DOT HS-801 302

ALCOHOL IMPAIRMENT OF PERFORMANCE ON STEERING AND DISCRETE TASKS IN A DRIVING SIMULATOR

Contract No. DOT-HS-227-2-388
December 1974
Final Report

PREPARED FOR:

U.S. DEPARTMENT OF TRANSPORTATION

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

WASHINGTON, D.C. 20590

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS-801 302		

4. Title and Subtitle	5. Report Date
ALCOHOL IMPAIRMENT OF PERFORMANCE ON STEERING AND DISCRETE TASKS IN A DRIVING SIMULATOR. Part I: Effects of Task Loading. Part II: Moderate vs. Heavy Drinkers	December 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Henry R. Jex, R. Wade Allen, Richard J. DiMarco, and Duane T. McRuer	TR-1021-1
9. Performing Organization Name and Address	10. Work Unit No.
Systems Technology, Inc. 13766 South Hawthorne Boulevard Hawthorne, California 90250	11. Contract or Grant No. DOT-HS-227-2-388
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Department of Transportation National Highway Traffic Safety Administration 400 Seventh Avenue, S. W. Washington, D. C. 20590	Final Report June 1, 1972-Dec. 31, 1973
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In this program a simplified laboratory simulator was developed to test two types of tasks used in driving on the open road: a continuous "steering task" to regulate against gust induced disturbances and an intermittent "discrete response task" requiring detection, scanning, recognition, and motor response typical of, for example, horn or brake operations. The development and details of this simulator, the many behavioral and performance measures, and some basic effects of blood alcohol concentrations of up to 0.11 BAC on a mixed group of 18 moderate and heavy drinkers is given in Part I of this report. Part I concentrates on the differences between the driving and discrete tasks both alone and combined, to establish the foundations for Part II.

Part II covers the main objective of this program, the differences in alcohol impairment of driving performance between "moderate" and "heavy" drinkers. This objective was successfully met using a cross-section of 20 typical licensed drivers ranging in age from 21-65 years, 10 of each type of drinking habit. For selected cases, eye-point-of-regard measures were taken which gave new insights into the detection and recognition aspects of the discrete tasks. Blood alcohol concentrations equivalent to around 0.11 percent of moderate drinkers and 0.16 for heavy drinkers were used, with distinct and self-consistent differences noted between drinker types.

17. Key Words	18. Distribution Statement
Alcohol Impaired Driver Performance Driving Performance of Moderate vs. Heavy Drinkers Driving Simulation and Performance Measurement	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	63	

Form DOT F 1700.7 (8-69)

PREFACE

The Driver Performance Research Branch of the National Highway Traffic Safety Administration is sponsoring a number of research projects to investigate how alcohol impairs various aspects of driving, with the ultimate goal of providing improved countermeasures. Because the systematic testing of drunk drivers on open highways would be dangerous, and field testing is too expensive for broad coverage exploratory research, much of this basic work can most efficiently be done in fixed base car simulators.

In this program a simplified laboratory simulator was developed to test two types of task used in driving on the open road: a continuous "steering task" to regulate against gust induced disturbances and an intermittent "discrete response task" requiring detection, scanning, recognition, and motor response typical of, for example, horn or brake operations. The development and details of this simulator, the many behavioral and performance measures, and some basic effects of blood alcohol concentrations of up to 0.11 BAC on a mixed group of 18 moderate and heavy drinkers is given in Part I* of this report. Part I concentrates on the differences between the driving and discrete tasks both alone and combined, to establish the foundations for Part II.*

Part II covers the main objective of this program, the differences in alcohol impairment of driving performance between "moderate" and "heavy" drinkers (defined later). This objective was successfully met using a cross-section of 20 typical licensed drivers ranging in age from 21-65 years, 10 of each type of drinking habit. For selected cases, eye-point-of-regard measures were taken which gave new insights into the detection and recognition aspects of the discrete tasks. Blood alcohol

*The two parts of this report have been prepared in the format of separate papers for publication in appropriate journals, so each has its own abstract, text, conclusions, and references.

concentrations equivalent to around 0.11 percent of moderate drinkers and 0.16 for heavy drinkers were used, with distinct and self-consistent differences noted between drinker types.

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ALCOHOL EFFECTS ON DRIVING BEHAVIOR AND PERFORMANCE IN A CAR SIMULATOR*

R. Wade Allen, Henry R. Jex, Duane T. McRuer,
and Richard J. DiMarco†
Systems Technology, Inc., Hawthorne, California

ABSTRACT

A fixed-base simulation has been developed to test the effect of alcohol on driving performance. The simulation includes both lateral steering control and a discrete visual detection, recognition, and response task set up to provide the workload and division of attention typical of real world driving. Measurements of both driver control behavior and driver/vehicle performance were obtained for the steering task, and detection and recognition indexes and reaction time were measured on the discrete task. Preliminary results on scanning behavior as measured with an eye-point-of-regard monitor are also presented.

Data are given for eighteen drivers, ranging in age from 21-65, at BAC $\doteq$ 0, 0.06, and 0.11. Alcohol causes larger lane and heading deviations, and increases detection and reaction times on the discrete task. Control-behavior measures show that the driver's control gain decreases but stability margins are maintained under alcohol, while driver remnant increases. Such effects could be due to indifference thresholds and/or intermittent attention in the control task.

Both continuous steering control and discrete peripheral "sign" response tasks were performed, singly and combined, to investigate the effects of divided attention. Performance on the steering control task was decreased when both tasks were done concurrently, but the sensitivity to alcohol effects was similar.

The driving simulation has proven an efficient tool for alcohol research. It has gained acceptance from subjects as a valid approximation of driving, and the various related measurements have proven to be reliable and sensitive to levels of intoxication.

*This work was sponsored under Contract DOT-HS-227-2-388 by NHTSA's Office of Driver Performance, with Dr. Leland Summers as Contract Technical Manager

†Senior Research Engineer, Principal Research Engineer, Technical Director, and Staff Engineer, Analytical, respectively.

INTRODUCTION

The epidemiological connection of alcohol with automobile accidents is fairly well established (e.g., Refs. 1 and 2). It has been found that the probability of involvement in serious crashes increases dramatically for blood alcohol concentration beyond 0.08 g/100 ml* (Ref. 3). A great deal of research has been devoted to identifying driving-relevant behavior impaired by alcohol. Past studies have employed a range of approaches including actual field test situations (e.g., Refs. 2 and 4), laboratory driving simulations (e.g., Refs. 5 and 6), and simpler laboratory tasks which measure psychomotor and/or cognitive skills (e.g., Refs. 7 and 8).

Although alcohol studies are hampered in general by procedural problems with dosage administration and measurement, and between-subject variability due to motivation and personality factors, some relatively generalizable results have surfaced from past research. First, the performance on divided attention tasks seems particularly sensitive to alcohol (Ref. 8-10). Further, in tasks requiring peripheral visual detection, alcohol seems to cause a "tunneling" effect such that peripheral information is either missed, ignored, or results in increased reaction times over sober performance (Refs. 9 and 11). Finally, although it has proven difficult to correlate the effects of alcohol on simple laboratory psychomotor tests with simulated and actual driving performance (Refs. 6 and 12), alcohol does consistently degrade driving performance both in terms of lateral (lane) position control (Refs. 6 and 13) and response to discrete events (Refs. 5, 13-14).

A great deal of effort has been devoted to determining the behavioral elements associated with discrete tasks, such as detection, information processing, etc., that are degraded by alcohol (Refs. 5, 10-11). This level of effort has not been carried through to the continuous control behavior portion of driving, however, which produces lane deviations that ultimately influence the probability of accident involvement.

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*Blood alcohol levels are given here in conventional units of grams ethanol per 100 millileters of blood, as measured by breath alcohol concentration, BAC (Ref. 23).

Research on driver control behavior has often been stymied in the past by the lack of appropriate behavioral models and efficient measurement techniques; however, recent advances in manual control technology have changed this situation. Guidance and control laws for driver/car steering have been developed and analyzed (Ref. 15), and validated with simulator and field test measurements (Refs. 16 and 17). Finally, efficient procedures have been developed which allow the driver's complex multiloop control behavior to be interpreted with simple describing function measurements (Ref. 18).

The purpose of this paper is to describe a simple, yet realistic and relevant, set of laboratory driving tasks and to present results from their use in a study of the basic effects of alcohol on driving. The driving tasks included both continuous steering control and discrete visual-motor response tasks requiring detection, scanning, and recognition. The two types of task were performed both separately and in combination in order to determine the effect of task interference on alcohol impairment. The other objective of this research was to determine if there is differential impairment between moderate and heavy drinkers, and these results are presented in a companion paper (Ref. 19).

SIMULATION AND MEASUREMENTS

Past research has shown divided attention tasks to be sensitive to alcohol impairment, and in fact typical driving situations involve a combination of both continuous control behavior and visual monitoring of discrete events, performed in parallel (Ref. 20). Accordingly, our simulation was set up to present the driver with both types of tasks as shown in Fig. 1, for which the scenario was driving on a rural road at night in stormy weather. The driver's control task was to drive down the center of a lane presented on a CRT display, while regulating against disturbances similar to those caused by wind gusts and/or road roughness. The discrete task consisted of peripheral "signs" which randomly flashed messages requiring response with the horn or brake. The details of the tasks and measures are as follows.

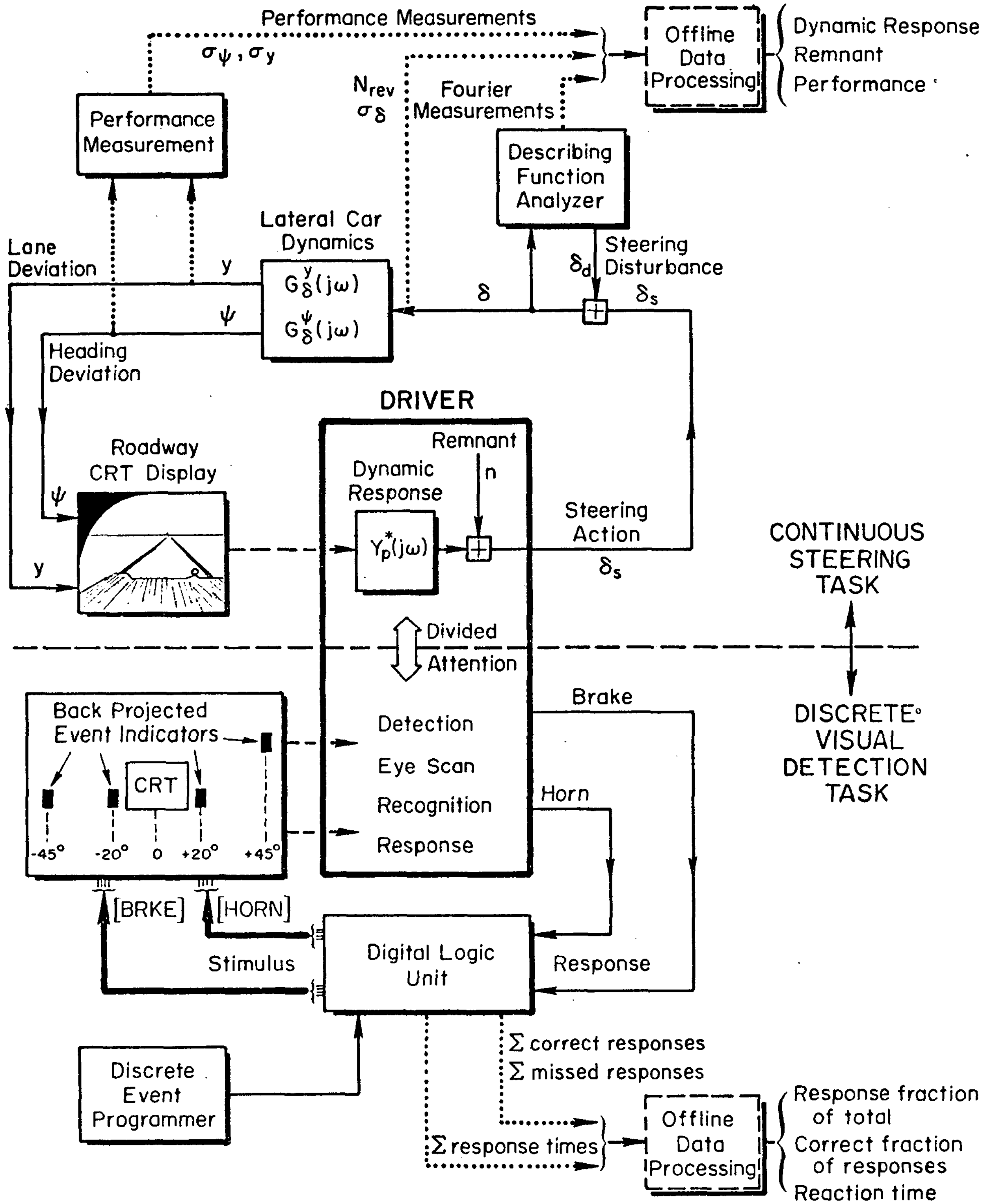
Steering Control Task

The control task scenario was similar to driving down a single lane road at night. The lane edges were drawn in perspective on the CRT with decreasing intensity in the distance. Heading and lane deviations of the car were represented properly by motions of the road relative to a fixed mask of a car hood, left fender, and windshield outline as shown in Fig. 1. An 8" × 10" CRT was used and the entire scene (mask and road) scaled down by 0.6 times in order to preserve the natural framing provided in a real car. A modified 1968 Mustang cab was used with the CRT mounted on the hood 24 in. in front of the driver. The steering wheel feel was set up to approximate the force feel characteristics of a power steering unit.

Two-degree-of-freedom equations were used for the car dynamics (Refs. 16 and 18) such that steering wheel inputs generate heading (ψ) and lateral (y) deviations which then drive the display. The dynamics used for this study were representative of an American sedan traveling at 30 mph and are summarized in Table 1. A disturbance signal was combined with the driver's steering signal as shown in Fig. 1, to simulate an equivalent wind gust input against which the driver had to regulate in order to maintain a center lane position. The disturbance was composed of a sum of five nonharmonically related sinusoids which appeared subjectively to be random.

The driver's steering behavior is modeled as quasi-linear response operations on ψ and y, plus an additive noise (remnant) as shown in Fig. 1. It is the parameters characterizing these two processes that we wish to measure in order to define the effect of alcohol on driver control behavior. The driver's dynamic response, Y_p^*, characterizes the portion of total steering control linearly correlated with heading and lateral deviations of the car. Since the perspective display is integrated and perceived as an entity, it is difficult to determine the manner in which ψ and y information is combined and processed. This problem is circumvented, however, with a recent development in multiloop car/driver measurement (Ref. 18). The technique results in an equivalent single-loop measurement of the driver's describing function, Y_p^* which combines the individual operation on functions of ψ and y. A typical form of Y_p^* is shown in Fig. 2. The magnitude of the low-frequency amplitude reflects the driver's sensitivity (gain) to path error

Figure 1



Performance Measurements
σ_ψ, σ_y
N_{rev}
σ_δ
Fourier Measurements
Offline Data Processing
Dynamic Response
Remnant
Performance
Performance Measurement
Describing Function Analyzer
Lateral Car Dynamics
Lane Deviation
y
$G^y_\delta(j\omega)$
ψ
$G^\psi_\delta(j\omega)$
Heading Deviation
δ
δ_d
Steering Disturbance
δ_s
DRIVER
Remnant
n
Dynamic Response
$Y^*_p(j\omega)$
Roadway CRT Display
Steering Action
δ_s
CONTINUOUS STEERING TASK
Divided Attention
DISCRETE VISUAL DETECTION TASK
Back Projected Event Indicators
CRT
-45°
-20°
0
+20°
+45°
Detection
Eye Scan
Recognition
Response
Brake
Horn
[BRKE]
[HORN]
Stimulus
Digital Logic Unit
Response
Discrete Event Programmer
Σ correct responses
Σ missed responses
Σ response times
Offline Data Processing
Response fraction of total
Correct fraction of responses
Reaction time

TABLE 1

CAR DYNAMICS AND DISTURBANCE INPUT

TRANSFER FUNCTIONS:

Path Control Dynamics

$$G_{\delta}^{y} = \frac{K_{ay}[s^2 + 2\zeta_y\omega_y s + \omega_y^2]}{s^2[s^2 + 2\zeta_1\omega_1 s + \omega_1^2]} = \frac{90.9[s^2 + 2(.36)(7.6)s + 7.6^2]}{s^2[s^2 + 2(.94)(5.6)s + 5.6^2]}$$

Heading Control Dynamics

$$G_{\delta}^{\psi} = \frac{19.5(s + T_r^{-1})}{s[s^2 + 2\zeta_1\omega_1 s + \omega_1^2]} = \frac{19.5(s + 6.1)}{s[s^2 + 2(.94)(5.6)s + 5.6^2]}$$

where ζ_1, ω_1 = damping and natural frequency of car heading response

T_r^{-1} = heading response zero

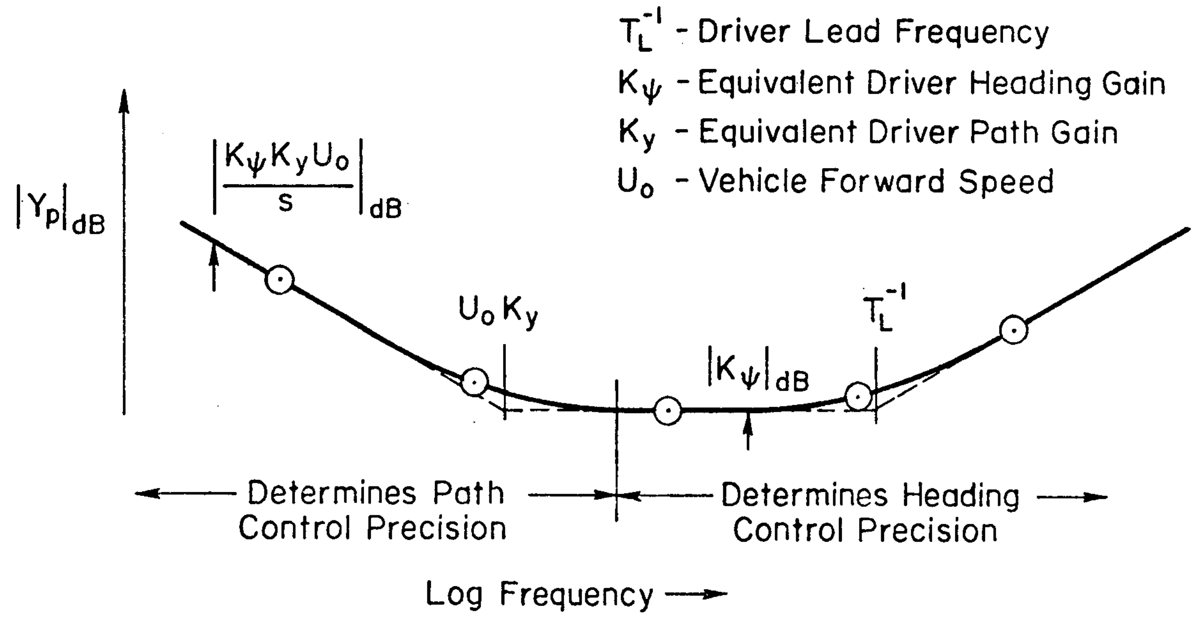
ζ_y, ω_y = damping and natural frequency of car lateral acceleration numerator

DISTURBANCE: $\delta_d = \sum_{k=1}^{5} A_k \cos(\omega_k t + \varphi_k)$

k	ω_k (rad/sec)	A_k STEERING WHEEL degrees
1	.19	6.36
2	.50	3.18
3	1.26	1.59
4	3.02	0.80
5	6.28	0.80
σ_{δ_d}		5.2

Figure 2

EQUIVALENT DRIVER DESCRIBING FUNCTION AMPLITUDE



(K_y), while the mid- and high-frequency amplitude reflect heading sensitivity (K_ψ). The high-frequency break point represents lead (anticipation) generated by the driver to offset the lags in the vehicle heading response (Refs. 15 and 18). Generally, higher open-loop gains imply better closed-loop performance, up to the level at which stability margins are reduced to the point of diminishing returns, and oscillatory resonance sets in.

The above measurements were made using the STI Describing Function Analyzer (Ref. 21) as shown in Fig. 1. Associated performance measurements were also obtained with an analog computer and combined in further off-line data processing to yield a comprehensive set of performance and underlying driver control dynamic response measurements. The dynamic response measurements included the equivalent driver describing function, $Y_p^*(jw)$; unity-gain and 180-deg-phase "crossover" frequencies (ω_c, ω_u) which are measures, respectively, of the actual and maximum achievable heading loop bandwidth; phase margin (φ_M), a measure of the heading loop closure stability margin; system rms performance measures of key signals such as steering wheel motion (δ_s), heading (ψ), and lane deviation (y); and overall linear coherency of the driver's steering action relative to the input disturbance ($\rho^2_{\delta_s}$) in which deviation from unity gives a measure of the remnant generated by the driver. A typical run lasted 120 seconds with the above measurements made over the last 100 sec.

Visual Detection Task

The visual detection task was set up to represent discrete events that the driver might encounter up ahead beside the road or through his rearview mirrors, and require response reflexes typical of driving. Back-projected one-inch indicator lights (IEE Series 0120) were mounted in the standard rearview mirror positions (roughly ±45 deg off center and at ±20 deg on either side of the CRT roadway display as shown in Fig. 1. Each indicator presented the messages [HORN] or [BRKE], requiring the subject to respond by depressing, respectively, the horn ring or brake pedal. The message was approximately 0.18" × 0.56" in size and the brackets were used to preclude the driver from recognizing the message content parafoveally. The message brightness was adjusted through trial and error to be just barely supra-threshold for parafoveal detection under sober conditions.

The indicator units were driven by a special purpose Digital Logic Unit (DLU) and event programmer which activated the messages in quasi-random sequences among the four indicators. Four different programs were used to minimize chances of learning the sequences. During a 100-second run, four messages were presented on each indicator (2 HORN, 2 BRKE), with the order of indicator and message randomized and counterbalanced during a run. The inter-message interval varied between one and five seconds and was also randomized. The DLU also accumulated the number of correct responses, the number of missed responses, and the reaction time of all responses. Each message was presented for (nominally) three seconds, and responses beyond this interval were counted as misses. As a result of subsequent off-line processing, the accumulated data were reduced to measures of signals detected, signals correctly responded to, and average reaction time.

In order to gain insight into the eye scanning process for the present task setup, eye motions were recorded during selected runs using an STI EPR-2 eye-point-of-regard monitor (Ref. 22). This device provides a continuous indication of vertical and horizontal head and eye points-of-regard. It consists of a goniometer, held fixed relative to the subject's head by a rigid bite, and four light-sensitive sensors mounted on modified eyeglass frames. The goniometer measures head movement while the frame-mounted sensors measure eye movement relative to the head. EPR-2 electronics provide for individual adjustment and sensitivities of the goniometer and each of the sensors, and subsequent combining of goniometer and sensor outputs to provide eye point-of-regard with respect to an cab-fixed reference.

EXPERIMENTAL METHODS AND PROCEDURES

The subject population for the experiment consisted of 18 licensed drivers (17 males, 1 female) screened for normal intelligence (on the basis of results on a shortened version of the Shipley-Hartford Test, Ref. 24). Selected subjects were equally divided between moderate and heavy drinkers and were further selected to span the age range 21-65. This aspect of the study is discussed in detail in a companion paper (Ref. 19). The subjects were given training on the task during 2 sessions and performed the test battery (i.e., driving task only, sign task only, and combined driving and sign tasks) 5 to 9 times prior to the formal data sessions. Three subjects each from the moderate and heavy drinker categories were also selected to run single-blind placebo sessions in addition to their formal test sessions to determine whether other factors such as fatigue or learning might appreciably influence task performance during the formal data sessions. Subjects were tested in groups of two to four, usually including one placebo.

Formal data sessions were begun in the morning or early afternoon, and subjects were asked to refrain from eating immediately prior to reporting on the test day in order to obtain maximum alcohol absorption rates. Subjects were administered a warmup run and formal baseline tests prior to receiving their first drink. During normal drinking sessions it was desired to test subjects at ascending and descending blood alcohol concentrations (BAC) of nominally 0.06 and peak levels of 0.11 (just beyond the legal limit for intoxication in many states). BAC was measured with a Mark II Gas Chromatograph Intoximeter. Heavy drinkers were also tested in additional sessions at higher BAC's, and this data is discussed in Ref. 19.

A lounge with games and reading material was provided for the subjects' relaxation during drinking and resting between tests in order to promote a modest social atmosphere. The drinks consisted of vodka or whiskey (for a few subjects who refused to drink vodka), diluted to 20 percent ethanol concentrations with a standard mixer. Alcohol dosage was adjusted for body weight to yield desired BAC's. Subjects were given two drinks calculated to give a nominal ascending BAC of 0.06 for testing. A third drink was then given to allow achievement of a maximum BAC on the order of 0.11. After testing at maximum BAC, subjects were given a meal, with no further drinks, and a final test was run at a nominal descending BAC of 0.06. A plot of the mean and standard deviation of BAC's achieved over all subjects as a function of time is given in Fig. 3. For placebo subjects a small amount of vodka was "floated" on top of a glass of their customary mix to give the illusion of a mixed drink.

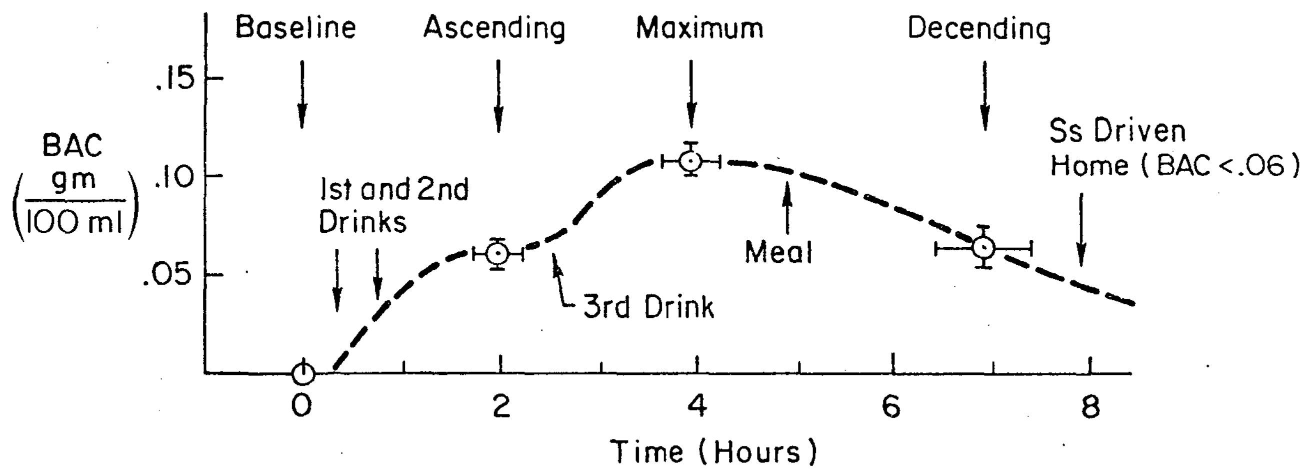


Figure 3. BAC as a Function of Time Averaged Over Subjects

RESULTS

Typical time traces of experimental trials conducted under sober and intoxicated conditions are shown in Fig. 4, and exhibit many of the experimental effects of alcohol on driving. For the continuous task it is apparent that both the heading and lane deviations of the car increase under alcohol. Also, the driver's steering actions seem to be less responsive with longer periods of constant wheel position under alcohol, although wheel motion does roughly correspond to the input disturbance as it should for regulation against the disturbance.

From a diagnostic standpoint, the EPR data allow the partitioning of the multiphasic discrete task response process into its components as quantified by the time interval allotted to each phase (initial delay to scan initiation, scan dwell, and time to respond following the initial scan). By such partitioning, the individual contributions of each phase to overall performance degradation can be assessed.

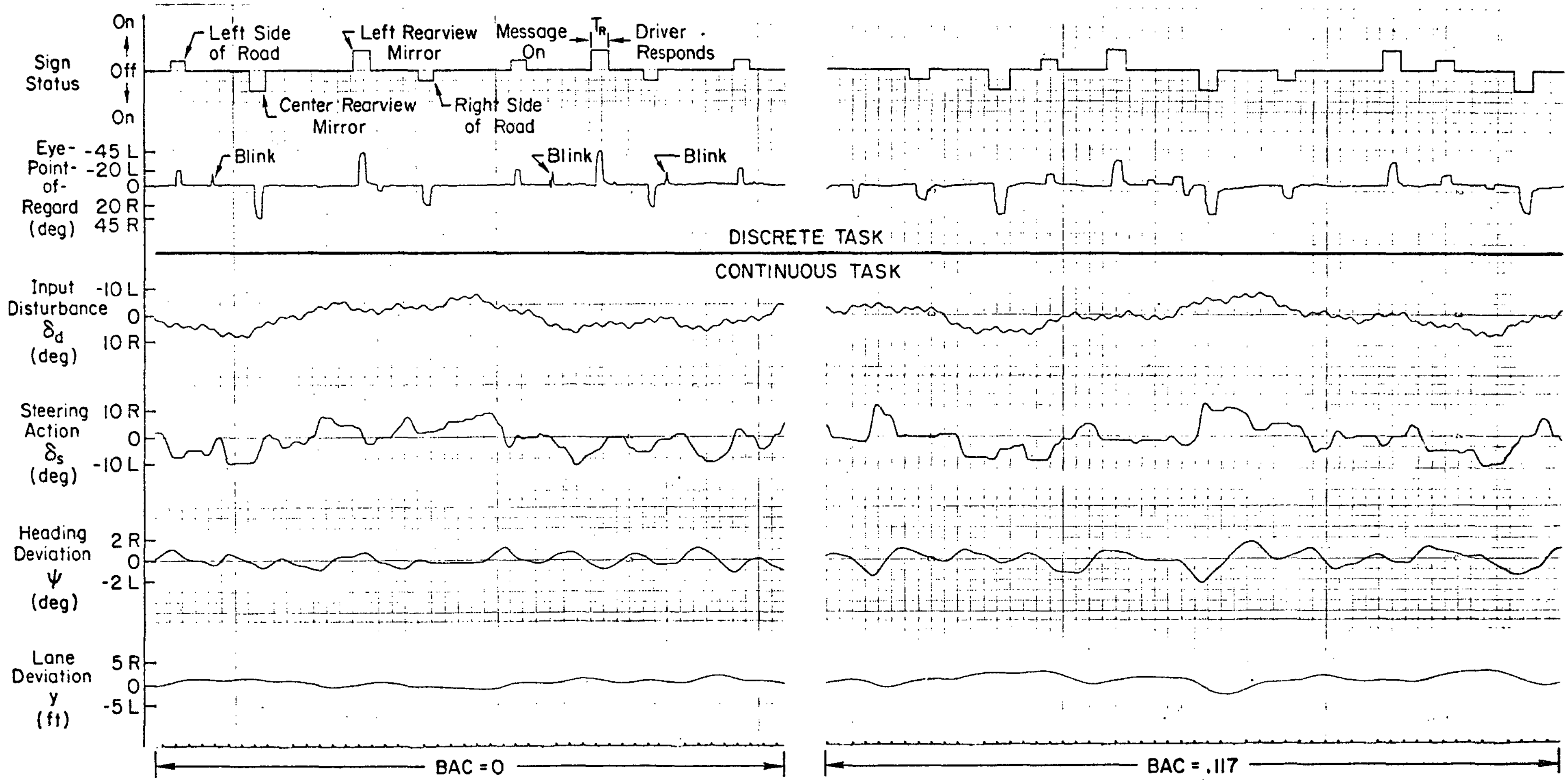
For the discrete task the EPR (eye-point-of-regard) trace shows that the driver did not continuously scan, but looked away from the road (CRT) in response to the appearance of sign messages, although under alcohol there are several cases of extra scans. This behavior is consistent with the stated primary nature of the control task and indicates the signs were detected parafoveally. Event "detection" is indicated by a scan in the correct direction.

Under sober conditions the scanning is made with single, rapid saccades (Fig. 4). Scans are initiated shortly after message onset and last 0.3-0.5 seconds, and there is no apparent interaction with steering wheel motions during the scanning and response processes. Under alcohol the scanning is much more sluggish, however, with multiple saccades and dwells on the order of 0.6-1.0 seconds which seems to correlate with a slight increase in the total response reaction time. There is also evidence of holds in the steering action under alcohol during the scanning and response process.

A preliminary review of EPR data from two subjects indicates that the typical response process, sober, can be broken down into: a 0.2-0.4 second initial delay between event onset (sign light-up) and the beginning of the

Figure 4

TIME TRACE OF COMBINED CONTINUOUS AND DISCRETE TASK OPERATION UNDER SOBER AND DRUNK CONDITIONS



eye motion from the roadway to the sign; a 0.3-0.6 second dwell period during which the subject "recognizes" the sign; and a 0.1-0.3 second interval preceding response to the sign, after the eyes have returned to the roadway. With increasing BAC, typical initial delay and dwell increased, reaching values of 0.4-0.9 seconds and 0.7-1.1 seconds, respectively, at peak BAC, while the time to respond after scan diminished until both subjects would frequently respond before looking back to the roadway. Behavior for the discrete-task-only was markedly different. While typical detection delays were generally comparable to those observed for the combined task, typical scan dwell was always larger and the EPR usually returned to the road just after the response was made.

Under sober and intoxicated conditions, the response process was more consistent and showed much less evidence of random scanning (and no sober random scanning) when combined with the driving task. Other idiosyncratic behavior exposed by the EPR measurements included scanning from one roadway edge to the other rather than using a single fixation point for the continuous task reference and occasional failure to respond to signs after detection and apparent visual recognition (verifying subject's comments to that effect) while under the influence of alcohol.

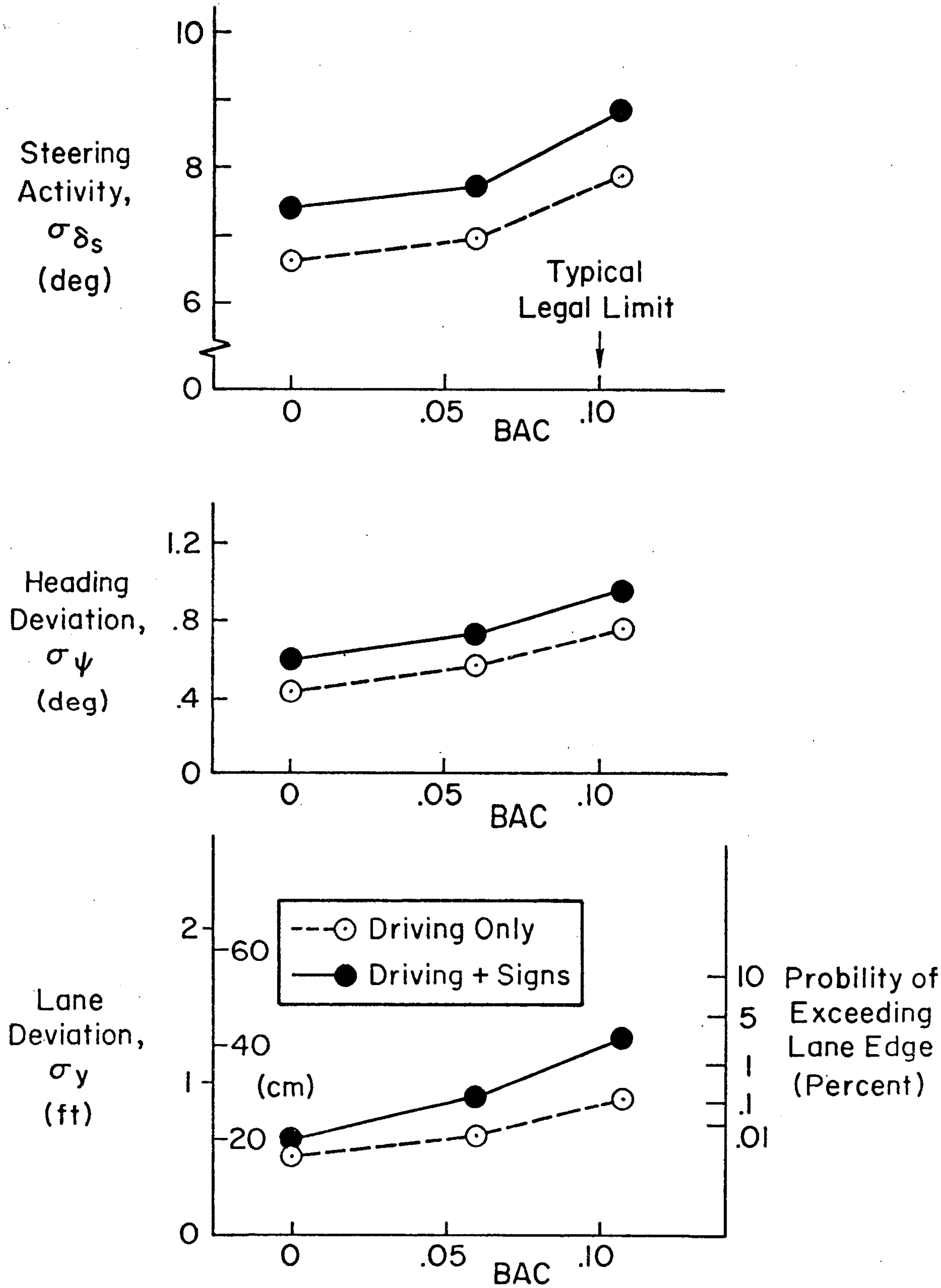
While the above results are tentative, it is apparent that the EPR data can contribute considerable, and otherwise unavailable, insight to the scanning and response processes involved in driving and their deterioration under alcohol. Further analysis along these lines should be quite fruitful.

Analysis of the placebo data showed little effect on task performance during a given experimental session. Also analysis of the ascending vs. descending data at comparable BAC's failed to show any appreciable effect on performance. Consequently, the following discussion will be confined to results obtained at the baseline, ascending, and maximum levels of BAC (Fig. 3).

Performance data averaged across 18 subjects is plotted in Fig. 5. Steering activity and heading and lane deviations generally increase with BAC. The addition of the discrete task causes a constant increment in steering activity and heading deviations, while only the sensitivity of σ_y decrements to BAC is increased by the divided-attention nature of the combined task. The combined-task results show that path-following errors double ($0.65 \rightarrow 1.3$ feet) when attentional demands are placed on the intoxicated

Figure 5

ALCOHOL EFFECTS ON DRIVING CONTROL PERFORMANCE AVERAGED OVER SUBJECTS



driver. The occasional peak deviations of a random path with this rms level will clearly extend a car past lane boundaries or off on the shoulder of a single lane road which increases the probability of accident involvement.

Driver control behavior responsible for the above performance effects is shown in Fig. 6. From the averaged describing function data it is obvious that the driver's sensitivity or gain is reduced when he is intoxicated. This is particularly true in the low-frequency region which mainly influences path following errors. The describing function phase data (Fig. 6a) are not particularly affected, so the change in the driver's dynamic response under alcohol is mainly a gain phenomenon. Furthermore, alcohol acts to increase driver remnant (Fig. 6b).

Both the remnant and describing function results might be explained by an increase in intermittency* and/or indifference threshold†. Alcohol may increase the driver's indifference threshold to lane deviations, a nonlinear behavior which would increase remnant while at the same time reducing measured gain. Also, as suggested by the time trace data in Fig. 4, the discrete-sign-task interference under alcohol seems to elicit intermittent steering actions, which could lead to further remnant increase and gain reductions as shown in Fig. 6.

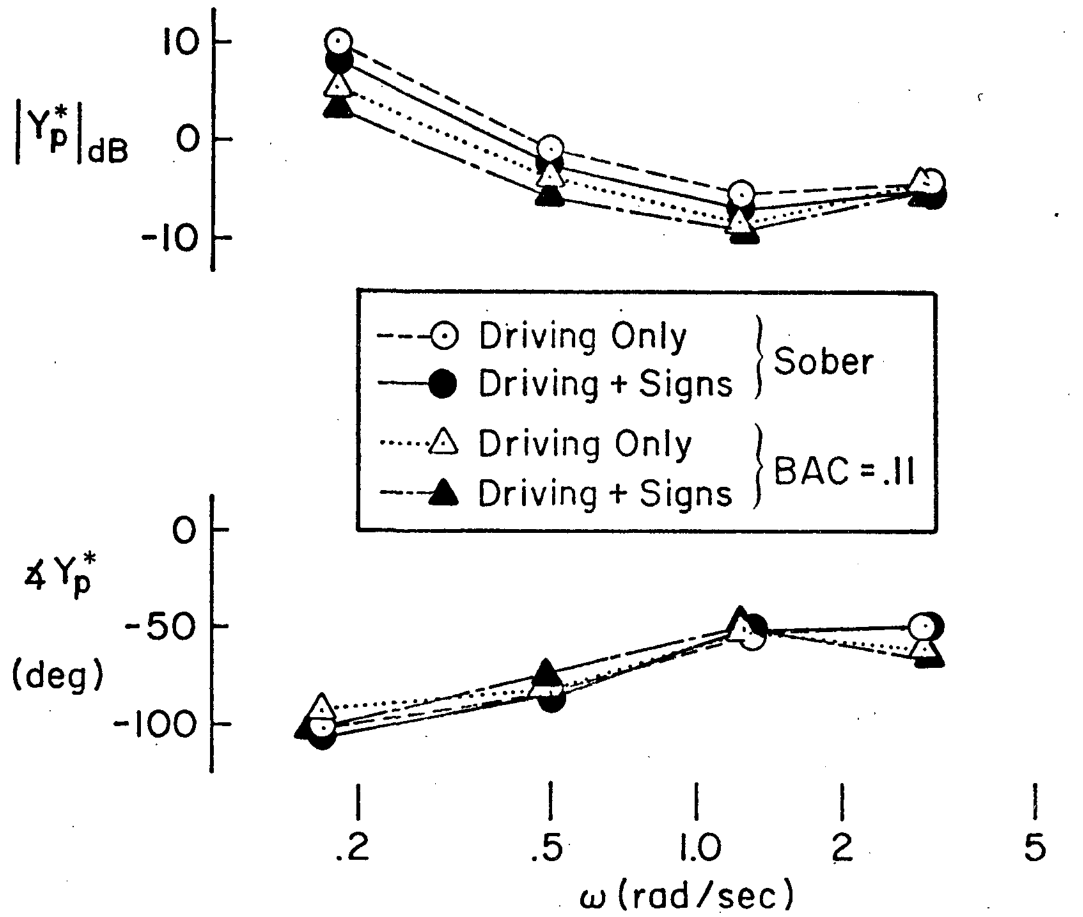
In spite of the changes in dynamic response described above, alcohol does not seem to decrease the basic closed-loop stability of the driver/vehicle system, as shown in Fig. 7. The crossover frequencies and phase margin are computed from the equivalent single-loop driver/vehicle dynamics and relate mainly to the heading control loop. While the gain crossover frequency decreases under alcohol, which is consistent with the describing function data in Fig. 6, the phase margin stays relatively constant. In a similar vein, ω_u and ω_c change uniformly implying a constant gain margin. Also, with

*Indifference Threshold ≡ thresholds in a perceptual-motor control loop which are not specifically sensory or proprioceptive threshold; e.g., control inaction while the error is within some tolerance zones (Ref. 25 and 27).

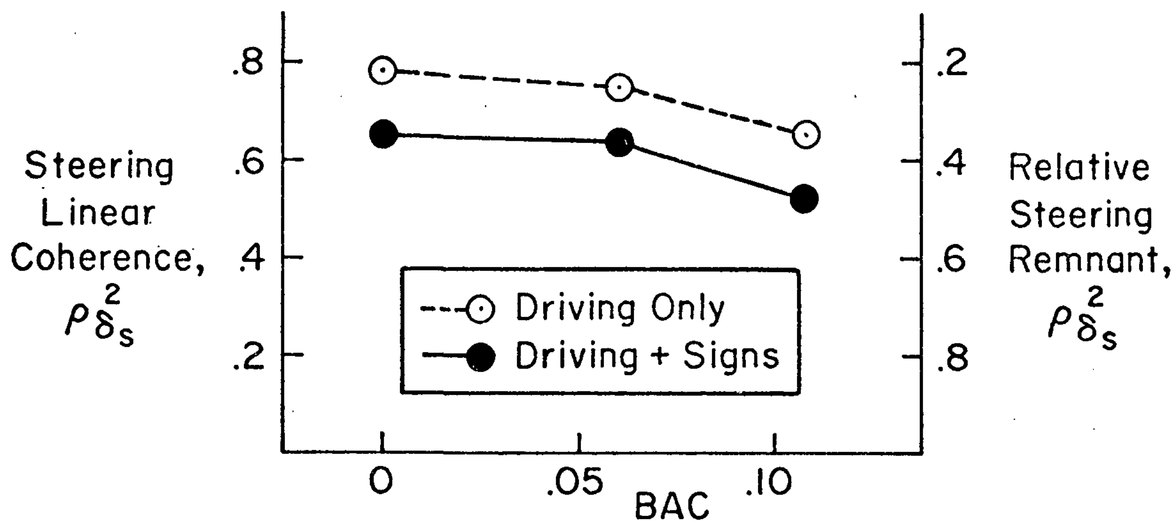
†Attentional Intermittency ≡ switching of control attention frequently, and usually asynchronously, from task to task (or loop to loop); often (but not always) evidenced by eye-point-of-regard or control inactivity (e.g., Ref. 25 and 26).

Figure 6

EFFECTS OF ALCOHOL ON DRIVER CONTROL BEHAVIOR AVERAGED OVER SUBJECTS



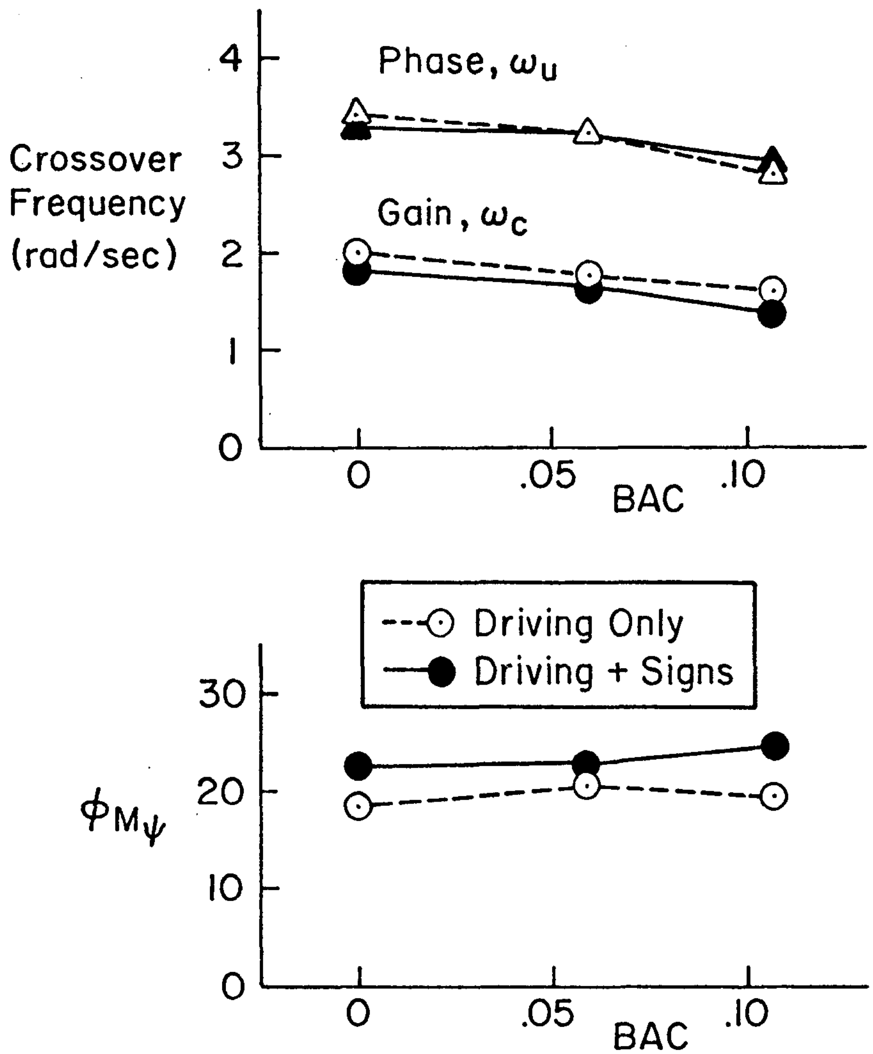
a) Equivalent Driver Describing Functions



b) Remnant

Figure 7

DRIVER/VEHICLE DESCRIBING FUNCTIONS PARAMETERS AVERAGED ACROSS SUBJECTS



the added distraction of the sign task, the driver lowers his gain to further increase his stability margin. Finally, all the dynamic response and remnant data show similar effects between the single and combined tasks, implying little influence of divided attention on the driver's control behavior.

Performance on the discrete task is plotted in Fig. 8. The response ratio, N_R/N, is the fraction of signals responded to, and gives a measure of signal detectability. Dectection decreased with increasing BAC, and the added distraction of the control task seems to add an extra decrement at high blood alcohol levels. Signs were seldom incorrectly responded to (less than 3 percent at 0.1 BAC), so this was not a factor in task performance. The response times to the signs generally increased with BAC and was not influenced by the presence or absence of the control task. Finally, the reaction times measured here are quite similar to past simulator results (Ref. 5).

DISCUSSION

The results presented so far show a general deterioration in performance with increasing BAC in both the continuous and discrete tasks. The effects occur both when the tasks are performed singly and in combination; however, the divided attention aspect of the combined task does not seem to have affected the general sensitivity of the results to BAC, except for the path deviation. In order to further substantiate these findings, the key measurements were subjected to analysis of variance procedures, and the results are summarized in Table 2.

The BAC level effect was highly significant for all parameters as indicated in Table 2, except phase margin (φ_M), which was previously noted to remain relatively constant over the range of BAC's tested. The Task effect in Table 2 shows that performance of the steering task was significantly impaired by the presence of the discrete task; however, the reverse was not true. This is possibly because the discrete task interrupts the continuous nature of the steering task; whereas the discrete task is always performed on demand, so the detection process is not interferred with. The 3.0 sec "gate" on the signs probably motivated this behavior to a certain extent, which is realistic in the driving context where signs, unexpected obstacles, etc., must be reacted to before they are overrun. (At 30 mph, the car travels 132 ft in 3 seconds.)

Figure 8

ALCOHOL EFFECTS ON DISCRETE TASK PERFORMANCE AVERAGED OVER SUBJECTS

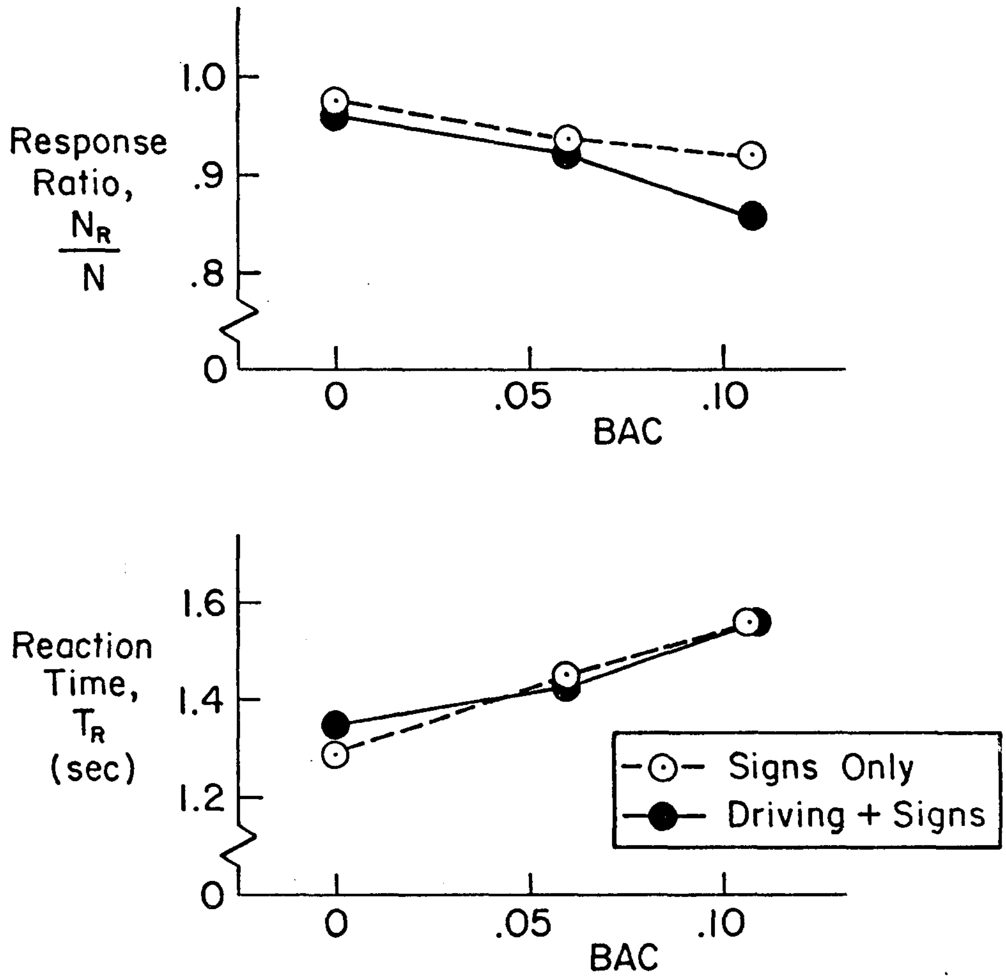


TABLE 2

ANOV SUMMARY OF KEY EXPERIMENTAL MEASUREMENTS†
(F-RATIOS AND LEVEL OF SIGNIFICANCE)

EFFECTS OF ↓ ON →	STEERING TASK MEASURES							DISCRETE TASK MEASURES		DEGREES OF FREEDOM
	STEERING		HEADING CONTROL			PATH CONTROL				
	δ_s	$\rho^2_{\delta_s}$	σ_ψ	ω_c	φ_M	σ_y	$\lvert Y_p^* \rvert_{\omega=.5}$	N_R/N	T_R	
BAC Level (Baseline; 0.06; 0.11)	14.2 ***	17.6 ***	31.0 ***	19.7 ***	0.56 NS	21.4 ***	16.9 ***	8.86 **	27.5 ***	2, 12
Task (Single vs. Divided Attention)	60.8 ***	44.0 ***	84.7 ***	12.4 **	7.64 *	30.1 ***	12.4 **	3.46 NS	0.36 NS	1, 12
BAC × Task (Divided Attention Interaction with Alcohol)	0.58 NS	0.78 NS	2.28 NS	0.61 NS	0.68 NS	14.64 ***	1.96 NS	1.01 NS	1.76 NS	2, 24

*** = 0.001 Level of Significance
** = 0.01 Level of Significance
* = 0.05 Level of Significance

†The experimental design included all combinations of BAC Level and Task. Subjects were also included as a variable in the analysis, and were further subdivided into groups by drinking habit and age, thus resulting in a nested design for the complete analysis. Subjects were considered a random variable and subject interactions were used for the F ratio denominators.

Finally, Table 2 bears out the previously-noted result that there is no significant interaction between BAC and Tasks other than for the lane deviation measurement. This one exception is quite important, however, since lane deviations influence the probability of accident involvement.

CONCLUDING REMARKS

A rather simple, yet directly driving-relevant, fixed-base laboratory driving simulator was developed which has elicited many of the anecdotal phenomena attributed to intoxicated drivers in past investigations. With a scenario of driving on a rural road on a stormy night, the simulation gained the acceptance of the 18 typical drinking driver subjects and has provided a reliable data base with many clearcut effects. The more important findings may be summarized as follows:

Driving Task

- Lane deviations increase with BAC level, which is explained by measures of lower driver control gain and increased remnant. Distraction of the sign response task further increased the impairment of path control by alcohol. These effects are consistent with increased indifference thresholds and/or control intermittency and significantly increase the probability of lane exceedances.

- Heading control gain also decreases under alcohol with a concomitant increase in heading deviations. Phase margin for the heading loop closure remains constant under alcohol, however, so that intoxication apparently does not decrease control stability.

Discrete Task

- The fraction of misses and the response time increase under alcohol, while incorrect responses are negligible under all conditions up to BAC = 0.11.

- The driving task does not interfere with the discrete task in either the detection or response processes, indicating the signs are acted upon on demand much as might be expected in a real driving situation in response to signals, unexpected obstacles, etc.

- EPR (eye-point-of-regard) measurements show that drivers do not continuously scan for signs. Scans are normally prompted by peripheral detection of a sign, although occasional unnecessary scans occur at higher BAC. Scanning is degraded in general under alcohol, and an observed increase in scan dwells may be partially responsible for increased reaction times and interference with the steering control task.

- The EPR measurements have given a great deal of insight into the detection and response processes in the discrete task and further analysis of the simultaneously recorded EPR, discrete response, and steering data would be fruitful.

This simulation was used successfully (in an experiment interleaved with this one) to investigate effects of different drinking habits (Moderate vs. Heavy) on the various measures of driving performance and behavior (Ref. 19), and additional data therein on heavy drinkers at 0, 0.11, and 0.16 BAC tends to support and extend the present findings.

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IMPAIRMENT OF MODERATE VERSUS HEAVY DRINKERS IN SIMULATED DRIVING TASKS*

Henry R. Jex, Richard J. DiMarco, and R. Wade Allen†
Systems Technology, Inc., Hawthorne, California

ABSTRACT

The objective of this program was to test, under carefully controlled and measured conditions at various blood alcohol concentrations, whether or not Heavy drinkers (i.e., those who ususally exceed 0.10 BAC when drinking) might have different driving impairment than Moderate drinkers (i.e., those who seldom reach 0.10 BAC when drinking). Two groups of ten drinking drivers, representing a typical distribution of age, education, and occupation were selected to have drinking habits near either extreme. The primary task was a steering control task in the presence of crosswind gust disturbances using a roadway perspective display in the STI Fixed-Base Car Simulator. A secondary discrete task included detection, interpretation, and response to simulated "signs" located at ±20 deg and ±45 deg in the peripheral fields. (The methods, setup, and comprehensive measurement schemes are described in a companion paper, Ref. 6). Two interleaved experiments were performed. In one, both Moderate and Heavy drinkers went to just over legal limits (Blood Alcohol Concentration, BAC ≐ 0.11 g/100 ml), and in the other the Heavy drinkers went up to BAC ≐ 0.16. The experiment design included a test battery of: steering only, discrete task only, and combined tasks; partial placebo sessions; and tests during sober (baseline), ascending, peak, and descending BAC phases. Also presented are some eye motion traces giving insight as to the nature of the discrete task decrements.

Results showed that Heavy drinkers were less impaired than Moderate drinkers at 0.11 BAC (near legal limits), in terms of larger heading and path errors, describing function gain decrements, increased remnant, more discrete task misses, and longer response times. However, the Heavy drinkers were somewhat more impaired at 0.16 BAC than the Moderate drinkers at their 0.11 BAC peak.

Based on lane deviation variance, the probability of lane exceedance of a standard sedan in a 12-foot lane was increased from 0.0001 when sober to 0.05 for the Moderate drinkers at 0.11 BAC, and for the Heavy drinkers to 0.01 at 0.11 BAC and to 0.10 at 0.16 BAC. A number of the observed effects of BAC (i.e., worse performance, lower driver sensitivity to lane and heading

*This work was sponsored under Contract DOT-HS-227-2-388 by NHTSA's Office of Driver Performance Research, with Dr. Leland Summers as Contract Technical Manager.

†Principal Research Engineer; Staff Engineer, Analytical; and Senior Research Engineer, respectively.

deviations, less control coherency, constant stability margins, and missing of discrete responses despite their accurate peripheral detection) are all consistent with an increase in the intoxicated driver's indifference thresholds and/or attentional intermittency.

INTRODUCTION

Objectives

The **underlying motivation** behind the present research has been clearly stated by the Office of Driver Performance Research of the National Highway Traffic Safety Administration (NHTSA) in Ref. 1, as follows:

> "The 1968 Alcohol and Highway Safety Report showed that alcohol related accidents account for 50% of the highway fatalities and that 80% of these fatalities have blood alcohol concentrations of 0.10% or higher. It has also been shown that the accident risk factor increases 6 and 20 fold for BAC levels of 0.10% and 0.15% (Ref. 2) respectively and the fatality risk factor is 9 and 35 fold for the same BAC levels (Ref. 3). It has also been found that heavy users of alcohol were over represented among those responsible for fatal and serious injury accidents and among those convicted of driving-while-intoxicated or other serious moving violations (Ref. 2). In fact it is generally concluded that problem drinkers who constitute a small portion of the population account for a very large part of the overall problem (1968 Alcohol and Highway Safety Report).
>
> Past and current research on alcohol and driving has shown that alcohol impairs driving and performance tests related to driving. However, the majority of this research was performed on college students who were social drinkers and did not differentiate between heavy or light drinkers. It is the intent of this procurement to determine if there is a difference between heavy versus light drinkers in their driving performance level and if there is a interaction between drinker type and alcohol dosage level."

NHTSA's **basic objectives** in this ongoing program are: 1) to determine, via laboratory driving tests, the primary causes of deterioration in driver performance under alcohol; and 2) to reveal performance indicators which might be used to differentiate "light" or "heavy" drinkers from the standpoint of applying selective countermeasures, and for revealing the most effective avenues for reducing the risk of subsequent crashes. The **specific purpose** of this investigation was to determine, via a simplified but relevant driving simulation, if there is a difference in driving performance on the basis of an individual's drinking habits (Ref. 1). By using a simplified set of tests relevant to driving behavior, the task variables could be readily controlled, and the detailed characteristics of heavily drunk drivers could be safely and efficiently measured. The most promising of these tests and possible countermeasures could later be validated in the more risky (and expensive) field trials.

Research Approach

A relatively simple, fixed-base laboratory driving simulator and tasks and measures to test driving performance are described in detail in a companion paper (Ref. 6), which also presents some basic effects of Blood Alcohol Concentration (BAC)* and effects of divided attention, as noted below. Without repeating unnecessary details, we will comment here on the key considerations and features of our approach.

Drunk driving accidents usually occur at night, on "rural (non-urban) streets, and involve one car driven into a collision (usually out of the lane) by a male driver (Refs. 4 and 5). The relevant driving tasks are of two general types operating in parallel: continuous **control tasks** (steering and speed) which intrinsically involve closed-loop operation of the car and driver (Ref. 6); and **discrete tasks** (e.g., brakes, horn, turn signals) which require responses to stimuli detected (often peripherally), recognized (usually by a visual scan), and responded to (in a practiced movement) all in an "open-loop" manner. When both types of task must be performed concurrently performance on one type can be affected by interference from the other due to divided attention. It was hypothesized that alcohol might more adversely affect performance on combined steering-plus-discrete driving tasks than either one alone. The overall experimental plan tested this hypothesis, and the results are reported in the companion paper (Ref. 6). For simplicity, and because they represent the more

*Blood alcohol concentration is given here, as customary, in grams ethanol per 100 ml blood, which approximates the volume percentage of ethanol in blood (whose specific gravity is about 1.05)(Ref. 4). The blood levels are inferred from measurement of breath alcohol concentration, for which the term "BAC" is used interchangeably.

realistic situation, only results for combined steering-plus-discrete tasks will be reported here.

Great care was expended on selection of a representative sample of subjects. Because the selection, training, drinking sessions, high BAC and placebo sessions were very costly per subject, the sample was limited to a total of twenty finalists (ten in each drinking category) from a set of some 50-80 "promising" candidates. We found that most "light" drinkers* could not reach the desired typical "legal limit" levels of 0.10 BAC without getting sick (under our somewhat intensive drinking regimen). Consequently, we had to raise the "light" category to "moderate" drinkers*, trying to find the lightest drinkers among those who would not get sick at 0.11 BAC. "Heavy" drinkers* were easy to find among the young, but were surprisingly hard to obtain in older ages, because we did not wish to test serious problem drinkers or alcoholics under rehabilitation. Various drinking habit questionnaires proved unreliable indicators of true alcohol capacity, so we conducted "screening drinking sessions" for the majority of candidates in order to verify and calibrate their alcohol capacity prior to more expensive training and test sessions.

These efforts to select subjects were further complicated by an effort to have in <u>each</u> drinking habit group: 1) a demographically representative and balanced spread of ages; 2) an average range of IQ and educational and driving experience; and 3) mostly male subjects (because females comprise only a few percent of the drunk driver fatalities, e.g., Ref. 5). These criteria were fairly well met.

The overall experiment was divided into two sets. The "main" experiment carried both Moderate and Heavy drinkers to a peak BAC = 0.11, just over the legal limit, and an extra "high BAC" session was run separately for the Heavy

*The type of drinker is defined here in terms of level of BAC reached in a typical drinking session:

Light:	BAC rarely exceeds 0.05.
Moderate:	BAC usually exceeds 0.05, may occasionally exceed 0.10, unlikely to ever reach 0.15.
Heavy:	BAC usually exceeds 0.10, and at least occasionally exceeds 0.15.

drinkers to take them toward their customary limits near BAC = 0.16+, with stops at BAC = 0.11 to tie in with the main experiment. The idea here was to compare Moderate and Heavy drinkers not only at the **same** (supra-legal) **BAC**, but also near **each group's customary limit**. This plan was successfully accomplished with interesting results, as will be shown later.

Previous experience with placebo sessions for each subject (Ref. 7) had shown little effect of time of day or fatigue, so we were reluctant to waste previous test time on non-drinking runs. Nevertheless, to establish similar placebo insensitivity of the current test battery, a partial set of single-blind placebo runs was made, with one subject per session having the placebo drinks to retain all of the social factors affecting performance through the session.

With this overview of our approach and rationale in mind, we will next briefly describe the subjects, apparatus, tests, measures, experimental design, and procedures.

EXPERIMENT SETUP, DESIGN AND PROCEDURES

Subjects

As explained in the Introduction, ten subjects in each drinking category were finally selected so as to achieve a demographically representative sample of mostly male licensed drivers of all ages, average intelligence, and average driving experience. (Data from one subject in each group in the main experiment and for two subjects in the high-BAC sessions were unusable.) Salient characteristics of the subjects are given in Table 1.

As a result of screening for drinking capability in a group drinking session, approximately 50 percent of the candidates failed to qualify for formal experiments. For the majority of those who did qualify, good calibrations of BAC vs. ethanol per drink were obtained, so it was possible to achieve fairly close levels of BAC for each subject in the final experiment. Even though we attempted to provide a multi-subject social ambience in an apartment-like living room, the drinking regimen was somewhat more intense, and the test atmosphere was somewhat more "tense" than a typical social drinking experience.

TABLE 1. DATA ON TEST SUBJECTS

a. "Moderate" Drinkers (Frequently to .05+ BAC, occasionally to .10 BAC)

SUBJECT*	AGE yrs	WEIGHT kgm	EDUCATION LEVEL†	DRIVING EXPERIENCE (yrs)	OCCUPATION
H	21	84	HS	7	(Unemployed)
J	22	76	Coll	6	Student
U	25	84	Coll	9	Mortuary salesman
R	32	67	Coll	16	Photographer
X	37	79	Coll	22	Data processing supervisor
D^f	43	55	Coll	26	Homemaker
P̸	47	66	HS	28	Maintenance supervisor
V	47	77	HS	25	Real estate salesman
S	52	88	Coll	40	Driving instructor
N	65	82	HS	50	(Retired)

b. "Heavy" Drinkers (Frequently exceed .10 BAC; often to .15+ BAC)

SUBJECT*	AGE yrs	WEIGHT kgm	EDUCATION LEVEL†	DRIVING EXPERIENCE (yrs)	OCCUPATION
C	22	62	HS	6	Messenger
B	22	83	Coll	8	Student
A	23	74	HS	7	(Unemployed)
E	28	80	Coll	11	Student
K	37	82	HS	20	Truck driver
M	37	78	HS	20	Auto salesman
L̸	42	79	HS	24	Auto salesman
W	42	98	Coll	27	Bar owner
Q	54	75	HS	36	Insurance agent
T	58	91	Coll	43	Realtor (retired)

*$(\ )^f$ denotes female subjects; (/) denotes formal test data incomplete

†HS = High School; Coll = College

Perhaps because of this, subjects reported somewhat more than usual likelihood of feeling nauseated at their maximum BAC's.

Subjects were trained in the driving simulator for two half-day sessions in which they alternated runs with another subject. The simulated scenario was driving at 30 mph on a rural road at night in stormy weather — a difficult task at best — yet the subjects readily adapted to both the control and discrete tasks because they were based on well-practiced driving reflexes. The noticeable lack of motion cues was offset by a realistic (actual) car interior and controls, correct vehicle response dynamics, and a large-field-of-view moving roadway perspective. Consequently, the training required was similar to that required for any new car. All subjects accepted the simulator as a plausible approximation to a real car driving situation, and they produced behavior typical of actual car driving. (These attributes have been notably lacking in many earlier laboratory investigations of alcohol effects on driving.)

Subjects were motivated by an incentive pay formula which included: a base hourly rate through training and formal sessions; and a "get home" reward per run completion, which was increased with BAC. Approximately $4/hour was earned, on the average.

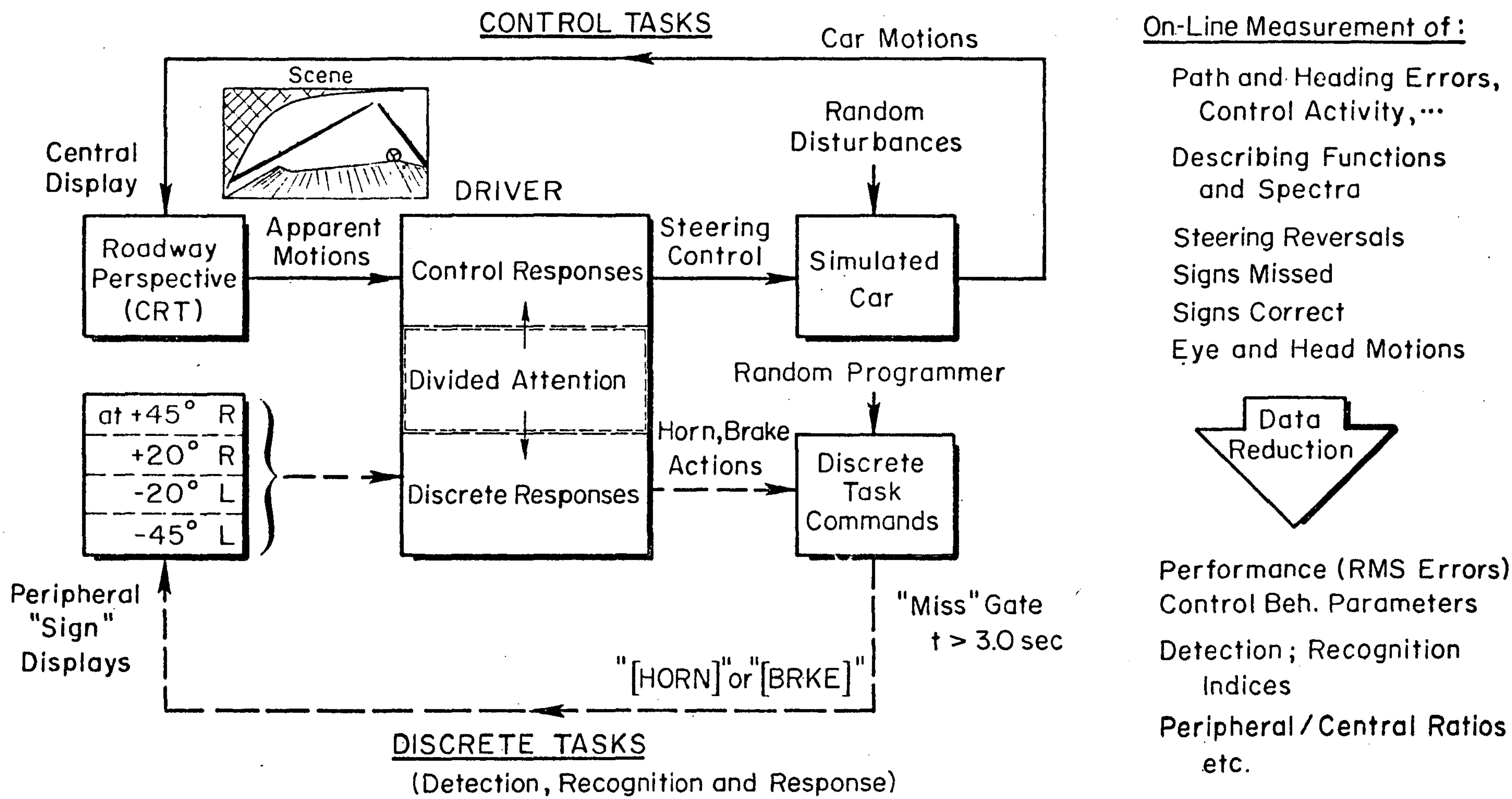
Apparatus

As noted earlier an appropriate scenario for drunk driving accidents is night driving on a rural road in stormy weather, which our tasks simulated (see Fig. 1). Reference 6 gives further details. The driver sat in an actual car cab with realistic steering, accelerator, brake, and turn signal controls. The road display was a slightly shrunken (0.6 scale) view over the car's hood towards a one-lane straight road fading into the distance. The dynamic perspective was drawn on a 25 cm (10 inch) CRT 60 cm from the subject's eyes at a refresh rate of 60 Hz, so that no blur, flicker, or jerk were apparent.

Peripheral, lightable "signs" were placed at the side and overhead rear-view mirror locations (±45 deg, respectively) and at ±20 deg alongside the CRT (corresponding to signs or events adjacent to the car lane ahead on the road). These signs had small 4-letter words (i.e., [HORN], [BRKE]) which were lit by a random program to command the driver to respond accordingly (i.e., tap the

Figure 1

BLOCK DIAGRAM OF TASKS AND MEASURES



horn ring or brake pedal). The letters were small enough (10 mm) and dimly lit so as to be just detectable parafoveally when turned on, but to require a fixation (scan) to read the discrete command. The two peripheral signs were adjusted brighter than the central pair to compensate for the cosine falloff of pupil aperture, thereby starting with **uniform detectability** across all lights at sober conditions (Ref. 12).

The dynamic response of the car-and-roadway perspective to steering control was simulated on an analog computer by two-degree-of-freedom (heading and lateral path displacement) equations of motions, set for a constant speed of 30 mph (50 km/hr). (Preliminary tests had shown that 60 mph was undrivable when intoxicated.) Unseen gust disturbances were simulated by a sum-of-five-sinusoids random forcing function. The task was subjectively like driving in strong crosswinds and was scored over a 100 sec period. Special analog and data logging equipment was developed to provide efficient on-line data reduction of path and heading errors, control activity, driver describing functions and spectra, and steering reversals. See Ref. 6 for details.

A sequence of 16 discrete sign commands was provided (4 each at 4 locations), ranging from 1-5 sec apart, with a 3 sec criterion for response time limit. The taped program was changed frequently to prevent learning of the pattern of events. A special Digital Logic Unit was developed for the discrete tasks to handle: programming, light operation, response scoring logic (misses, corrects, and response times), and data logging.

The highly compressed on-line data (roughly 30 numbers per run) were analyzed off-line by a previously developed STI program to yield a comprehensive array of performance and behavioral parameters such as: rms steering wheel activity, σ_{δ_s}; rms heading error, σ_ψ; rms path error, σ_y; crossover model fit parameters for the car/driver describing function, ω_c, ω_u, φ_M, τ_e (see Refs. 6 and 8); various open- and closed-loop describing functions, $Y_p(j\omega)$, spectra, and signal coherences, ρ^2 (remnant noise effects). This program also computes a number of discrete task measures such as: Detection Index, N_R/N (fraction of signs responded to); Recognition Index, N_C/N_R (fraction of non-missed responses which are correct); Response Time, T_R (from onset of sign to completion of response). The discrete task measures are computed for each location and for various combinations, but only the overall averages are considered here because the peripheral and central pairs gave similar results.

For a number of runs, the STI Model EPR-2 Eye-Point-of-Regard System (Ref. 13) was used to monitor and tape record the driver's scanning behavior. This was the first known application of this device to a highly intoxicated human operator, but it worked surprisingly well and excellent data were recorded on 3 out of 4 subjects so instrumented.

Blood alcohol concentration was inferred from breath alcohol concentration, measured with an Intoximeters, Inc., Mark II Gas Chromatograph Intoximeter, which was calibrated daily against reference samples of 0.10 and 0.15 BAC. A minimum wait period of 15 minutes from the last drink was allowed for residual mouth alcohol to dissipate. The average of before- and after-run BAC's was used.

EXPERIMENTAL DESIGN

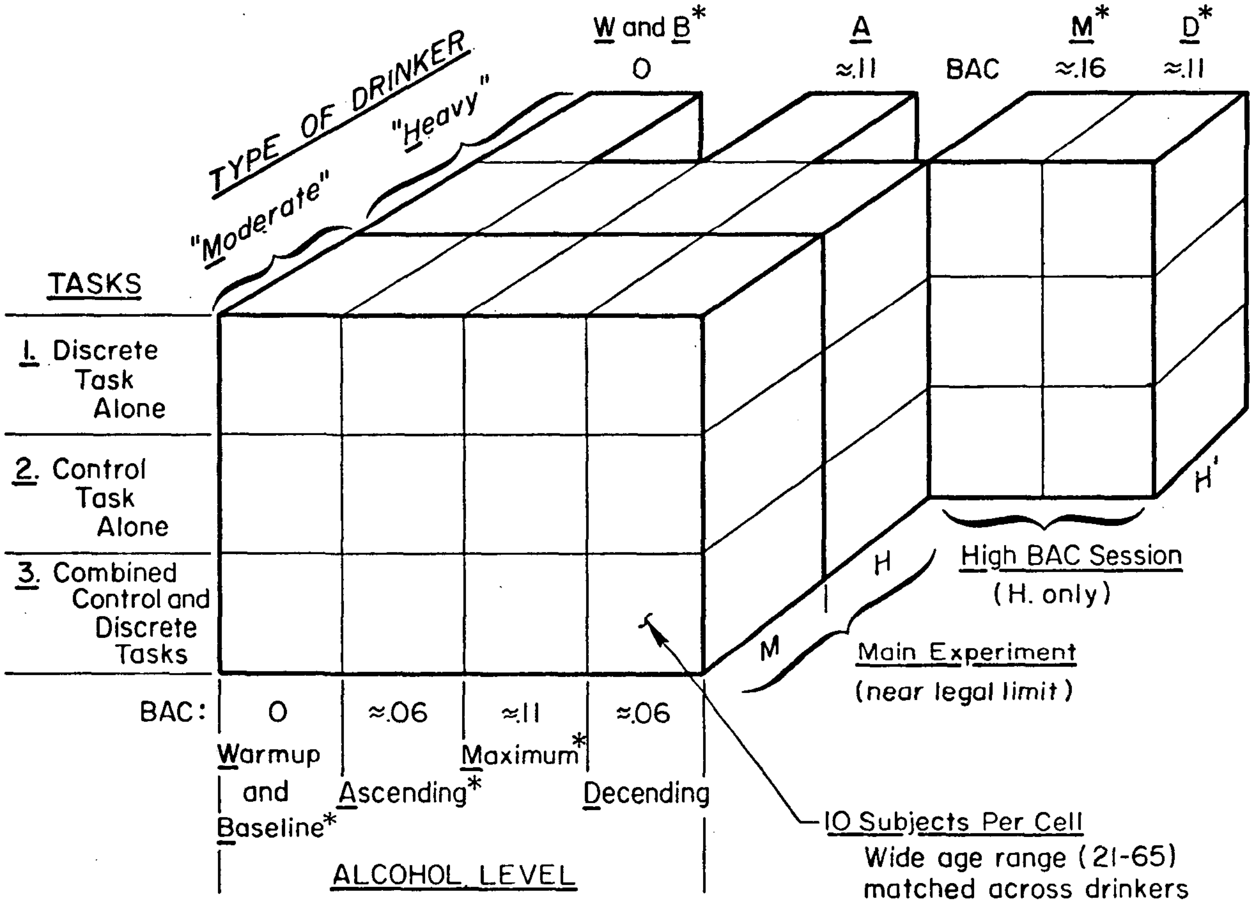
The rationale for the experimental design has been given in the Introduction. To meet the basic objectives, the main experiment contrasted the Moderate vs. Heavy drinkers at three equal levels of BAC up to just over the legal limit (0, ≐ 0.06 BAC ascending, ≐ 0.11 BAC maximum, ≐ 0.06 BAC descending). A high-BAC session was given additionally to the heavy drinkers (0, ≐ 0.11 BAC ascending, ≐ 0.16 BAC maximum, ≐ 0.11 BAC descending) to permit comparisons of alcohol effects at each group's maximum BAC (i.e., 0.11 BAC for Moderate vs. 0.16 BAC for Heavy drinkers).

The resulting matrix of experimental treatments is given in Fig. 2, along with a summary of other relevant conditions and tests. Each of the three types of test (Discrete, Control, and Combined Tasks) was given at each condition. Because the Moderate and Heavy groups intrinsically contain different people, the experimental design confounds Subjects with Drinking Habits, making it a nested design.

Unless a subject specifically requested otherwise (as did a few heavy whiskey drinkers), the standard drink was 80 proof vodka in orange juice for a roughly 20 percent ethanol drink, heavy in fructose for optimum absorption and elimination.

Figure 2

EXPERIMENTAL DESIGN



Drinks: Vodka in orange juice (20% ethanol, adjusted for weight)
3 drinks in ~3hrs; meal after maximum

Tests: BAC Measured via Gas Chomatograph Intoximeter
Driving Tests, per above (Eye motion records for 4Ss)
Clinical Sobriety Tests
Intoxication Ratings by Experimenters and Subjects

*Denotes cases used for statistical analyses herein

TABLE 2. EXPERIMENTAL PROTOCOLS

Session A. Orientation and Initial Training (4 hr)

- (Initial encounter) General briefing on overall program task description and instructions, first trials of test battery
- 2-5 additional rounds of test battery (control task only, discrete task only, and combined task)

Session B. Training (4 hr)

- Review task and instructions
- 3-4 repeat trials of test battery, until asymptotic

Sessions C, D, or E. Formal Experimental Session: Placebo, Drunk or High Drunk (8 hr)

- If AM, give light breakfast (toast and juice); if PM wait 2-3 hr from lunch
- Intoximeter check for 0 BAC
- Sober Warmup and Baseline runs — battery of driving* and clinical sobriety† tests
- Imbibe 2 vodka and orange juice drinks in 1-1/2 hr, alcohol quantity adjusted for body weight to give "Ascending" BAC level (0.06 for Main and 0.11 for Heavy Drinking Sessions)
- One Placebo‡ subject per session of 3-4 subjects
- Ascending BAC runs: driving (0.06+ for Main and 0.11+ for Heavy Sessions) and sobriety tests plus subjective questions§ and Intoximeter BAC
- Third drink, adjusted to give Maximum BAC level
- Peak BAC driving and sobriety runs: BAC = 0.11 for main and 0.16 for Heavy sessions; tests as above
- Light lunch or supper
- Descending BAC runs: at same BAC as Ascending tests

*Driving tests: Steering Task alone, Discrete Task alone, Combined Tasks; given in random order.

†Clinical sobriety tests: walking heel-to-toe; Rhomberg test (balance); positional nystagmus at periphery (PAN-1).

‡Placebo drink: 15 ml vodka floated on diluted orange juice mixer.

§Subjective questions: level of intoxication; capability of driving; degree of nausea and vertigo.

PROCEDURES

The protocols and sequencing of tests in each type of session are summarized in Table 2. Details of the drink administration and resulting BAC vs. time data are given in Ref. 6. Placebo drinks had 15 ml of vodka floated on the watered-down mixer to delay awareness of a non-intoxicating drink. During the Formal Experimental Sessions, from 2-4 subjects were present to lend a more sociable air to the drinking (when there were only 2 subjects an experimenter often joined their group conversationally). Despite every effort to prevent sickness (and the resulting loss of key data, as well as subject cooperation), a few cases did occur and some data cells are thereby missing on a few subjects.

RESULTS AND DISCUSSION

As noted in the Introduction, even though Control and Discrete Tasks were given along with the combined task, the present paper only discusses the combined task results, which are the most relevant for revealing differences between Medium and Heavy drinkers. Reference 6 analyzed the effects of separate vs. combined tasks in detail, for the main experiment only. The key results of that analysis apropos of our work are as follows:

- The discrete task interferes with the driving task when performed concurrently, the interference always being detrimental but small and causing differences in **degree** rather than **kind** of behavior.
- For most measures, the sensitivity to alcohol level is roughly parallel between driving tasks done singly vs. combined. Path deviations are more sensitive to BAC under combined tasks.
- Differences among placebo runs are not large or significant, meaning that time of day effects can be ignored.
- Ascending and descending BAC runs yield similar data at comparable BAC levels, thus either can be used.

So, we will consider only the **combined** control and discrete task data in this section. However, to simplify the presentation, the relatively straightforward discrete task results will be discussed first, saving the more complex control task results for last.

Before proceeding to the reduced data, let us first examine selected signals in a pair of time histories of tracking runs, sober and drunk (see Fig. 3). Points worth noting are as follows, starting at the top:

- The eye-point-of-regard fixations show that even when drunk the subject detects nearly all of the peripheral light onsets (as evidenced by a scan); however, some of the required **responses** are simply ignored.
- Once detected, the response is usually accurate, implying near-perfect recognition of the "sign" details.
- There are more blinks (b) sober than drunk.
- Longer scan latencies and dwells are seen at the high BAC condition, as well as some spurious scans.
- The steering and path errors both increase at high BAC, with some steering traces showing more "holds" than at sober conditions.
- The increased path error at high BAC is more of a wandering than oscillatory type, implying a looser steering control loop rather than any approach to oscillatory instability. (However, a few subjects showed occasional "weaving" of a neutral damped type.)

The parameters selected for analysis clearly reflect these qualitative observations.

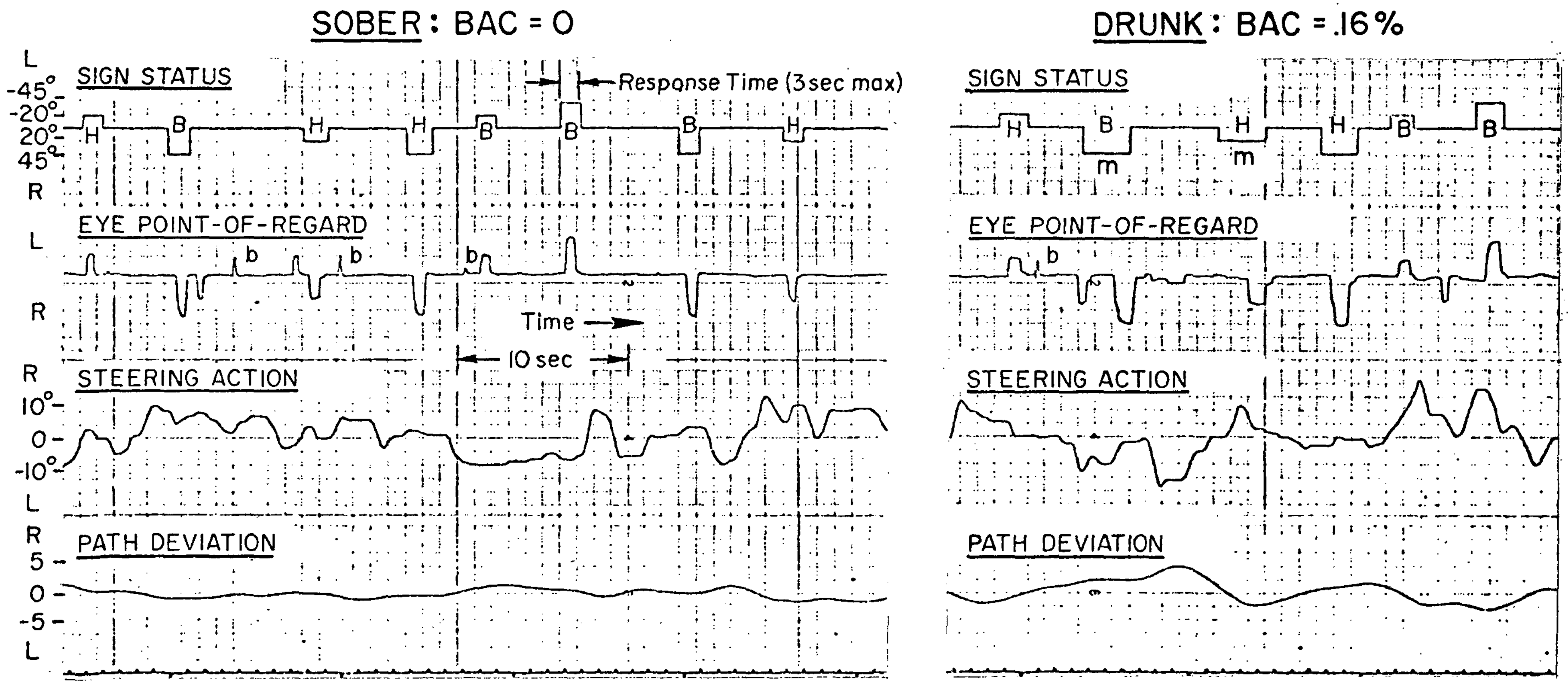
Analysis of Variance

Before proceeding to the discussion of specific results, a summary is presented of an Analysis of Variance for the main experiment which covers Moderate vs. Heavy drinkers at alcohol levels up to the legal limit (BAC = 0, 0.06, 0.11; Moderate vs. Heavy drinkers with nine subjects per group). A partially-nested design was employed because a different set of subjects was necessary for the Moderate and Heavy drinking categories; otherwise there were full-factorial combinations of habit and BAC level, with nine subjects and one observation per cell. Subjects were considered a random variable, and Type of Drinker and BAC were included as fixed effects. Subjects were used as a systematic random variable in the ANOV so as to separate out any stratification in their own skill levels from the other sources under investigation (in effect, using each subject as his own experimental control).

Figure 3

TIME TRACES OF TYPICAL SOBER AND DRUNK DRIVING BEHAVIOR IN THE SIMULATOR

Legend: H = "Horn", B = "Brake", m = "miss", b = "blink"
Subject = E (young heavy drinker)



A summary of the resulting F-ratios for key measures of steering and discrete tasks, and their statistical reliability is given in Table 3. Taken across the board, this ANOV tells the following:

- The effects of BAC on both types of drinker are large and very reliable statistically.
- Averaged across all BAC up to legal limits, differences between the two drinker types are not statistically reliable.
- There are a number of parameters for which the effect of BAC was reliably different for the Moderate vs. Heavy drinkers.

Other implications of the ANOV will be used in the subsequent discussions.

Discrete Tasks

Key results from the discrete tasks are presented in Fig. 4, as a function of BAC for Moderate vs. Heavy drinkers in the main experiment and for Heavy drinkers in the high-BAC session. Cursory examinations of the data from central (±20 deg) vs. peripheral (±45 deg) locations showed only small differences, probably because the sober detectability was equalized for all angles. Thus, we will consider only the averaged data from all sign locations. Also, note that each pair of Heavy points near BAC = 0.11 lie close together, implying consistent behavior at a given BAC, because these data were measured in different sessions several days apart.

It is apparent that alcohol level does not impair discrete task performance as much as might be expected (though the impairment is very reliable, statistically), and that Moderate and Heavy drinkers appear to have different trends with BAC (although only "possibly significant" statistically). At BAC near legal limits, the Detection Index*, N_R/N (fraction of signs responded to within 3 seconds) shown in Fig. 4a, decreases about 20 percent for Moderates but negligibly for Heavies (this difference is possibly reliable; $t' = 1.4$ at 8 df, $\alpha = 0.1$). However, near their customary limits (Moderate at 0.11 BAC vs. Heavy

*In view of the evidence of peripheral detections from scanning data, N_R/N might more correctly be called the "Response Fraction."

TABLE 3. ANOV SUMMARY OF KEY EXPERIMENTAL MEASUREMENTS†
(Tables Give F-Ratios and Resulting Significance Levels)

EFFECTS OF ↓ ON →	DOF† (N,D)	STEERING TASK MEASURES							DISCRETE TASK MEASURES	
		STEERING		HEADING CONTROL			PATH CONTROL			
		N_{rev}	$\rho^2_{\delta_s}$	σ_ψ	ω_c	φ_M	σ_y	$\left\|Y_p^*\right\|_{\omega=.5}$	N_R/N	T_R
BAC {0, .06, .11}	2,24	0.79 —	16.89 ***	28.99 ***	15.17 ***	0.54 —	28.46 ***	13.20 ***	5.90 **	18.95 ***
Type of Drinker {M, H}	1,12	1.12 —	0.59 —	0.25 —	0.61 —	0.18 —	0.39 —	0.16 —	2.26 —	1.71 —
BAC × Drinker	2,24	3.24 ?	6.91 **	2.24 —	3.22 ?	0.89 —	3.82 *	1.51 —	2.38 —	1.86 —

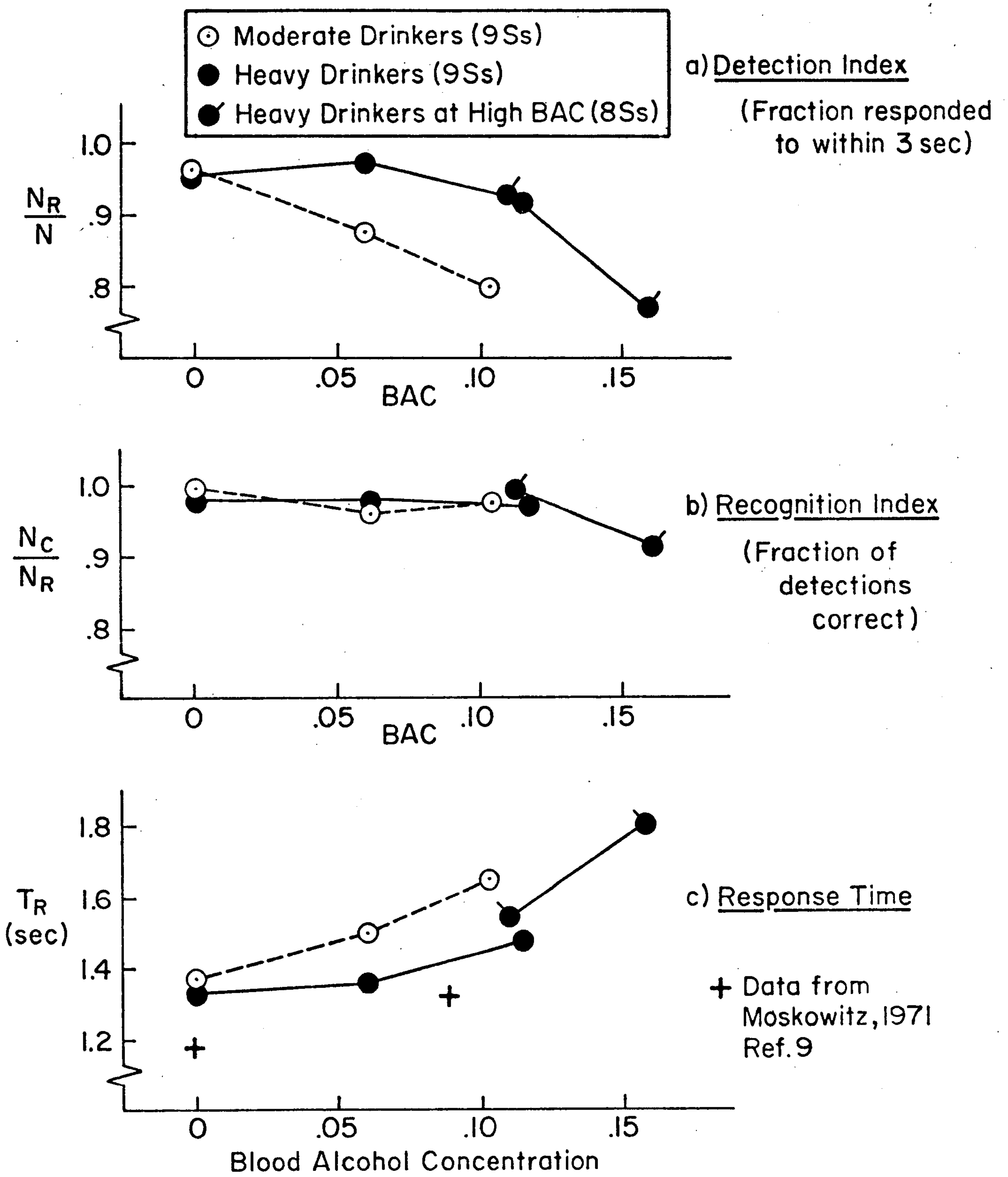
Values are F-ratios, symbols denote significance

DOF (N,D)	1,12	2,24	α <	STATISTICAL RELIABILITY	
If F-ratio =	3.18	2.54	0.10	Possibly reliable	?
	4.75	3.40	0.05	Probably reliable	*
	9.33	5.61	0.01	Reliable	**
	18.6	9.34	0.001	Very reliable	***

†This analysis corresponds to a nested experimental design, with subjects nested within the drinker type categories. Subjects were further subdivided into age categories, however these results are not considered here. Subjects were considered a random variable and subject interaction terms were used as the F-ratio denominators.

Figure 4

DISCRETE TASK PERFORMANCE VS BAC AND HABITS



at 0.16 BAC), the Heavy drinkers' performance deteriorates to a slightly worse degree than does that of Moderate drinkers (not statistically reliable; $t' = 0.6$, 8 df; $\alpha > 0.1$).

The "Recognition Index," N_C/N_R (fraction correct of those not missed), shown in Fig. 4b, remains within a few percent of 1.00 for Moderate or Heavy drinkers up to BAC = 0.11, beyond which the Heavy drinkers show a small (6 percent) deterioration. This somewhat surprising result is consistent with the eye-point-of-regard data (discussed in connection with Fig. 3). Our interpretation is that most BAC-caused misses are due neither to lack of peripheral detection (all signs are fixated) nor to poor pattern recognition (because $N_C/N_R \doteq 1.0$); therefore, they must be due to the driver being excessively late, or even omitting the motor response — another manifestation of an "indifference threshold" effect noted in Ref. 6 and later herein.

This interpretation finds support in the Response Time data of Fig. 4c, where at legal limit BAC's, the Moderate drinkers show a 20 percent and the Heavy drinkers a 12 percent increase. Nearer their limit (BAC = 0.16) the Heavy drinkers show a 35 percent increase over their sober response time levels. As noted for the Detection Index, the response times of Heavy drinkers are impaired less than Moderates at near-legal limit BAC's, but are more impaired at BAC's nearer their drinking limits.

As the average response times increase from around 1.3 sec near 0 BAC to 1.5-1.8 sec at higher BAC's, some misses ($T_R > 3.0$ sec) will be expected from the longer-time "tails" of the T_R distributions, even though recognition remains nearly perfect. The trends in the M vs. H data for N_R/N and T_R in Fig. 4 are consistent with this explanation below 0.11 BAC, and should be further investigated using eye-point-of-regard data. As a tie-in with other related data, the open crosses in Fig. 4c are the response times from a roughly similar experiment conducted recently by H. Moskowitz at the UCLA Insitute of Traffic Engineering (Ref. 9). (In that experiment the subject, in a driving simulator, was asked to respond to a pair of colored lights mounted on the sun visor at ±15 deg off center by pressing up or down on one of a pair of turn-indicator-like switches.) Although the levels differ slightly, the trend with BAC is quite similar and indicates that our data are compatible with that from other investigators.

Steering Tasks

Performance Measures. Figure 5 presents the most important measures of overall steering task performance. Although the plots progress from the inner to outer loops (steering, heading, path), it is more instructive to consider them in reversed order. Just as for the discrete task data, the tie-in at the two Heavy drinker sessions near 0.11 BAC is excellent, indicating reliable data for the steering tasks.

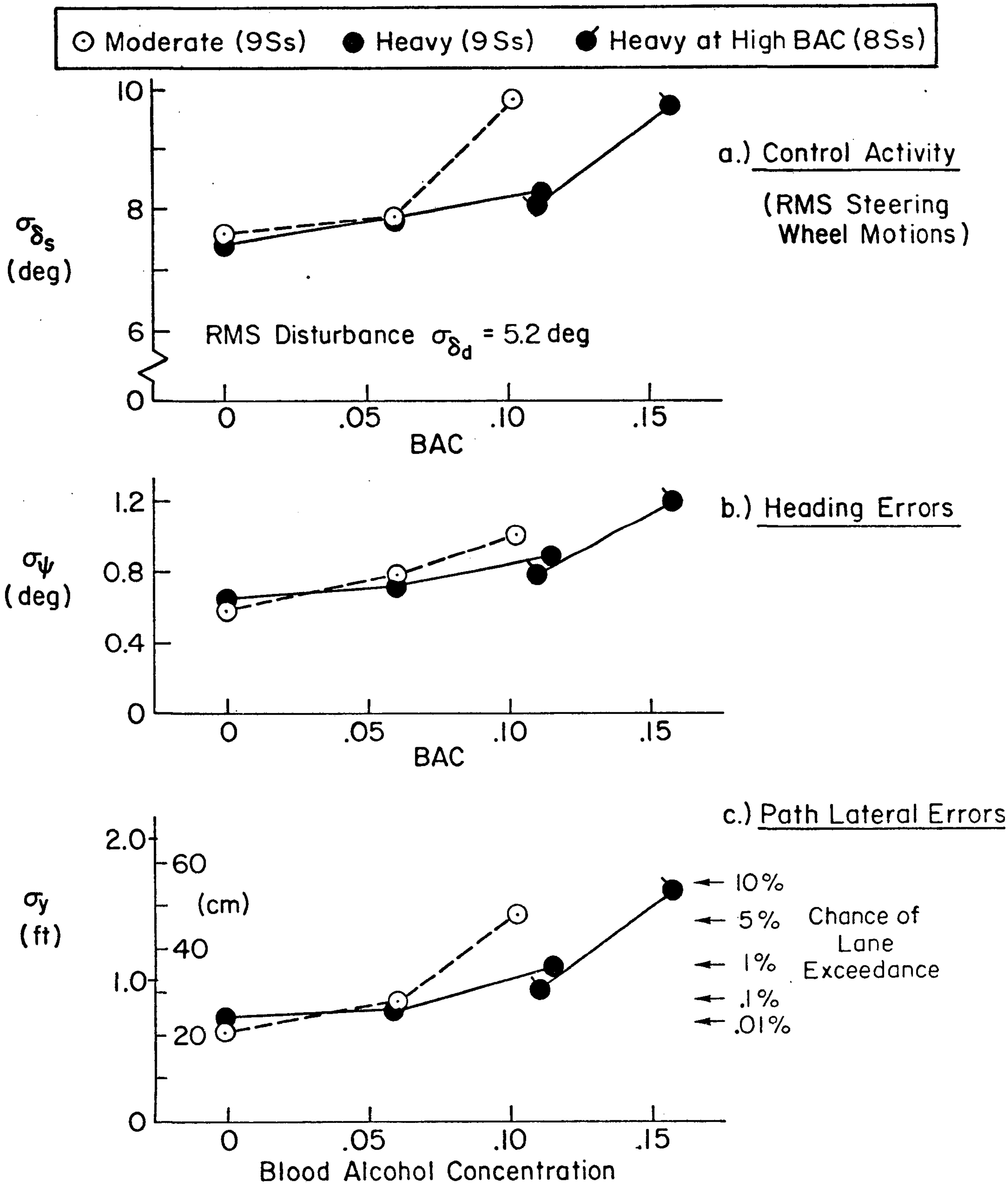
Considering the path deviations of Fig. 5c first, it is apparent that alcohol seriously impairs the control performance of both Moderate and Heavy drinkers (ANOV: $\alpha < 0.001$). Furthermore, over the 0-0.11 BAC range, the differential effects of alcohol on Moderate vs. Heavy drinkers are statistically reliable ($\alpha < 0.05$).

On the right of Fig. 5c is noted the probability (computed on the basis of a Gaussian path-error distribution) that at any given time some portion of a standard size car 80 in. = 2m width may exceed a 12 ft (2.7 m) lane width. It is apparent that sober drivers will stay well within their lane, but drunk drivers may not. For Heavy drinkers this chance of lane exceedance goes from around 1 in 10,000 when sober to 1 in 100 near legal-limit BAC (0.11), and to 1 in 10 near their maximum levels (0.16 BAC). For Moderate drinkers the chance of lane exceedance grows more rapidly; from less than 1 in 10,000 when sober to around 1 in 20 when near legal limit (0.11 BAC). From another point of view, these results imply that, at near-legal limits of alcohol (0.11 BAC), experienced Heavy drinkers have on the order of one-fifth the lane exceedances as Moderate drinkers; but at levels of alcohol near each group's likely (nausea) limits the Heavy drinkers will have twice the number of lane exceedances of Moderate drinkers.

The heading deviations shown in Fig. 5b also increase drastically and reliably with BAC (ANOV: $\alpha < 0.001$). Again, Moderate drinkers show **more sensitivity to BAC** than Heavy drinkers (but the interaction is not quite statistically reliable), and here, too, Heavy drinkers perform better than Moderates at legal levels of BAC but significantly worse than Moderates at more customary limits ($t' = 2.2$, 8 df; $\alpha < 0.05$).

Figure 5

STEERING PERFORMANCE MEASURES VS BAC



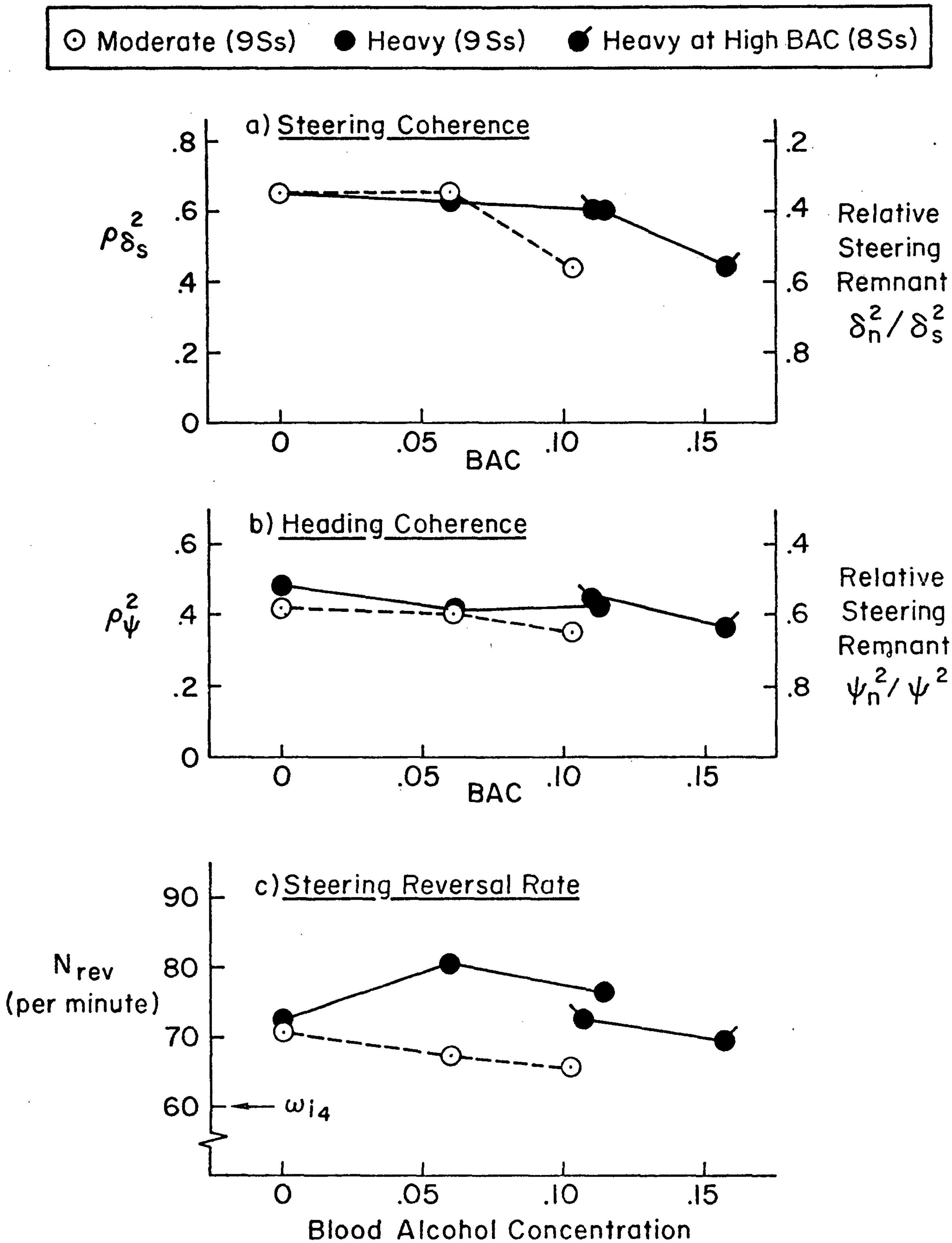
In both heading and path control the Moderate group performed slightly better **when sober** than the Heavy group. This difference is not statistically significant ($t' < 1.0$, $\alpha > 0.10$), but it masks any overall differences between the **general** performance of Moderate vs. Heavy drinkers at BAC < 0.06. It was observed that a number of Heavy drinkers performed better (in σ_y) at 0.06 BAC than when sober. (In the light of Figs. 4b and 4c, it might be more correct to say some Heavy drinkers performed slightly worse when sober than with a slight amount of alcohol.) This would tie in with anecdotal observations that some Heavy drinkers are "nervous" or "jumpy" when sober, and "calm down" at mild BAC levels. Detailed data on each individual are available to follow up on these leads, but we have not yet done so.

Lastly, consider the control activity performance σ_{δ_s}, given in Fig. 4a. If the driver perfectly cancelled the steering disturbance inputs, his score would be constant at $\sigma_d = 5.2$ degrees of steering wheel motion. In practice, he can cancel out low frequency disturbances (i.e., frequencies well below the unity-gain-crossover frequency, ω_c), but will lag and overshoot his corrections near ω_c, and will attenuate those above ω_c. In addition, any spurious steering actions such as "holds," "dither" or "limiting" will add remnant noise to the σ_{δ_s}. Since so many factors can influence σ_{δ_s} it serves mainly as an indicator of seriously excessive corrections; or if it drops, it indicates that the driver is not even attempting to correct most disturbances, and is in effect opening the heading control loop. Our results show that control activity always exceeded the disturbance-cancelling value, and was increased on the order of 20 percent at higher BAC's. As before, the Heavy drinkers show less sensitivity to BAC than Moderate drinkers at legal-limit levels, and comparable sensitivity at maximum BAC's.

Figure 6 shows additional performance measures of insightful value. At the top are shown the coherence data for steering activity and heading. "Relative remnant" (the fraction of noise in the total signal power) is measured by the complement of the coherence, as shown on the righthand scales. These data (with the ANOV of Table 3) imply that alcohol reliably increases relative steering remnant, but only at levels above 0.06 BAC for Moderate drinkers and above 0.11 BAC for Heavy drinkers. Overall, the effects of BAC on coherence are smaller than one might expect considering

Figure 6

CONTROL COHERENCY AND STEERING REVERSAL RATE VS BAC



the more nonlinear appearance of the time traces. Apparently, this is explained by the fact that the increased remnant mainly reflects a constant proportion of increased linear errors.

We recorded steering wheel reversal rate, N_{rev}, (presented conventionally as + or − reversals per minute for small reversals) for comparison with other investigators who use this measure of steering activity (e.g., Refs. 9 and 10) and these are shown in Fig. 6c. There is not much variation with BAC (note the suppressed origin scale), although there appears to be a slight rise in N_{rev} for Heavy drinkers at low BAC. (The ANOV implied no significant effects of BAC on Moderate vs. Heavy, but their differences **at 0.11** BAC are possibly reliable.) Also shown is the nearest input frequency (ω_1 = 6.28 rad/sec) which might possibly influence (stabilize) the steering reversal counts.

As a matter of interest, a rough estimate of the closed heading loop frequency was made, which turns out to be around ω_{CL} = 3.5 rad/sec. If the damping ratio is low (as the low phase-margin data presented later implies), then a spectral peak due to circulating remnant would occur at this frequency, and it might give rise to steering reversal rates of N_{rev} = 65-70 per minute, just in the range observed! This possibility is worthy of further investigation as a simple indicator of car/driver closed-loop bandwidth.

Driver Behavior Data (Describing Functions). As noted earlier, several factors can influence the overall measures of driver control performance, because these are intrinsically closed-loop measures wherein the output characteristics (e.g., path error) are a product of the input spectrum and level, the car/driver dynamics (measured via the frequency response describing functions), and the injected remnant (noise) contributions which circulate around the heading and path control loops (see Ref. 8 for the complex details). An essential ingredient in understanding the net effects of alcohol on performance is its effect on the driver's describing function, $Y_p(j\omega)$, with a realistic roadway dynamic perspective display to the perceptual system and with realistic car dynamic response properties in heading and path. Such describing function measurements have been made for every run and they clearly show the effects of alcohol. Reference 6 presents typical examples of $Y_p(j\omega)$ averaged over numerous subjects, and shows that a few key parameters suffice to model their salient features. Some findings from Ref. 6 relevant to this discussion are the following:

- The driver's describing function can represent the sensitivity to both heading and path deviations, these being reflected in the gains, $|Y_p|$, at, respectively, high ($> \omega_c$) or low ($< \omega_c$) frequencies.
- Alcohol causes reductions in both heading and path gain, but mostly in path gain, best characterized by $|Y_p|$ at 0.19 rad/sec and/or 0.5 rad/sec, the latter being more reliable.
- Alcohol causes only small changes in phase lags below or near ω_c because decreases in neuromuscular subsystem bandwidth at higher frequencies are somewhat offset by their lower damping ratio (e.g., see also Ref. 11). As a result, the 180 deg phase crossover frequency, ω_u, is a better indicator than effective delay, τ_e, of the reduction in maximum driver bandwidth as limited by neuromuscular delays.
- Alcohol affects stability margins (phase or gain margins) surprisingly little when averaged across all types of subjects.

We will present some additional describing function data over Ref. 6 to extend these findings to higher BAC, and to investigate differences between drinking habits. Figure 7 gives the describing function parameters representing the driver's: bandwidths ($\omega_u \sim$ maximum bandwidth; $\omega_c \sim$ actual bandwidth — also to heading deviation sensitivity); stability margin, φ_M (margin in phase lag relative to 180° = instability); and path error sensitivity (magnitude of $Y_p(j\omega)$ at 0.19 and 0.50 rad/sec).

At the top of Fig. 7 the bandwidths ω_u and ω_c both show a monotonic reduction with BAC which is very reliable statistically ($\alpha < 0.001$, Table 3). The Heavy-drinker data show that this trend extends to 0.16 BAC, with no sudden dropoff apparent. In fact, somewhat unexpectedly, ω_u tends to level off at 0.16 BAC, implying no drastic neuromuscular impairment at heading control frequencies. Moderate drivers start out at 0 BAC with slightly better bandwidths which decrease with BAC faster than for Heavy drinkers. This interaction is possibly reliable ($\alpha < 0.1$, Table 3), but the bandwidths averaged over 0-0.11 BAC are no different for Moderate and Heavy drinkers.

Figure 7

CONTROL-LOOP AND DESCRIBING FUNCTION PARAMETERS VS BAC

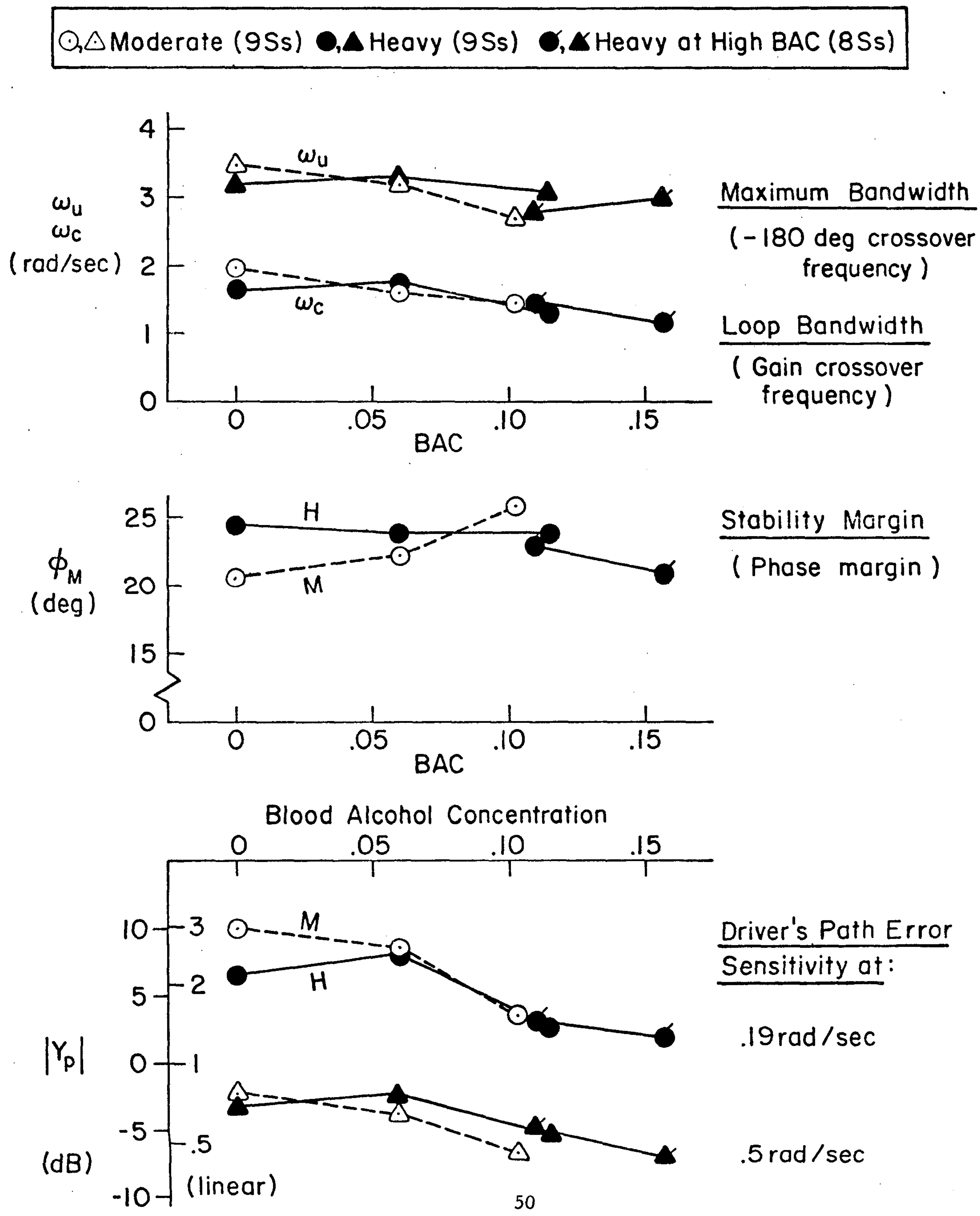


Figure 7b shows that the stability margins (φ_M) for Heavy drinkers fall off very slowly with alcohol, while those for Moderate drinkers actually seem to increase slightly up to 0.11 BAC (these effects are not statistically significant). Since the gain margin (roughly measured by the ratio of ω_c/ω_u) is slightly reduced for 0.11 BAC, while phase remains about constant, these gain and phase margin effects reflect a more conservative control strategy at high BAC.

Finally, the path-sensitivity data at the bottom of Fig. 7 show a strong and consistent reduction with increasing BAC, the reduction relative to sober BAC being slightly more for Moderate than Heavy drinkers (main BAC effect very reliable, $\alpha < 0.001$; interaction not so, per Table 3). Considering the linear ratio scale of Fig. 7c, it is apparent that, typically, the path sensitivity decreases, from 100 percent at 0 BAC to about 70 percent at 0.11 BAC and 50 percent at 0.16 BAC, with Heavy drinkers being less sensitive than Moderates.

An hypothesis is proposed in Ref. 6 that an increase of the driver's "indifference threshold"* and/or more "intermittency of attention"† could account for a number of the behavioral and performance effects of alcohol (e.g., lower gains, small phase effects, constant stability margins, more remnant, larger errors of a wandering rather than oscillatory type, etc.). The present results for Heavy drinkers up to 0.16 BAC are consistent with the Ref. 6 trends and support the same conclusions. Further, the observed relative insensitivity of phase lags near ω_c and decreased control coherency are consistent with the simple compensatory tracking data of Ref. 11 at BAC < 0.08.

Taken as a whole our results, for discrete-plus-control tasks which crudely simulate driving on rural roads at night in stormy weather, show

*Indifference Threshold ≡ thresholds in a perceptual motor control loop which are not specifically sensory or proprioceptive thresholds, e.g., control inaction while the error is within some tolerance zone (Ref. 14).

†Attentional Intermittency ≡ switching of control attention frequently, and usually asynchronously, from task to task (or loop to loop), often (but not always) evidenced by eye-point-of-regard or control inactivity (e.g., Ref. 15).

reliably increasing impairment of driving performance and skill as alcohol levels reach and exceed typical legal limits, near 0.11 BAC. Heavy drinkers show less sensitivity than Moderate drinkers at legal limits but are more impaired than Moderates when compared near each group's cusomary drinking habits.

SUMMARY AND CONCLUSIONS

Summary

A simplified laboratory driving simulator was developed to test both types of tasks used in driving a car on the open road: a continuous compensatory "steering task" to regulate against heading and path deviations; and an intermittent "discrete response task" requiring detection, scanning, recognition, and response (e.g., horn and brake operations). The description of this simple simulator, with an investigation of the basic effects of alcohol up to 0.11 BAC for 18 subjects under different task loadings (steering task alone, discrete task alone, and combined tasks requiring divided attention), is given in a companion paper (Ref. 6).

The objective of the present experiment, which formed the main facet of the overall investigation, was to determine if there is a difference in driving performance (and the underlying behavior) on the basis of an individual's drinking habits. This objective was successfully met, using a typical cross section of 20 licensed drivers who drink either moderately or heavily. They were divided into two drinking habit groups of 10 each (balanced as well as feasible for representative IQ and wide age range): Moderate drinkers (usually exceeding 0.05 BAC and occasionally reaching 0.10+ BAC); and Heavy drinkers (usually exceeding 0.10 BAC and occasionally exceeding 0.15+ BAC). Light drinkers (rarely exceeding 0.05 BAC) could not be tested at the desirable legal limit level of 0.10+ BAC due to excessive nausea. The main experiment compared Moderate vs. Heavy drinkers at BAC = 0, 0.06, and 0.11; the maximum just exceeds a common legal limit of BAC, and was very near the maximum limit for most of the Moderate drinkers due to nausea or other reasons. A separate session took the Heavy drinkers to 0, 0.11, and 0.16 BAC, the maximum being near their customary limit. (Serious problem drinkers or alcoholics were not tested.) Two subjects could not complete their runs.

The combined (divided attention) task analyzed herein included steering control against random disturbances, plus discrete commands (to tap the horn or brake) appearing randomly on small peripheral signs at locations corresponding to the road edges (±20 deg) and rear view mirror (±45 deg). The scenario was driving a rural road on a stormy night. Several parameters were measured including: heading, path, and steering deviations; driver's describing function and coherency; and discrete task detection index, recognition index, and response time. Discrete response and steering signals were recorded for all runs, plus eye-point-of-regard signals for selected subjects. As a target of opportunity, clinical ratings and tests of sobriety were also logged, but these have not yet been analyzed. Generally speaking, the data are quite repeatable (e.g., same group on separate sessions), are self-consistent (e.g., within tasks and drinking-habit groups), and show some effects very sensitive to BAC and to type of drinker.

Conclusions

The major conclusions from this experiment are as follows:

- At sober conditions (including one set of placebo runs during each session) there were no significant differences between the Moderate and Heavy drinkers. The chance of lane exceedance by some part of the car is less than 0.0001 for both groups when sober.

- Alcohol levels above common legal limits (0.11 to 0.16 BAC) cause very appreciable and statistically reliable **impairments** of the driving performance of both Moderate and Heavy drinkers, in particular to: path and heading deviations; driver's sensitivity to errors in path and heading; steering remnant; and discrete task misses and response times. Driver control loop stability margins, discrete task recognition accuracy, and steering wheel reversal rate are <u>not</u> changed significantly.

- Compared at legal limit alcohol levels (0.11 BAC), Heavy drinkers tend to be less impaired in the above measures than Moderate drinkers (probability of lane exceedance of 0.01 vs. 0.05); but compared near their customary drinking limits (0.11 BAC for Moderate vs. 0.16 BAC for Heavy drinkers) the Heavy drinkers are usually <u>more</u> impaired than Moderate drinkers (chance of lane exceedance of 0.10 vs. 0.05).

- The above effects could be explained by alcohol-induced increases in the driver's "indifference threshold" and/or more "attentional intermittency," plus some reduction in neuromuscular bandwidth at higher BAC.

- Eye-point-of-regard measurements showed that, in these reasonably stressful, combined steering and discrete tasks, the driver does not search (scan) for discrete events; rather he fixates primarily on the road ahead and detects "interesting" events peripherally, then fixates the event, recognizes it (usually perfectly), then makes the required response (sometimes late or ignored at high BAC).

- Peripheral discrete task data at ±45 deg were usually within 10 percent of those at ±20 deg at BAC = 0.11, partly because the outer sign brightness was increased for equal just-detectable levels when sober.

- The rate of steering wheel reversals corresponds roughly to the car/driver's closed heading loop frequency and follows a similar small decrease at higher BAC.

- The response time and describing function data tie in well with other investigators' results on similar setups.

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