A Vehicle-Mounted Drunk Driving Warning System (DDWS) Concept, Laboratory Validation, and Field Test

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ABSTRACT

A brief manual control test and decision strategy have been developed, laboratory tested, and field validated, which provide a means for detecting human operator impairment from alcohol or other drugs. The test requires the operator to stabilize progressively unstable controlled element dynamics. Control theory and experimental data verify that the human operator's control ability on this task is constrained by basic cybernetic characteristics, and that task performance is reliably affected by impairment effects on these characteristics. Assessment of human operator control ability is determined by a statistically based decision strategy. The operator is allowed several chances to exceed a preset pass criterion. Procedures are described for setting the pass criterion based on individual ability and a desired unimpaired failure rate. These procedures were field tested with an automobile-installed apparatus designed to discourage drunk drivers from operating their vehicles. This test program, sponsored by the U.S. Department of Transportation, demonstrated that the control task and detection strategy could be applied in a practical setting to screen human operators for impairment in their basic cybernetic skills.

Reviewed in this paper are the development and validation of a behavioral testing device that can detect human operator impairment. These skills are important in performing tasks that require continuously manipulating displayed variables with a control device, such as driving or machinery operation. The manual control skills required to perform these types of tasks have been extensively studied (1), and the test described herein has been developed to detect impairment in these skills.

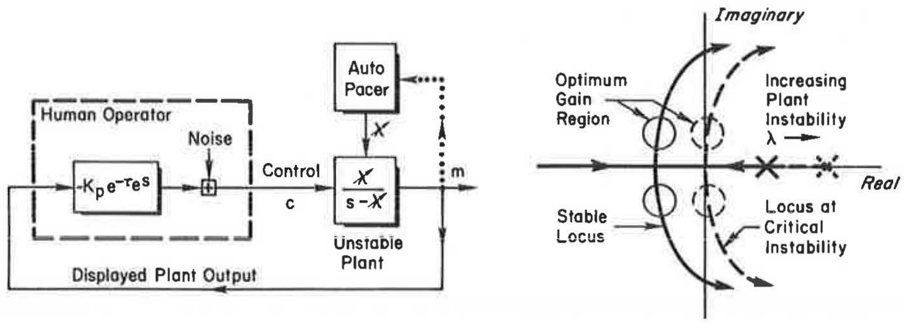
The test involves two components: a control task and a detection strategy. The control task, called the Critical Tracking Task (CTT), was developed in the early 1960s to test the visual motor performance of pilots and astronauts (2,3). Over the years, it has proven to be an effective indicator of the effects of environmental stresses [e.g., noise (4), space station confinement (5), ship motion (6), spacecraft re-entry (7), and human operator impairment (8,9)].

The use of the CTT as an alcohol impairment detection device was first tested in automobiles by the General Motors Corporation (10). Subsequent research sponsored by the U.S. Department of Transportation (11-14) was conducted to optimize the test strategy. In subsequent research, the statistical decision theory for optimizing the detection strategy was developed and validated in laboratory tests (15). Following this, vehicle-mounted devices were assigned to convicted drunk drivers to obtain field validation data (16). In the remainder of this paper, the control theory basis for the CTT will be described, as will the statistical theory behind the impairment detection strategy, and laboratory and field test results that validate tester performance in a practical, operational environment.

CRITICAL TRACKING TASK (CTT)

The task description and theory of operation for the CTT have been previously documented (2,3). A summary is illustrated in Figure 1. The task dynamics consist of an unstable controlled element, and an autopacer unit that controls the location of the unstable pole. No input is necessary because the operator's remnant (noise) is sufficient to disturb the system. The unstable root, λ, is initially set at a small value. As the subject begins to perform the task, the plant instability is increased (the root moves further into the right half plane). When a filtered version (with a 1-sec time constant) of the displayed plant output deviations, m, exceed about 15 percent of the display range, the rate of increase of λ is reduced by a factor of four in order to slowly approach the point of closed loop instability and avoid overshoot. When m exceeds the display limits, control loss is assumed, and the pole location at this point, termed the critical instability limit (or λ_c), is used as the task performance metric. The total test time for experienced subjects is approximately 30 sec.

As indicated in Figure 1, the subject's task performance depends on visual-motor dynamic time delay (τ_e), gain (K_p), and internal noise or remnant (random control actions). The subject's time delay dictates the shape of the root locus (the pure time delay causes the complex branches to bend to the right) while K_p determines the operating point on the locus. Increasing the task instability (λ) translates the entire locus to the right or unstable direction. The pure gain closure dictates two primary closed-loop roots (a pure time delay actually gives an infinite number of roots, but the lowest frequency pair dictates the stability characteristics). The operator's optimum strategy is to set K_p to locate both closed-loop poles on the imaginary axis as indicated. The task is continually perturbed by the operator's internal noise source. As the point of closed-loop instability is approached, the underdamped closed-loop system response tends to increasingly amplify display deflections, at first causing a reduction in the autopacing rate,



a) Block Diagram *b) Root Locus*

FIGURE 1 CTT task elements and root locus stability analysis.

then finally terminating a trial when the display bounds are exceeded. These theoretical aspects have been carefully validated by experiments in the United States (2,3) and The Netherlands (17).

Impairments can affect the human operator's control capability in three ways: (a) increased visual-motor time delay (τ_e); (b) interference with accurate K_p adjustments; and (c) increased noise. Any combination of these three impairment effects would tend to reduce the achievable task score, λ_c. Several studies have been conducted on the effects of alcohol on λ_c and summary results are plotted in Figure 2. As noted here, results have been extremely reliable across several past studies.

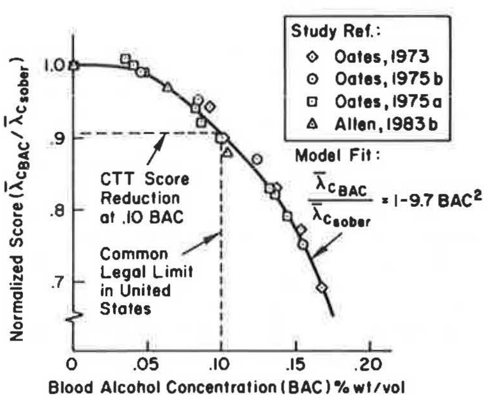


FIGURE 2 Experimental results of alcohol effects on CTT performance over several past research studies.

The critical tracking task can, of course, be described in simpler terms. The test is similar to balancing a broomstick on the end of ones' figure--only the stick decreases in length as time progresses. At some point, the stick is too short to balance, and it falls over. The length of the stick when control was lost is compared to the individual's unimpaired ability, and if certain criteria are not met, the trial is failed. If the driver fails four trials in a row, the alarms (flashers and horn) stay active and the driver must wait 10 min before attempting the test again. If any one of the trials is passed, the alarms are shut off and the car operates normally.

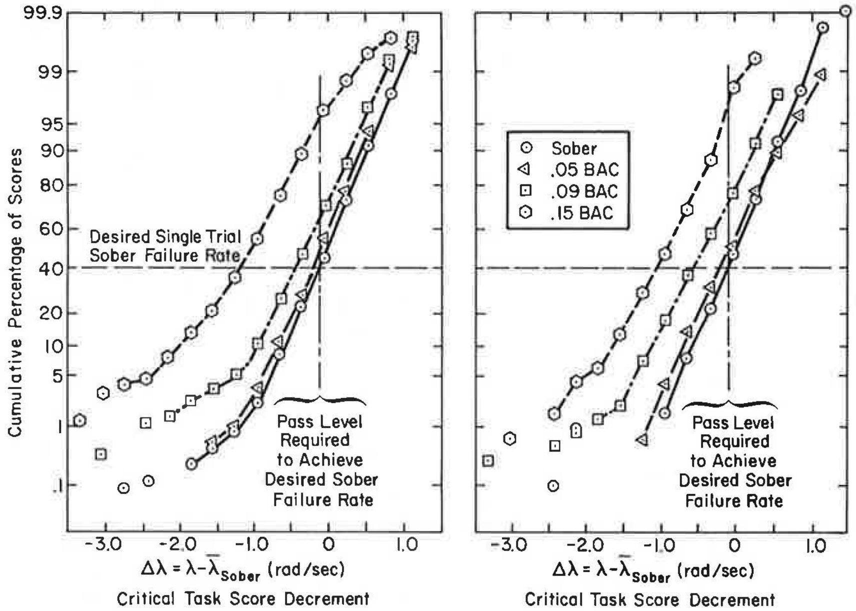
One of the most important aspects of this test is that it measures the impairment level of the operator regardless of the cause. Although blood alcohol concent (BAC) is an effective predictor of impaired driving ability, there are many other factors that may impair driving ability that BAC cannot address. Some of these impairing factors may only impair driving ability at certain times. For example, loss of sleep or stress may, alone, not affect the driver's ability, but when combined, may have devastating effects. As another example, an over-the-counter cold remedy, or a single beer may, alone, not impair the driver, but when combined, can have an effect greater than a BAC of 0.15 percent (one and one-half times the common legal limit for alcohol).

IMPAIRMENT DETECTION STRATEGY

Details of the development and optimization of the impairment detection strategy (IDS) have been described previously (15,18). The objective of the IDS is to maximize the chance of detecting operator impairment with a minimum number of CTT trials. This research developed a statistically based decision strategy to maximize test discriminability (i.e., low failure rate for normal operators and high failure rate for impaired operators). The IDS development and optimization strategy started with an analysis of the statistical properties of CTT performance (λ_c). Analysis of past data showed trial-to-trial and between-subject performance variability to be quite consistent across several studies (15,18) and a reliable effect of alcohol impairment was noted as illustrated in Figure 2. It was also found that subjects could be rapidly trained on the CTT but residual, long-term skill improvement would have to be accounted for.

Based on the statistical analysis of past data, several IDS requirements were established: (a) significant performance differences between operators require individualized pass criteria; (b) stable performance score variance and relatively independent trial-to-trial performance variability allow the use of simple multiple sampling strategies; and (c) long-term residual skill improvement would require procedures for sampling and periodically upgrading performance criteria.

The important statistical characteristics of CTT performance relative to IDS development can be illustrated with cumulative distribution functions as shown in Figure 3. The distributions are normalized and averaged across a large number of subjects and plotted on probability paper (a Gaussian distribution plots as a straight line). The data are normally distributed over a wide range, and the alcohol effect is clearly indicated. The basic requirement of the IDS is that sampled subject performance must exceed a preset pass level. Several sampling strat-



a) Data From Oates, 1975b *b) Data From Oates, 1975a*

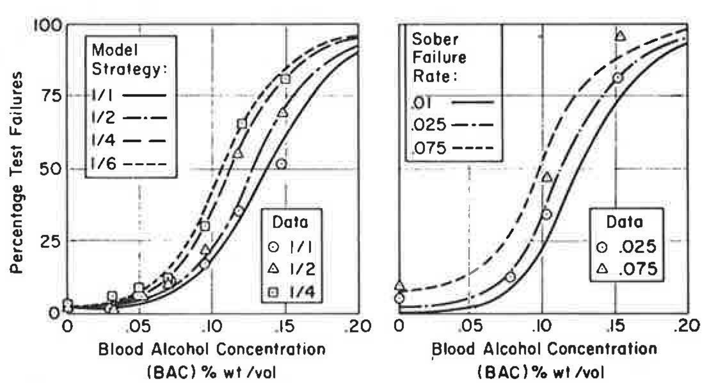
FIGURE 3 CTT differential score distributions averaged across 24 subjects in each experiment.

egies were analyzed and tested with past data bases (15,18) and, for various reasons, a "one-pass" out of several permitted attempts was selected. With this strategy, and assuming independent trials, the probability of failing the test is the single trial probability of failure raised to the power of the number of permitted attempts:

$$P_{fail}(N \text{ trials}) = [P_{fail}(\text{single trial})]^N$$

This approach permits us to simply define the pass level given a subject's performance distribution and a desired probability of test failure when sober. For example, for a 2.5 percent failure probability given four attempts, the single trial probability must be approximately 40 percent [i.e., $(0.4)^4 \cong 0.025$]. Given this sober pass level as indicated in Figure 3, one can also derive the expected drunk failure rates [i.e., at BAC = 0.10, $(0.76)^4 \cong 0.35$, and at BAC = 0.15, $(0.96)^4 \cong 0.85$]. A statistical model based on this procedure was developed, and IDS model predictions of failure rates were compared with failure rates obtained with the IDS applied to past experimental data (15). The discriminability results are illustrated in Figure 4.

The preceding good agreement between model and data suggest that the detection strategy is well understood, and that an adequate procedure for establishing task performance pass levels has been established. In addition, the strategy and procedures embody two other desirable features: (a) the pass levels are near a subject's average or median performance level, which is stable and can be determined reliably; and (b) a subject's cumulative distribution function can be used to easily determine pass



a) Variation in Permitted Attempts at Constant Sober Failure Rate = .025 *b) Variation in Sober Failure Rate for a One Pass in Four Attempts (1/4) Strategy*

FIGURE 4 Impairment detection strategy comparison between model analysis and experimental data (strategies involve one pass in several attempts—1/N).

level, and also to upgrade the pass level to account for residual skill improvement.

LABORATORY VALIDATION EXPERIMENT

To validate the effectiveness of the CTT and IDS just described, an experiment was conducted that compared the CTT score with both BAC (in weight per volume) and driving performance in a driving simulator (15). Subjects were convicted drunk drivers obtained through the cooperation of the Los Angeles Municipal Courts. Twenty-four so-called "volunteers" were permitted to participate in the experiment as a condition of probation, and, in exchange, received a reduction in their court-sanctioned fine.

After being accepted, the subjects were required to participate in three 2-hr training sessions and three full-day experimental sessions. On the two drinking days, the subjects were dosed to 0.15 percent BAS (±0.01 percent). CTT trials were recorded at the peak BAC (0.15 percent) as well as at descending BACs of 0.10 and 0.075 percent. On one of the days, driving simulator data were obtained at BACs of 0.15 and 0.10 percent. On the other day, these data were collected at 0.15 and 0.075 percent. Each subject participated in one placebo and two drinking sessions. The subject population was divided into three groups matched for age, sex, and driving experience, and the order of occurrence of placebo session was different for each group.

Validation experiment results are summarized in Figure 5. Notice, first, that the discriminability data agree with the statistical model developed from past experimental studies. More importantly, analysis of simulator data shows a high correlation between simulator accidents and test failure. As shown in Figure 5, pre-drive CTT failures detected 81 percent of subsequent simulator accidents at a BAC of 0.15 (i.e., 81 percent of the accidents at 0.15 BAC were associated with CTT failures). These correlations between predicted and actual test performance show that it is now possible to both predict and verify vehicle operator impairment using a cybernetic test such as the CTT in combination with a suitable IDS.

Additional findings were also obtained on subject training procedures. CTT performance obviously has a strong motivational component. The validation experiment subjects were assigned by the traffic court and were not truly motivated volunteers. Several subjects exhibited a lackadaisical attitude during training, and were not encouraged by the positive reinforcement payments that were offered for good performance. In a subsequent training experiment (19), it was found that giving a time penalty (30-sec wait) for test failures was a much more effective way to deal with nonvolunteer subjects who were motivated mainly to minimize their time involvement.

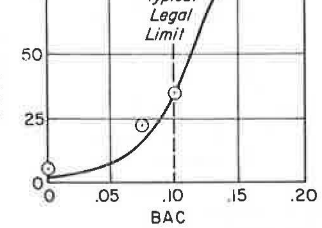
FIELD VALIDATION EXPERIMENT

The purpose of the field validation experiment was to demonstrate that a vehicle-mounted CTT-IDS could be assigned to convicted drunk drivers on a practical basis. This included selection and assignment by traffic courts and exclusive routine use by the recipients for a 6-month period. The vehicle-mounted test equipment, shown in Figure 6, combined the CTT-IDS into a system called the Drunk Driving Warning System (DDWS) and was installed in 10 1978 Chevrolet Nova automobiles. The subject had to pass the DDWS test in order to deactivate certain alarms: the car could be driven without passing the test but, in this case, the emergency flashers would operate and, if the car was driven over 10 mph, the horn would honk once per second. If the driver failed the test (four fail trials in succession), the computer required a 10-min wait before retesting was permitted.

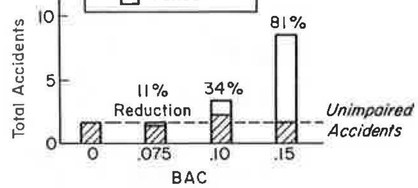
Various countermeasures were incorporated into the DDWS to prevent cheating. These included sealing components and cables to prevent or reveal physical tampering, and requiring retesting if the driver left the driver's seat or opened his door after starting the test. An event recorder was also incorporated into DDWS to monitor the driver's use of DDWS and record instances of test failure and/or driving with alarms activated. Extensive usage data by time of day were obtained.

Two municipal court judges were willing to administer the DDWS as a sanction to convicted drunk drivers. The California law was temporarily modified to permit experimental evaluation of the DDWS sanction. Approval and/or cooperation was obtained from various state agencies (e.g., the Department of Motor Vehicles) in order to carry out the field test program. Nineteen drivers were subsequently assigned DDWS vehicles to be used exclusively over a 6-month period. Their licenses were restricted so that they could not legally drive any other vehicle. After initial training, the alarm system was activated and the subjects were required to check in at 2-week intervals. During the check-in sessions, the car and DDWS system were inspected, the data tape was removed, and the computer was analyzed. The subjects were debriefed and questioned about test failure episodes. (There was no penalty for admitting such instances during the test period.)

The design of the field test experiment was



a) CTT Impairment Discriminability, Data and Statistical Model Comparison



b) CTT Failure Detection of Simulator Accidents

FIGURE 5 Results from laboratory validation experiment (one-pass-in-four-attempts detection strategy, desired sober failure rate = 0.025).

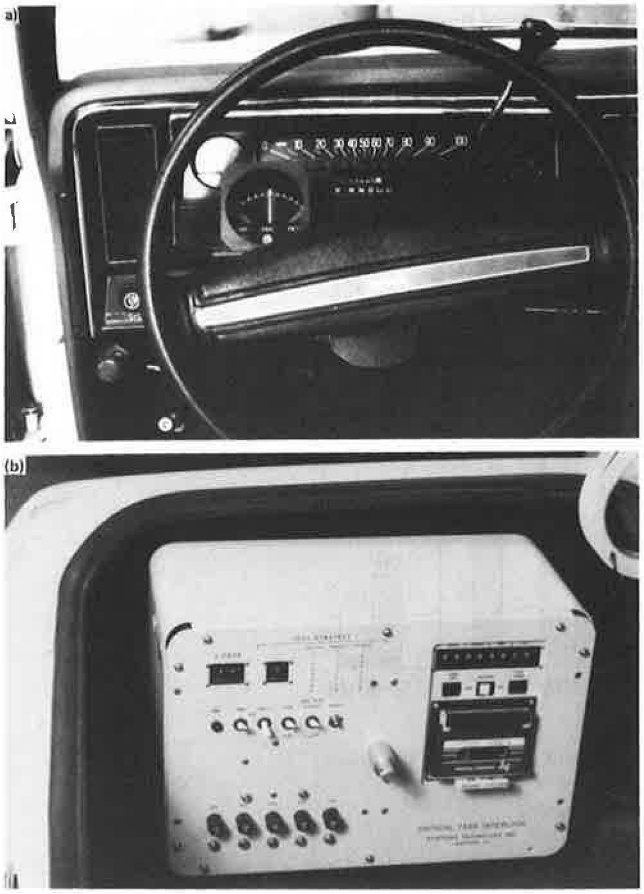


FIGURE 6 Vehicle-mounted field test apparatus (a) subject display and steering wheel control, and (b) trunk-mounted electronics and cassette data recorder.

divided into three major phases. The DDWS alarms were turned off during the initial and final 4-week periods (Phases I and III) and were activated during the middle 18-week period (Phase II). This design feature was incorporated to observe the influence of the DDWS system on driving patterns. Phases I and III were further subdivided into 2-week periods where the test was either active or inactive. This feature was included to see whether the requirement for taking the CTT test influenced driving patterns. Training on the CTT test took place during the second half of Phase I.

RESULTS

The overall results were derived from three basic data sources: (a) recorded data, which were retrieved and reviewed at the biweekly check-in sessions; (b) in-depth assessments developed during data reviews and debriefings at the biweekly check-ins; and (c) structured interview data obtained from subjects, colleagues, and relatives of subjects, court, and state agency personnel associated with the program, and others associated with the general drunk driving problem. Results from these three sources are described in the following paragraphs.

Recorded Data

Recorded data were analyzed to look for DDWS influence on driving patterns, subject performance, and the ability of DDWS to detect impaired drivers. Requiring the driver to take the CTT test with or without the DDWS alarms activated seemed to have little effect on day or night driving patterns (16). An analysis of test passes and failures was performed for check-in sessions at the beginning and end of Phase II (alarms on) and the end of Phase I and beginning of Phase III (alarms off). The purpose of this analysis was to determine whether having the alarms activated affected vehicle usage.

Data for test attempts as a function of time of day are shown in Figure 7. Chi-squared analysis showed the test attempt differences between alarms on and off to be marginally significant ($p = 0.038$). On a relative basis, the alarms-on versus alarms-off test attempts are small except for the early morning hours (12:00-4:00 a.m.). Time-of-day differences were ob- viously highly significant. Time-of-day interactions with test attempts and performance (pass/fail) were found to be significant while most weekday-versus-weekend interactions were found to be small or not significant (18). Thus, further analysis was restricted to time-of-day effects.

Failure rates for various time periods are shown in Figure 8. Daytime failure rates were about what was expected (i.e., ≅ 2.5 percent) based on the procedure used to set individualized CTT pass scores. Nighttime failure rates were three to seven times greater than this level, however, which is consistent with high incidence of drinking and driving during nighttime "recreational-social" periods versus daytime trips for commuting to and from work and running errands.

In-Depth Analysis

Because no objective data were available on subject BAC, the ability of DDWS to circumvent drinking-driving trips rests on circumstantial objective evidence such as is shown in Figure 8. Debriefing information was obtained on all test failures, however, and these data were combined with objective data as summarized in Table 1 to further classify test failure. Total test failures have been partitioned according to whether the driver was determined to be sober, impaired, or whether some equipment problem might have caused the failure (equipment malfunction episodes were experienced with several subjects).

Differential test scores (test score-pass level) were computed from the cassette-logged data, and when this score was greater than -0.4 (i.e., the test score was greater than a score 0.4 units below the pass level), the subject was assumed to be sober when the test was taken. This assumption was based on analysis of a statistical model for CTT scores and amounts to a 95 percent level of confidence that BAC was less than 0.05 percent weight per volume (18). In the case of subject 19, it was decided that his pass level in the beginning was set too high, so his total failures for $\Delta\lambda \geq -0.2$ were used. Problem failures were interpreted from the in-depth analysis, and the impaired failures were given by

$$F(\text{Impaired}) = F(\text{Total}) - F(\text{Sober}) - F(\text{Problem})$$

As noted in Table 1, even if the sober and problem failures are accounted for, there still remains a significant portion of impaired failures, with two subjects accounting for the majority of these. The DDWS alarms should deter the subject from driving, but as recorded by the data logger and indicated in Table 1, three subjects drove with the alarms activated.

Subjects 17 and 20 had isolated incidences where the car had to be moved a short distance. Subject 19

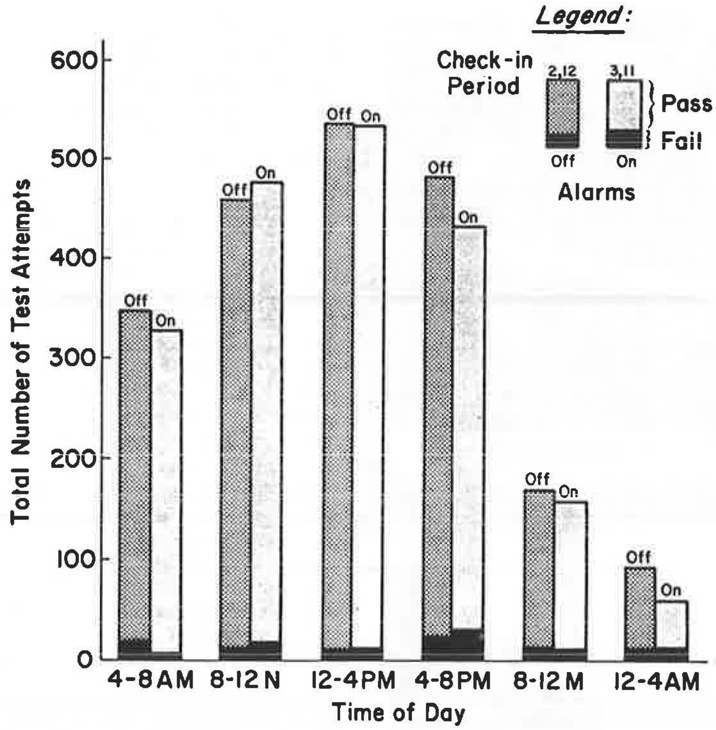


FIGURE 7 Effects of alarms on test attempts and performance (pass/fail) as a function of time of day.

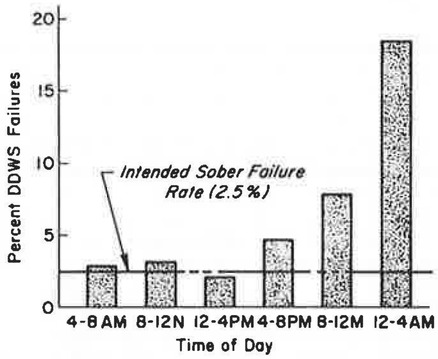


FIGURE 8 DDWS failure rate as a function of time of day.

TABLE 1 In-Depth Analysis of Test Failures

	Test Failures				
Subject No.	Total	Sober ($\Delta\lambda_p \geq -0.4$)	Problem	Impaired	Trips with Alarms
01	36	9	3	24	0
05	20	6	8	6	0
06	5	3	0	2	0
07	4	2	1	1	0
08	6	4	1	1	0
09	4	3	1	0	0
10	14	9	2	3	0
11	8	4	1	3	0
12	17	9	1	7	0
13	38	26	6	6	0
14	29	12	12	5	0
15	6	5	0	1	0
16	4	3	2	0	0
17	26	5	10	11	1
19	112	24[a]	8	81	5
20	13	12	0	1	1
22	9	4	2	3	0

[a] $\Delta\lambda_p \geq -0.2$.

actually admitted to occasionally driving his car without passing the test after drinking. This constituted a fairly serious violation of one of the conditions of probation, and the court was so notified. Subject 19 was cooperative, however, and it was recommended that he be permitted to remain in the program.

Debriefing Information Analysis

The municipal courts and the California Department of Motor Vehicles carried out their part in project support without serious problems. The courts do need an individual to take charge of subject screening, however, as was available through the West Los Angeles Municipal Court. Also, license restriction needs to be indicated on the front of the license to alert enforcement personnel and others (e.g., car rental agencies) of the DDWS user's restricted driving privilege. California is currently investigating this feature and may provide it in the near future.

Public acceptability for the DDWS concept has been quite good, once the objectives, approach, and background have been fairly presented. News media accounts of DDWS were fair and many times positive, although occasionally with some minor misinformation. Positive opinions have also been elicited by other individuals associated with the drunk driving problems, including relatives and colleagues of the DWI offenders employed here as subjects.

Finally, subject acceptance was quite good. No one found the DDWS to be a hardship, and most found it to be a desirable and effective sanction. Most

subjects would choose DDWS rather than fines, license restriction or suspension, or jail.

CONCLUDING REMARKS

The data presented here and elsewhere (18) indicate that a DDWS-equipped vehicle can maintain good impaired driver discriminability in a field setting. As to whether subjects drive after test failure, in-depth analysis showed that only three subjects drove with the alarms on (a violation of probation that is recorded by the DDWS data logger). One subject was determined to have driven while impaired and, even in this case, there is some indication that the drive was made at low speed. Thus, test failure would appear to significantly deter driving-while-intoxicated trips.

The CTT/IDS could be used as a cybernetic screening device in other scenarios such as daily screening of commercial or government vehicle operators, industrial process or power plant operators, and so forth. Card/key systems could be used to permit a common device to be used by a number of individuals wherein the individual scores are updated in the card via a magnetic strip. Finally, the IDS could be used with other cybernetic tasks that might prove to be sensitive to other aspects of human operator impairment (20).

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