired drivers were less than when they were unimpaired. This indicates that the subject gave more attention to secondary task detection than to the primary task of controlling the vehicle.

RESEARCH PROJECT DEVELOPMENT

It is difficult, as with much applied research, to make firm predictions about what courses may be pursued in the future. These frequently depend on the results obtained a few months earlier, and it is quite conceivable that much of the data obtained at that time will be discarded. Nevertheless, there are certain fairly obvious statements that can be made about future motor vehicle and driver research projects at NRCC.

Up to the present time, we have been concerned primarily with the measurement of driver control movements, and there do not appear to be any valid reasons for abandoning this basic approach. However, so that information on steering wheel position may be used more effectively, simultaneous recording of heading rate error is essential. There is also room for more and improved measurement of physiological functions.

The advantages of a real-time system with a high data acquisition rate are mainly for applying power spectral analysis techniques, particularly to the establishment of cross correlations. The instrumented vehicle should not, however, be regarded as a tool for the measurement of driver performance simply because one can look at two sets of data and arrive at the immediate conclusion that subject A is a better driver than subject B. Better describes the level of manipulative and cognitive skills that have been used in the task in which the measurements have been taken. There is absolutely no guarantee that a so-called better driver is necessarily a safer driver.

The instrumented vehicle can be used more for assessing differences in behavior in any set of circumstances, determining task difficulty, and probing for investigation of highway conditions that affect driver performance.

CONCLUSIONS

The real-time data acquisition system installed in the test vehicle is highly sophisticated and extremely useful for driver and vehicle research. It is completely open-ended because research is limited only by the time needed to develop such specialized data acquisition subsystems as may be required.

Because of the weight, size, and power requirements, use of the system is, however, obviously limited to full-sized North American vehicles. As a result of this limitation, we are currently engaged in the development of a miniaturized, highly flexible, and relatively simple real-time data logging system in which parallel binary data will be serialized and recorded on a dual-track analogue tape recorder. This system will operate from the standard 12-V electrical system of any vehicle, have a very low power requirement, and be small enough to be installed in subcompact vehicles.

The development of this system and improvements in transducer and other sensor circuitry are expected to increase the data acquisition rate to a maximum of 1,000 data samples/s.

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