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;

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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

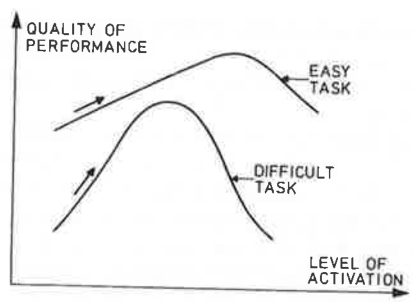


Figure 1. Relationship between level of activation and quality of performance.

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

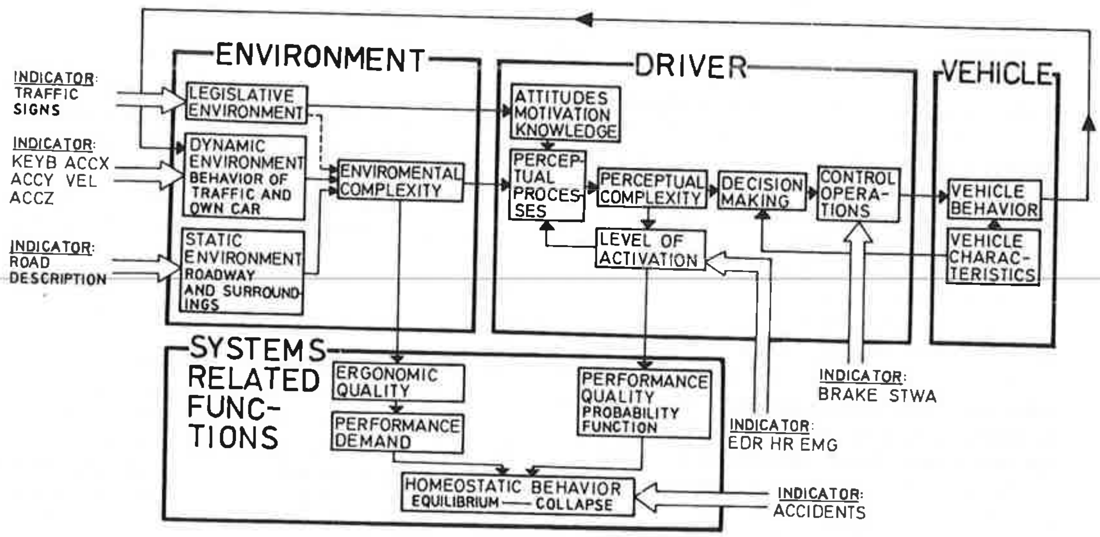
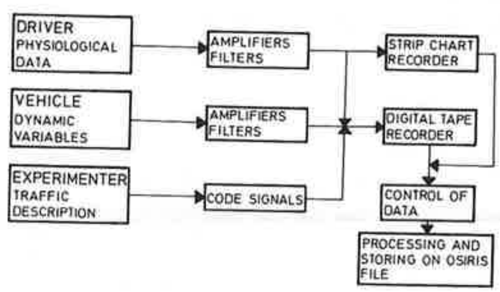


Figure 3. Plan for collecting data.



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.

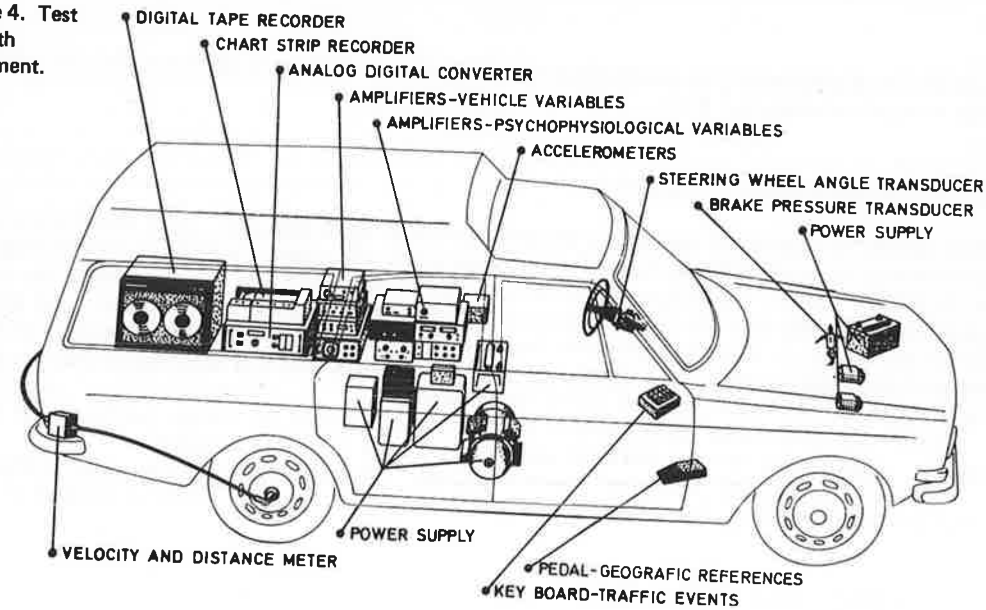
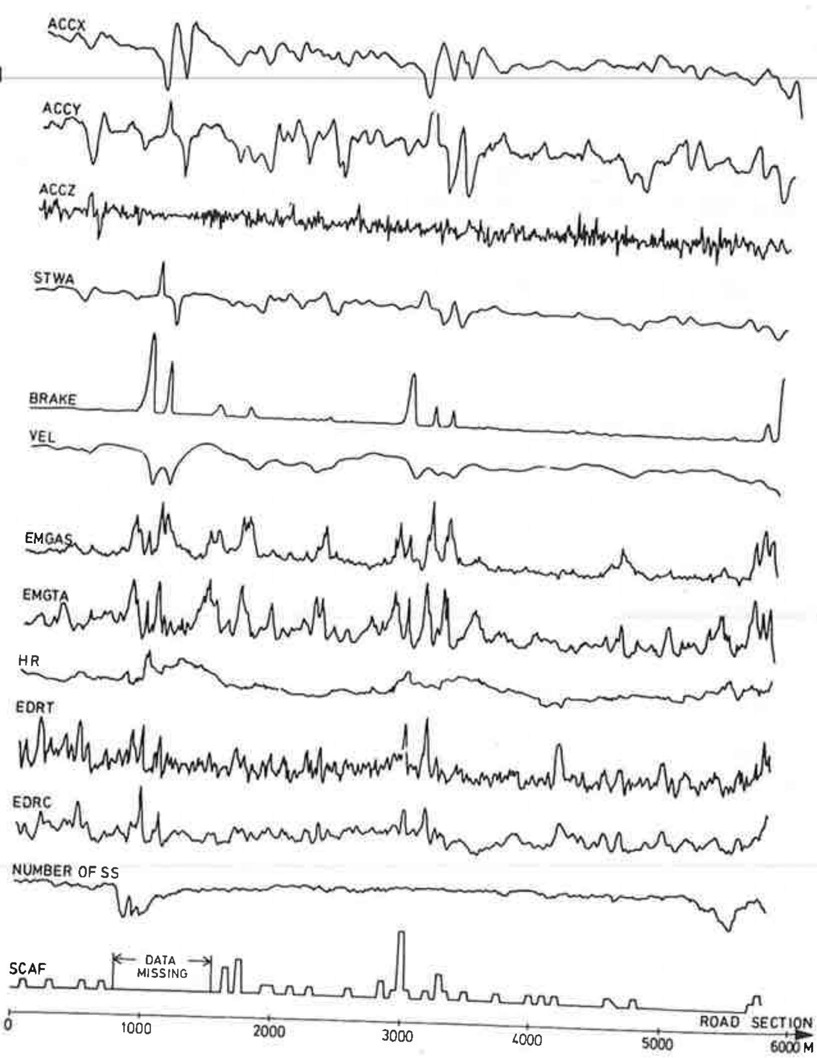


Figure 5. Average response profiles obtained on first road stretch for 60 drivers.



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.

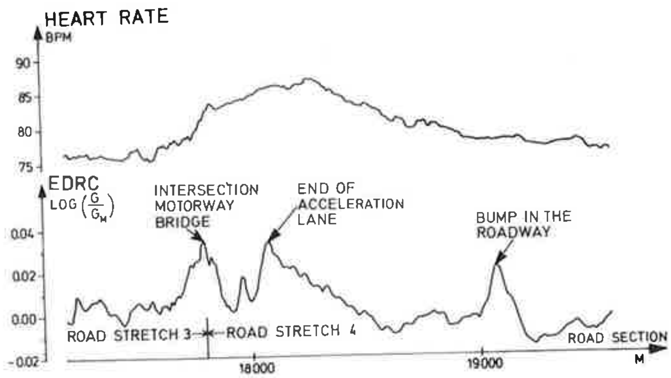


Table 1. t-tests of differences in environmental and accident variables obtained for low-and high-score conventional electrodermal response and heart rate.

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			-3	0.77
	EMGTA	-2		-1					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.

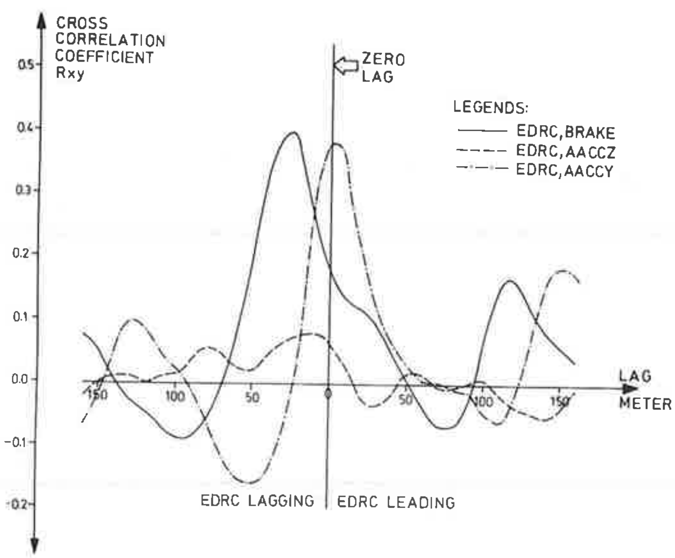
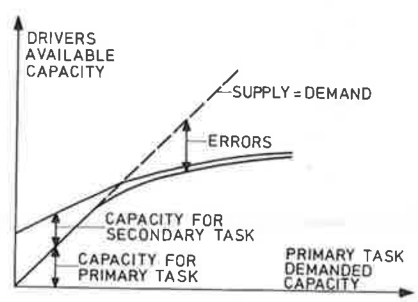


Figure 8. Driver's available capacity as function of primary task demand.



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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