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**Simulator Study of the Combined Effects of  
Alcohol and Marihuana on Driving Behavior**

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**A Simulator Study of the Combined Effects of Alcohol  
And Marihuana On Driving Behavior**

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16. Abstract <p>The study described in this report investigated the effects of alcohol and marihuana, alone and in combination, on driver performance and behavior in a fully interactive driving simulator. The simulator provided the driver a complex visual scene similar to a rural nighttime drive, and allowed the driver full control of steering and speed maneuvers. Performance and behavior data were collected during a 10-12 mile drive requiring about 15 minutes to complete. A variety of events were encountered during the drive, including curves, obstacles in the roadway, and winding roads. Accidents, tickets, and speed were recorded as traffic safety measures during the overall drive. Driver behavior, speed control, and steering performance were collected during each event to provide insight into the impairment mechanisms of alcohol and/or marihuana on the driver.</p> <p>A full placebo experimental design was employed which included all combinations of 3 marihuana (0, 100, and 200 <math>\mu\text{g}</math> <math>\Delta^9</math> THC/kg body weight) and 2 alcohol (0 and 0.10 percent BAC) levels. Based on a large number of driver performance and behavior variables, alcohol was found to have a pervasive and significant impairing effect. Simulator accidents increased reliably under alcohol, which was accounted for by increased steering and speed control variability. Marihuana effects were minimal, the primary one being speed reduction. This speed reduction, while statistically reliable, was minimal in terms of actual driving behavior and is probably of no practical significance. A significant drug interaction effect was observed in simulator accidents; however, the data do not allow us to identify the impairment mechanism leading to this result.</p>					
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## ABSTRACT

This study concerns research performed in a fully interactive driving simulator on the effects of alcohol and marihuana, alone and in combination, on driver control behavior and performance. The simulator allowed the driver to control steering and speed on a video-projected two lane roadway. Subject behavior and performance were measured during a 10 mile drive which required about 15 minutes to complete. A variety of events were encountered during the driving scenario, including wind gusts, winding roads, obstacles, and isolated curves. Accidents and speeding tickets were recorded as measures of traffic safety during the overall drive. During each event, measures of driver behavior and performance in steering and speed control were obtained in order to determine those driver factors which are impaired by alcohol and/or marihuana and to determine their contribution to reduced traffic safety.

A full placebo experimental design was employed which included all six combinations of two alcohol levels, 0 and 0.10 percent BAC (Blood Alcohol Concentration), and three marihuana levels, 0, 50, and 100  $\mu\text{g}$   $\Delta^9$  THC/kg body weight. Based on a large number of measures of driver behavior and performance, alcohol was found to have a consistent and significant impairment effect, while marihuana had only an occasional effect. Also, there was little evidence of interaction between alcohol and marihuana. Accidents and speeding tickets reliably increased under alcohol, but no marihuana or combined alcohol and marihuana influence was noted. The alcohol impairment effects on steering and speed control behavior and performance were consistent with the increased accident and ticket rate.

The primary alcohol impairment mechanism seems to be increased variability in steering and speed control behavior. Between-subject variability was found to be similar for alcohol and marihuana considered alone. Combined alcohol and marihuana treatments lead to significantly increased between-subject variability, however, which may partially account for the lack of reliable interaction effects between these two drugs.



## EXECUTIVE SUMMARY

A portion of the National Highway Traffic Safety Administration alcohol and drug research program is concerned with the effects of alcohol and/or marihuana on traffic safety. Epidemiological studies of the causes of accidents have definitely implicated alcohol involvement as a major factor, and control failures seem to be a significant impairment mechanism. Marihuana use is becoming more prevalent, and there is definite concern for potential traffic safety problems due to marihuana intoxication and the combined use of alcohol and marihuana. The objectives of this research program are twofold: 1) to determine the driver impairment mechanisms of alcohol and marihuana and how these lead to accidents; and 2) to develop countermeasures based on the impairment mechanisms.

This report covers the first phase of a two-phase study concerning the effects of alcohol and marihuana, alone and in combination, on driver control behavior and performance. This first phase involved tests with moderate doses of marihuana. Based on the inconclusive marihuana results reported herein, it was decided to double the dosage levels for an otherwise similar Phase II experiment.

### SIMULATION EXPERIMENT

#### Approach

The simulator used in these tests had full interactive capability allowing the driver to control steering and speed on a video-projected two-lane roadway. Subject behavior and performance were measured during a 10 mile drive which required about 15 minutes to complete. A variety of events was encountered during the driving scenario, including wind gusts, winding roads, obstacles, and isolated curves. Simulated accidents and speeding tickets were recorded as measures of traffic safety during the overall drive. During each event, measures of driver behavior and performance

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in steering and speed control were obtained in order to determine those driver factors which are impaired by alcohol and/or marihuana and to determine their contribution to reduced traffic safety.

A full placebo experimental design was employed which included all six combinations of two alcohol levels, 0 and 0.10 percent BAC (Blood Alcohol Concentration), and three marihuana levels, 0, 50, and 100  $\mu\text{g } \Delta^9\text{THC/kg}$  body weight. Alcohol effects on traffic safety have been well established, so only one non-zero BAC level was included which was set at a typical legal limit. Three marihuana dosage levels were included to allow measurement of a potential dose response relationship. Subjects were selected on the basis of good health, and being able to reach a BAC of 0.10 without getting sick.

## Results

Based on a large number of measures of driver behavior and performance, alcohol was found to have a consistent and significant impairment effect, while marihuana had only an occasional effect. Also, there was little evidence of interaction between alcohol and marihuana. Simulated accidents and speeding tickets reliably increased under alcohol, but no marihuana or combined alcohol and marihuana influence was noted. The alcohol impairment effects on steering and speed control behavior and performance were consistent with the increased accident and ticket rate.

The primary alcohol impairment mechanism seems to be increased variability in steering and speed control behavior. Variability between subjects was found to be similar for alcohol and marihuana considered alone. Combined alcohol and marihuana treatments lead to significantly increased variability between subjects, however, which may partially account for the lack of reliable interaction effects between these two drugs.

## Conclusions

- Alcohol at a BAC of 0.10 percent impairs driver control behavior significantly and consistently as evidenced in a wide range of measurements. These effects are correlated with degraded traffic safety as measured in terms of simulated accidents and speeding violations. Driver steering and speed control deteriorated with increasing BAC. Response speed and accuracy also deteriorated on a sign detection and recognition task.
- Marijuana doses of 50 and 100  $\mu\text{g } \Delta^9\text{THC/kg}$  body weight did not lead to consistent impairment of driver control detection and recognition processes.
- The effects of alcohol and marijuana in combination are not significantly different than the effects of alcohol or marijuana considered alone.
- The effects of combined alcohol and marijuana are not as consistent between subjects as are the effects of alcohol or marijuana considered separately.

## Recommendations

- The combined alcohol and marijuana conditions employed did not lead to any adverse or unexpected reactions from subjects, and higher marijuana dosages should be considered in a Phase II simulator experiment.
- The major driver/vehicle control performance effects observed in this experiment were reduced driver response speed and accuracy, as discussed above. Countermeasures should address these impairments. Road and vehicle designs should minimize requirements for driver response speed and accuracy. The trend toward smaller, more agile cars should help in this regard. Also, through driver education and public information, motorists should be made aware of the inevitable reduction in their vehicle control capabilities with alcohol impairment in order to discourage drinking and driving.



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## SECTION I

### INTRODUCTION

This research was performed as part of the overall NHTSA alcohol and drug research program with the twofold objective of (1) determining how the impairment in driving performance due to alcohol and marihuana leads to accidents, and (2) developing accident countermeasures based on the impairment mechanisms. Alcohol is already identified as a leading cause of driving accidents (Ref. 1), and with the increasing social acceptance of marihuana (Ref. 2) and lessening of criminal penalties against its use there is legitimate concern for its current and potential effect on traffic safety.

The effects of alcohol on both basic human behavior and driving capability have been studied quite extensively, and the dose response relationship between blood alcohol concentration and accident rate has been established (Ref. 3). Some of the more basic effects of marihuana on human behavior have been and/or are currently under study. We are a long way from understanding potential mechanisms for marihuana involvement in accidents, however, and even further removed from establishing a dose response relationship. Alcohol and marihuana are often used in combination (Ref. 4) and little is known about the combined effects, including possible antagonistic, synergistic, or cumulative combinations of effects.

This volume presents a study of the separate and combined effects of alcohol and marihuana on driver control behavior and safety using an interactive driving simulator. The study involves the measurement and analysis of driver/vehicle response characteristics in terms of manual control theory. The purpose is to identify alcohol and marihuana effects on steering control behavior and relate these effects to critical reasons for accident causation, and in particular to determine whether marihuana represents a potential highway safety problem.

In Section II of this volume we review known effects of alcohol and marihuana on driver behavior and safety and summarize those factors used to guide the approach taken in the simulator experiment described further on. In Section III the methods employed in conducting the simulation experiment are described. In Section IV the experimental results are presented and discussed. Finally in Section V we draw conclusions and recommendations based on the experimental results and discuss the implications for planning a Phase II experiment.

## SECTION II

### BACKGROUND

In this section we will first consider the relationship between driver behavior, system performance and traffic safety. Next we briefly review the literature on the behavioral and traffic safety effects of alcohol and marihuana both singly and in combination. This information is then summarized with emphasis on implications for the design and analysis of the experiment under consideration here.

#### A. APPROACH

To motivate this discussion, let us first consider how impairments to driver capabilities eventually affect risk exposure or accident potential. The block diagram of Fig. 1 illustrates some of the important considerations and relates driver impairment to risk exposure in a three-stage process:

1. Impairments degrade various driver capabilities which lead to deteriorated driver response. Impairments may affect one or more facets of driver behavior, and one of the goals in impairment research is to identify the mechanism(s) by which an agent influences human behavior.
2. Driver response is translated by the vehicle dynamics into vehicle path motions which determine driver/vehicle performance. This is an important consideration because of the time integrations involved in transforming driver response variables into vehicle motions. Changes in driver response often are not reflected in vehicle motions and vice versa, and both sets of measures should ultimately be considered.
3. The interaction of driver/vehicle performance with the highway environment then determines the accident risk exposure. For example, degraded lanekeeping performance or heading in heavy traffic could significantly increase accident probability, while with minimal traffic there might be little increase in risk.

Let us now consider some of the potential driver impairment mechanisms shown in Fig. 1.

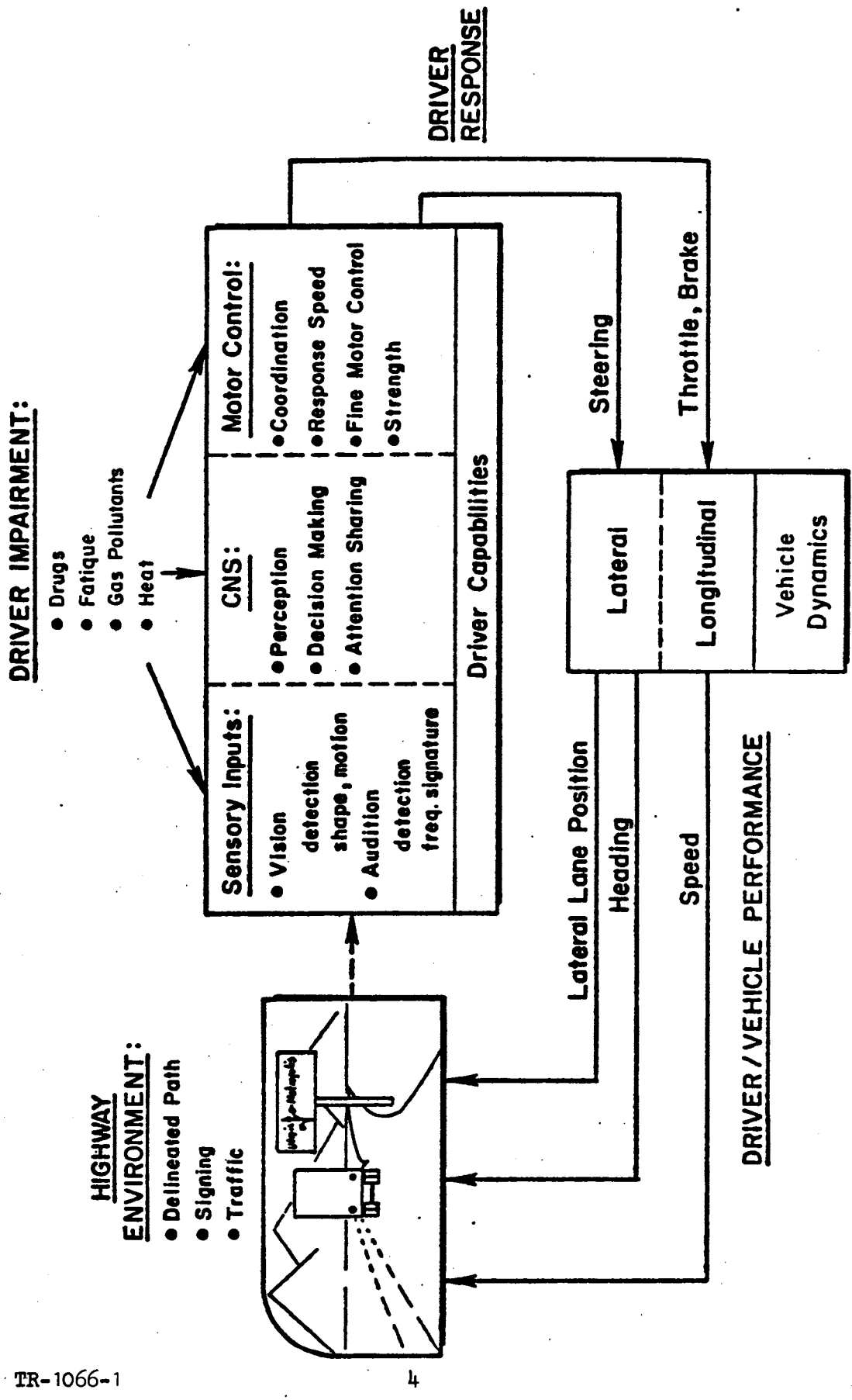


Figure 1. Driver/Vehicle System and Potential Impairment Modes

## 1. Sensory Input

This impairment mode primarily concerns psychophysical thresholds such as visually perceived luminance and contrast, motion, and various auditory stimuli. The driver might miss important cues, say, relating to interactive traffic, which could directly lead to an accident due to the absence of driver response. Sensory impairment may also lead to delayed driver response, which when reflected through the vehicle dynamics does not allow adequate margins for emergency maneuvers (braking and steering). These effects are most important for situations where sensory cues are down near threshold values such as night driving. Situations where cues are appreciably elevated beyond threshold values would not be influenced by simple sensory impairment.

## 2. CNS (Central Nervous System)

Impairments at this level would affect perception (interpretation of sensory information), decision making (deciding between alternative courses of action), and attention sharing or division of attention (e.g., steering and looking at highway signs). Misperception of information and/or incorrect decisions could clearly influence traffic safety. Research has shown that when focusing on one task the human operator can compensate for impairments, but that this compensatory mechanism becomes saturated when the operator has several things to attend to or the workload demands of a single task are high (Ref. 6).

## 3. Motor Control

This behavioral category includes coordination of limb motion (e.g., steering and braking), response speed, strength and fine-motor control. Truck and car controls do not typically require fine-motor control, so this factor is not critical to this application. Response speed, and strength and coordination are very important for emergency maneuvers, however. Even with good sensory perception and CNS processing, the commands to the motor system might not be carried out appropriately, thus resulting in degraded system performance.

In summary the above emphasis on safety-related performance effects is important because it will allow us to properly interpret driver sensitivity to various drug treatments. To understand driving performance we must consider the hierarchy of effects in driver impairment. First, driver impairment is manifested in behavioral factors such as attention, perception, cognitive processes (including decision making) and motor control. Second, behavioral impairments lead to system (driver/vehicle) performance effects such as increased braking and steering response times, increased lane wander, inappropriate maneuvers, etc. Finally, degraded system performance elevates risk exposure or accident potential.

Based on the above background we will now address the literature to assess the accident potential of the drug impairments under consideration here, in order to determine the experimental design implications for this current study.

## **B. ALCOHOL IMPAIRMENTS**

### **1. General Behavioral Effects**

In a fairly comprehensive review of the alcohol literature Levine, et al, (Ref. 5) categorized effects according to abilities or behavioral factors required for task performance. They found that sensory-perceptual tasks appeared to be the most impaired, while psychomotor tasks were affected the least with cognitive tasks falling somewhere in between.

Moskowitz (Ref. 6) reviewed several studies while exploring the hypothesis that alcohol affects the central processing involved in timesharing between tracking and perception. These studies found increased psychological refractory period delay, impaired short-term memory, increased reaction time under uncertainty, and increased eye fixation times while driving. These results indicate impairments which could affect a driver's judgment of the situation and hence his decision making. Moskowitz also pointed out that divided attention tasks (cognitive timesharing) are impaired by very low levels of alcohol (0.017 to 0.08 percent), with most subjects impaired at 0.05 percent.

The above divided-attention hypothesis is supported in a review of tracking performance (Ref. 7) which found that alcohol generally decreased performance, but that the decrement was more prominent with a parallel task. This view is further substantiated by more recent driving simulator work (Ref. 8), where alcohol effects on lane deviations were enhanced by the addition of a parallel sign recognition task.

Billings, et al., (Ref. 9) have reported increased serious procedural errors for experienced and inexperienced pilots flying instrument takeoffs and landings for BAC's as low as 0.04. The authors interpret the results with the view that complex visual tracking (landing) is a primary task, while procedural decisions are a secondary task and, as such, suffer under alcohol. Car driving, although less difficult, requires similar parallel tasks — steering and speed control combined with procedural decisions in response to environmental stimuli.

## 2. Driving

Heimstra and Struckman (Ref. 10) in comparing the results of 14 driving simulator studies concluded that the effects of alcohol on various motor control measures as tracking error, macro and micro steering reversals, accelerator reversals, average speed, and brake reaction time are at best inconsistent. However, several of the studies cited therein and more recent studies (Ref. 11, 12) did find increased reaction time under alcohol in response to stimuli presented in parallel with another task, such as lateral driving control.

Contrary to the inconsistent results found in driving simulators, studies of alcohol influences upon drivers on closed courses have consistently found impaired performance. Huntley's review of this field (Ref. 13) concluded that alcohol impairment shows up in various performance measures, and suggests that relatively unstructured task situations may be more susceptible to alcohol impairment than highly structured situations such as gymkhana courses.

Epidemiological studies also give insight into the effect of alcohol on traffic safety. Solid evidence is available for establishing the dose

response relationship between accident potential and blood alcohol concentration (Ref. 3). Single-vehicle accidents involving "loss of control" are quite prevalent (Ref. 14, 15) and typically involve excessive speed. High speed is likely to be a factor in alcohol-involved fatal crashes (Ref. 16), and inappropriately high approaching speed is typical of intoxicated drivers and the main cause of their involvement in curve accidents (Ref. 17). This result is also consistent with Perchonok's finding (Ref. 18) that accidents on curves involve the tendency to go straight more often than turning too sharply, which would be consistent with excessive speed. Degraded speed control seems to be an accident factor, so tasks involving speed are important.

Based on the above review it appears that complex or divided attention situations will be the most susceptible to alcohol intoxication and that sensory-perceptual factors are likely to be the primary locus of the effect. Loss of control on curves appears to be a driving situation particularly vulnerable to alcohol intoxication. Finally, Huntley's observation about unstructured situations (Ref. 13) may also be important in that task performance may be degraded more when the task is randomly imbedded in an overall scenario, with the scenario providing an effective distraction or division of attention from individual tasks.

### C. PERFORMANCE IMPAIRMENTS OF MARIHUANA

#### 1. General Behavioral Effects

There is a large, frequently polemic, and occasionally questionable, literature on marihuana use, much of which is well summarized in Ref. 18a and more recently in Ref. 18b. Within this literature a confounding of possible sources of effects often occurs. It is, for example, difficult to determine causal factors in such generalized findings as the "amotivational syndrome" which has been correlated with chronic marihuana use. Does the syndrome arise from the drug usage or is there a self-selecting process whereby persons possessed of this syndrome seek out the drug? A counter argument to many of the negative marihuana findings is provided in a recent extensive NIMH sponsored study (Ref. 18c) on the use of

marihuana in Jamaica. Where the use of the drug is socially approved and indigenous to the society, none of the social, motivational and psychological debilities found by researchers in American society were detected. In fact, marihuana appeared to increase the motivation to work!

There is cause for concern, however, regarding marihuana impaired performance. The primary locus of marihuana effects would appear to be in the sensory and perceptual processes. Moskowitz, et al., (Ref. 19) have found lengthened response times to a visual stimulus with THC doses of 100 and 200  $\mu\text{g}/\text{kg}$  body weight which was presented subsequent to an auditory stimulus, although this effect does not seem to be related to the psychological refractory period. Sharma (Ref. 20) has found a degradation in vigilance performance with 200  $\mu\text{g}/\text{kg}$  which is independent of task attention demand.

Using a simple tracking type psychomotor task (the "critical task" which has previously shown excellent alcohol sensitivity, Ref. 21), Sharma has found impaired performance over 4 hours after a smoked 200  $\mu\text{g}$  THC/kg dose of marihuana (Ref. 22). This result is somewhat unusual in that the psychological high and pulse rate peak rapidly after smoking ( $\sim 1/2$  hour), then decline fairly rapidly thereafter (Ref. 23), and marihuana effects have previously been considered to be fairly transitory.

In a more complicated task, Janowsky, et al., (Ref. 24) administered smoked 90  $\mu\text{g}/\text{kg}$  doses of  $\Delta^9$  THC to pilots participating in a flight simulator study. When compared to placebo treatments the marihuana grossly degraded flying performance, with increases in various procedural, control and navigation errors. These effects had generally returned to placebo levels at the end of four hours however.

Moskowitz, in summarizing his own work and that of others circa 1973, has advanced a tentative hypothesis on the general effect of marihuana (Ref. 25). That is that  $\Delta^9$  THC produces monotonically dose-related drop-outs of attention. A significant portion of traffic accidents are already related to factors such as "improper look out", "inattention" (Ref. 26) and "lack of care" (Ref. 27), and it would indeed be a serious problem if marihuana were to aggravate this state of affairs.

## 2. Driving

There is no compelling epidemiological evidence for correlation between driving safety and marihuana (Refs. 28, 29). This does not indicate a lack in correlation, however, because adequate methods for the detection and quantification of marihuana use are only now being perfected and coming into widespread use (Ref. 30). Most implications for marihuana effects on driving come from simulator tests. Moskowitz, et al., (Ref. 31) found no evidence of marihuana influence on the car control aspects of driving in a film simulator, while a dose-related increase in errors and reaction time was noted for a subsidiary visual response task (0, 50, 100, and 200  $\mu\text{g}/\text{kg}$  doses). Film simulators do not evoke realistic driver steering control, however. This could account for the lack of control sensitivity since psychomotor tracking testers have shown marihuana effects.

In another simulator study which emphasized risk taking behavior (Ref. 32), driver risk acceptance was found to decrease under marihuana intoxication (11.25 mg and 22.5 mg doses). It was not clear whether this was due to a compensatory mechanism or the fabled amotivational syndrome associated with marihuana use.

In Annex A of Chapter 2 of Ref. 18a, evidence is presented for a slight (about 1.5 mph or 7 percent) but consistent decrease in actual driving speed with increased  $\Delta^9$  THC. This study, which has not been reported in complete detail, involved 14 drivers to whom two levels of marihuana were administered by cigarette (21 and 88  $\mu\text{g}/\text{kg}$   $\Delta^9$  THC per kg of body weight producing average doses of 1.4 and 5.9 mg  $\Delta^9$  THC). In general the lower doses of marihuana showed no differences in car handling, accuracy of driving or speed control when compared with a placebo. The results showed some slight effects of the higher dose of  $\Delta^9$  THC. The implications for traffic safety were inconclusive.

## D. ALCOHOL AND MARIHUANA STUDIES

### 1. General Behavior

A study of evoked response in squirrel monkeys provides interesting data on the possible antagonistic effects of alcohol and marihuana. Boyd, et al., (Ref. 33) found that  $\Delta^9$  THC augmented both early and late evoked response while ethanol depressed response. With human subjects MacAvoy and Marks (Ref. 34) studied the combined effects of alcohol and marihuana on performance of a divided attention task (2.6 and 5.2 mg  $\Delta^9$  THC and 0.05 and 0.10 BAC). One subject group identified as marihuana users exhibited antagonistic effects between alcohol and marihuana while a non-marihuana user group evidenced synergistic effects.

Visual function seems differentially impaired by alcohol and marihuana. Static acuity is not altered by either alcohol (0.5 ml and 1.0 ml/kg body weight) or marihuana (8 and 15 mg  $\Delta^9$  THC) (Ref. 35). The same drug doses do degrade dynamic visual acuity (Ref. 36), with alcohol causing a greater degradation. In another experiment of visual scanning patterns of a film simulated driving situation, Moskowitz, et al., (Ref. 36a) found increased dwell duration, decreased dwell frequency, and increased pursuit duration and frequency under alcohol (0, 0.075 and 0.15 percent BAC) and no effects with marihuana (0, 50, 200  $\mu\text{g}/\text{kg}$   $\Delta^9$  THC).

Chesher (Ref. 37) measured the separate and combined effects of  $\Delta^9$  THC (143  $\mu\text{g}/\text{kg}$  oral dose) and ethanol (0.54 g/kg) on a variety of perceptual, cognitive and motor functions. There was little effect when tested alone, but in combination performance was degraded. In another study of the effects of alcohol alone (0.06 percent BAC) and alcohol plus marihuana (0.02 g THC), Burford (Ref. 37a) also found a significant combination effect over the alcohol alone case which would normally be considered a modest impairment.

Manno (Ref. 38), in 1971, conducted a study using 12 males, 4 of whom had prior experience with marihuana, only one of whom had as many as four experiences. They were naive to marihuana for all intents and purposes. They were administered alcohol to achieve 0 and 0.05 BAC and marihuana by

cigarette at doses of 0, 2.5 and 5 mg of  $\Delta^9$  THC. A pursuitmeter, delayed audio feedback and various physiological tests were administered. Marihuana plus alcohol was worse than marihuana alone only for the simplest pursuitmeter task of the four tasks used. No dose dependency for the two levels of marihuana was demonstrated. The higher dose of marihuana produced a decrement on all the tasks and tests measured.

Reid, et al., (Ref. 39), in 1973, conducted a tracking study of 12 males who were casual users of marihuana. A schedule including placebos was conducted for the following drug levels: alcohol 0, 0.03, 0.07 percent and 0, 21, or 88  $\mu\text{g}/\text{kg}$  of  $\Delta^9$  THC. Dynamic measurements of performance including describing functions were made. Alcohol and marihuana were found to separately degrade performance; however, there was some evidence of counteractive effects under combined doses.

In a study concerned primarily with cognitive tests, Rafaelsen, et al., (Ref. 40) included a placebo, 70 g ethanol (measured BACs averaged 0.95 g/l), and 8, 12 and 16 mg  $\Delta^1$  THC conditions. On addition and subtraction tests cannabis routinely showed decrements while alcohol did not. The most interesting observation was large day-to-day variations in cannabis effects which in their words "were probably due to a combination of normal physiological variations and the characteristic waxing and waning of cannabis intoxication."

## 2. Driving

In driving tests associated with the above referenced study (Ref. 41), both marihuana and alcohol were found to have similar effects on increased time to brake and start a car simulator (Redifon Auto Tutor). Counteracting effects were found on the number of gear changes per test, however, which increased under alcohol while decreasing under marihuana. Marihuana effects were also found to be dose related. These two concurrent studies (Refs. 41, 42) considered in combination would seem to indicate a predominate effect of marihuana on cognitive skills, while both alcohol and marihuana have some similar effects on the combined skills required in psychomotor tasks.

Crancer (Ref. 42), in 1969, conducted one of the early marihuana and driving studies. The subjects were 29 males and 7 females of mean age 22.9 years. All had smoked marihuana at least two times per month for at least six months. The subjects were administered alcohol so as to achieve a BAC of 0.10. Marihuana was administered via two cigarettes whose total weight was 1.7 g (1.3 percent  $\Delta^9$  THC). The drugs were not taken in combination. No placebos were used. The task was simulated driving. Measurements were made of brake errors, accelerator use, signals and speedometer control errors. The results indicated that alcohol increased all errors whereas marihuana only affected so-called speedometer errors which were an indicator of the time spent monitoring the speedometer, not of speeding.

Ellingstad, et al., Ref. 42a, have compared the effects of alcohol and marihuana on two tasks simulating a car passing situation. A control condition (no drug treatment) was compared with 0.05 and 0.10 BAC alcohol levels and 11.25 and 22.5 mg THC doses in cigarettes. Marihuana was found to affect time judgment in terms of longer and more variable time estimates on an abstract decision task apparatus, and alcohol was found to lead to more passing attempts on a film simulator apparatus, although more attempts were subsequently overridden under alcohol as well. No dose response relationship was found for either alcohol or marihuana. The conclusion here is that subjects are more willing to make snap decisions under alcohol intoxication.

A study involving actual in vehicle measurements on a driving course under alcohol and marihuana typifies some of the confusion in interacting drug effects. Smiley (Ref. 42b) administered (0.06 BAC) and combined alcohol and marihuana (three 0.5 g cigarettes at 1.1 percent THC) to 8 subjects in a full placebo design along with some other drugs not of interest here. Speed control, steering actions, pylons knocked down on a slalom course, stopping accuracy and reaction time to peripheral dashboard lights were obtained as measurements. Mean speed was found to decrease in going from placebo to alcohol to combined alcohol and marihuana. Cone count and steering activity increased and stopping accuracy decreased over the same condition order. The combined alcohol/marihuana condition led to high between-subject variability in

stopping accuracy, however. Also, somewhat equivocal results on peripheral light response time were obtained as alcohol alone led to the fastest RT with the placebo and alcohol plus marihuana inducing increased reaction time in that order.

Finally, in considering epidemiological evidence of combined alcohol and marihuana involvement in accidents, results are still not conclusive although a positive trend may be developing (Ref. 29). Considering the significant research effects of combined alcohol and marihuana cited above, the lack of conclusive epidemiological evidence may be due to inadequate field analysis techniques for measuring marihuana involvement.

#### **E. LITERATURE SUMMARY AND IMPLICATIONS FOR THIS STUDY**

The previous literature review leads to the following key points which are pertinent for the design of this current study.

- Alcohol effects on driver behavior and traffic safety are fairly well established and a clear dose response relationship has been established for accident involvement. A primary alcohol impairment mechanism appears to be interference with divided attention capability.
- Marihuana effects on driver behavior and traffic safety are not clear, and increased variability between drivers in their response to marihuana may be somewhat responsible for the confusion. The locus of primary marihuana effects seems to be in sensori-perceptual capabilities.
- There is some evidence for synergistic effects of alcohol and marihuana, but there are also occasional measurements of antagonistic effects. There is also no clear epidemiological evidence of combined effects on traffic safety.

## SECTION III

### METHODS

#### A. SIMULATION

##### 1. Overview

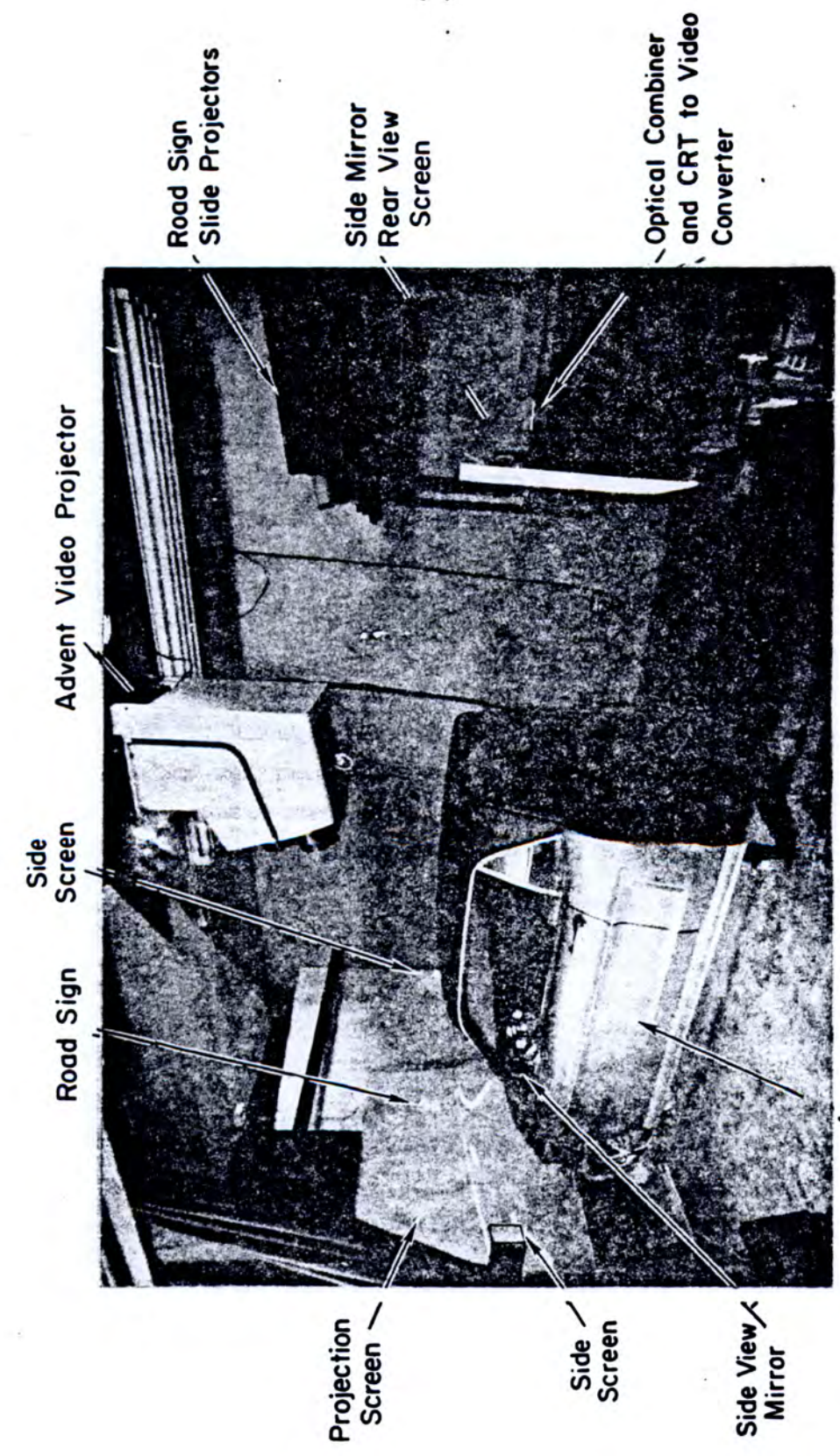
The simulator and driving tasks were designed to allow measurement of driver behavior, driver/vehicle performance, and traffic safety as discussed in Section II.A. The objective was to be able to measure drug effects on driver behavior, then establish the relationship between driver behavior, system performance, and traffic safety.

The basic goals for the simulation setup were to establish a reasonably face valid driving situation with workload and divided attention demands consistent with average every day driving. The emphasis in this research is on driver control capabilities, as opposed to decision making or other cognitive behavior. Thus the simulation, tasks, and measures primarily emphasize steering and speed control tasks, along with associated divided attention measures.

##### 2. General Setup

The physical arrangement for simulating car steering and speed control is shown in Fig. 2. An actual cut down car cab with operational controls was used in conjunction with a video projected roadway scene. The roadway scene consists of a two lane road with defined road shoulders as shown in Fig. 2. The road can be curved or straight, and various obstacles can be placed in the roadway scene requiring driver control in order to avoid accidents.

Using the steering wheel, accelerator pedal, and brake controls the car can be controlled over the full lateral extent of the road and from a complete stop up to high speeds well in excess of the current 55 mph national speed limit. Fixed signs can be projected randomly on the roadway screen



Mustang Car Cab

Figure 2. Simulator Physical Arrangement

requiring the driver to divide his attention between the signs and his primary vehicle control task.

A functional block diagram of the simulator setup is shown in Fig. 3. Electrical signals from the various car controls are fed into an analog computer which generates vehicle motion variables using simplified vehicle equations of motion. The motion variables are then used to drive the cab instruments and the road scene generator. A paper tape programmer is used to control roadway events and sign presentation and a PDP 11/10 minicomputer is used for data collection and scoring. The details of this simulation have previously been described in Refs. 43 and 44.

### 3. Driving Scenario

A typical trial in the simulator involved a modest length drive (i.e., about 10 miles) during which various events were encountered. A paper tape programmer, which proceeded at a rate proportional to the car speed, controlled the event occurrence. A typical sequence of events is illustrated in Fig. 4 and the individual tasks are described in more detail below.

The scenario and computer control circuitry were designed to present the driver with realistic motivations and constraints. Subjects were motivated by the reward/penalty structure given in Table 1 to minimize driving time, yet avoid speeding tickets and accidents.

TABLE 1. REWARD/PENALTY STRUCTURE

- \$10 stake for completing trial
- \$2 reward for each minutes saved in driving scenario to encourage timely progress
- \$1 penalty for speeding tickets
- \$3 penalty for accidents

The scenario speed limit of 45 mph was periodically presented to the subject via a projected speed limit sign. A logic circuit monitored speeding violations. Speeding tickets were given whenever a computer

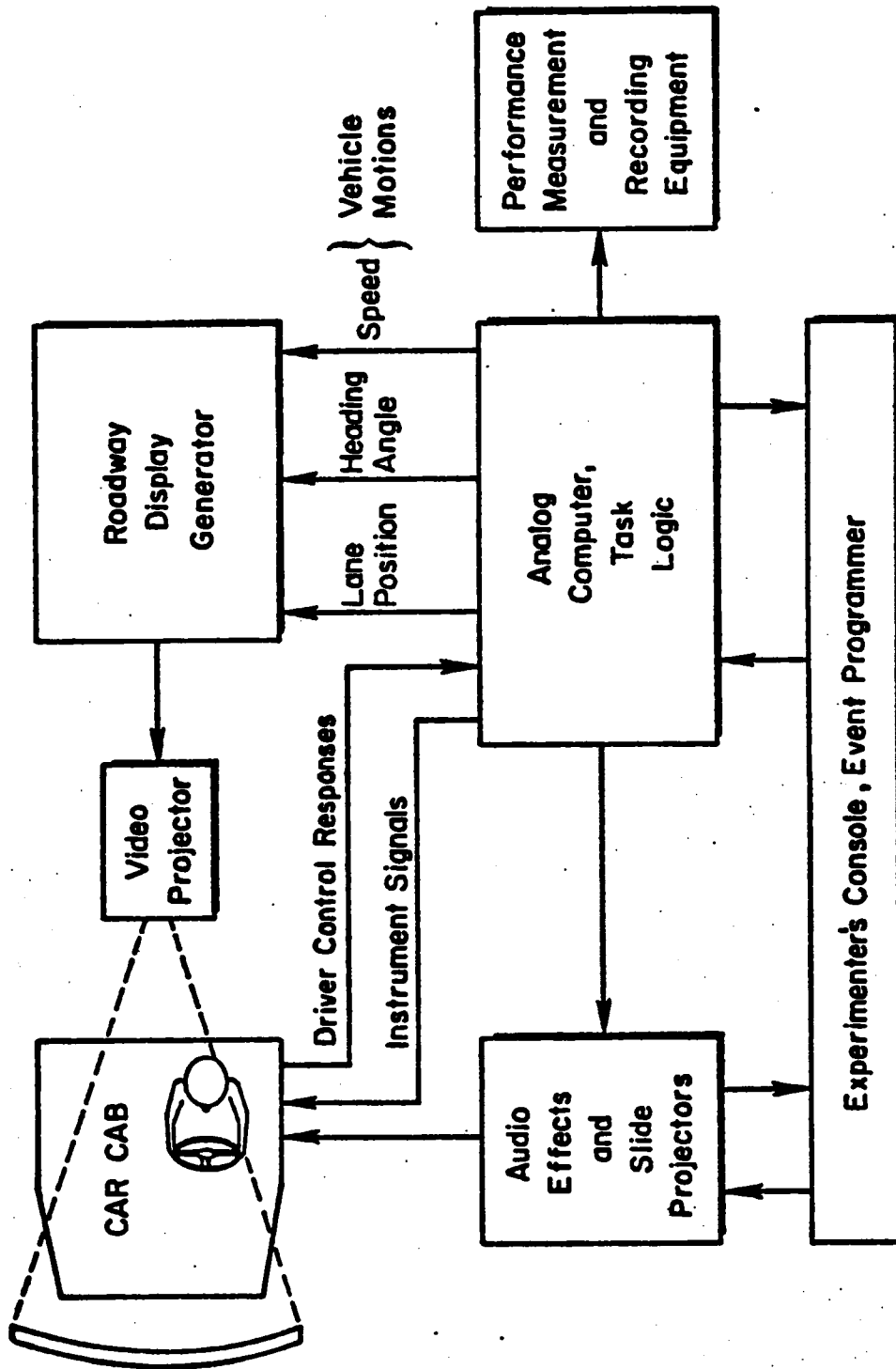


Figure 3. Block Diagram of Major Simulation Elements

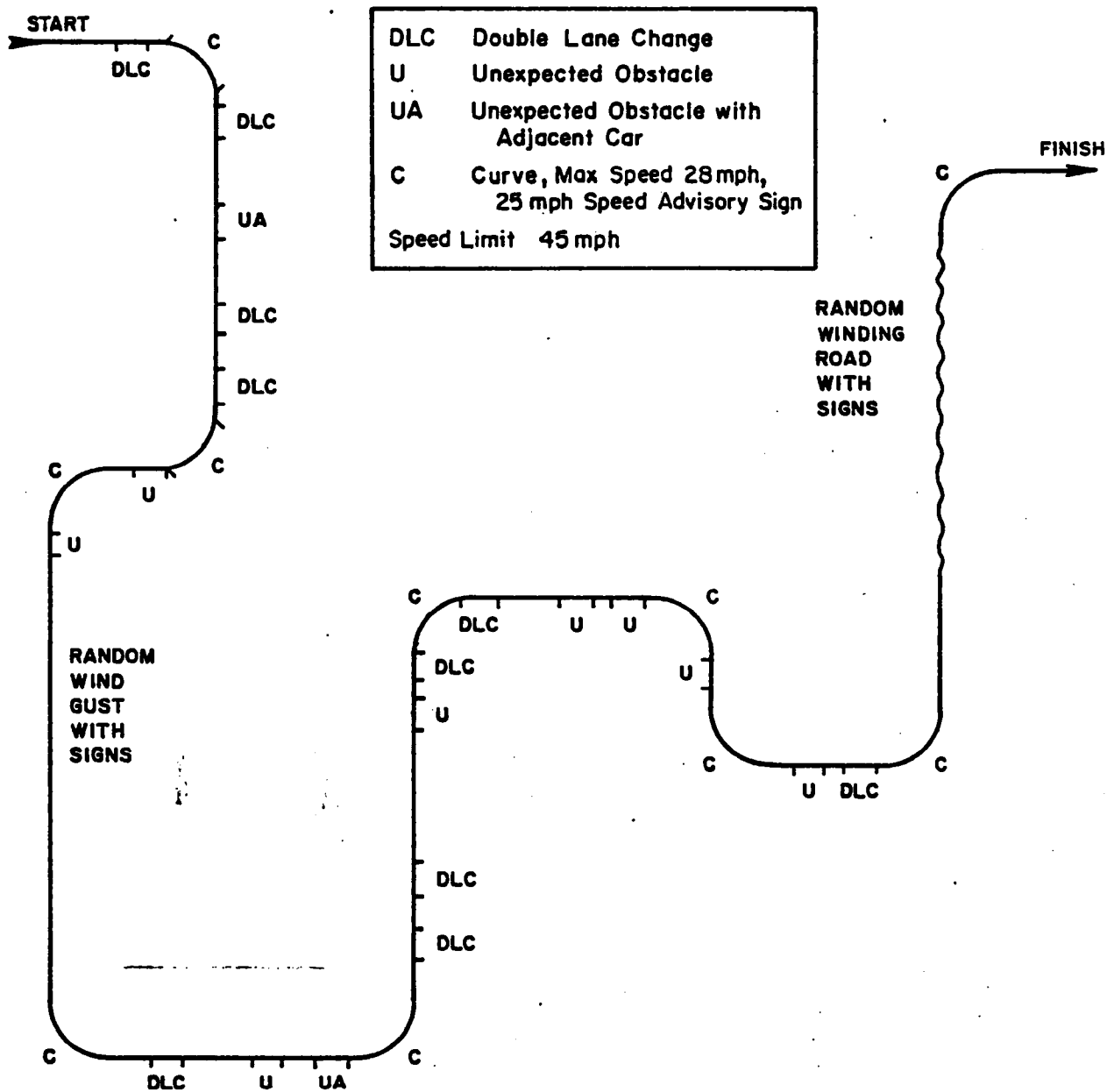


Figure 4. Typical Driving Scenario

"traffic cop" detected a violation. The traffic cop was placed randomly throughout 30% of the scenario via the paper tape programmer.

Accidents were defined as going beyond the road shoulder limits, or hitting the road obstacles defined below. The occurrence of an accident was announced with a buzzer sound and display jitter. The subjects were not required to stop, however.

The purpose of the driving scenario was twofold: first, to provide subjects with a complex driving task involving workload demands similar to real world driving; second, to provide traffic safety related performance measures such as ticket and accident rates.

A summary of the driving scenario tasks and performance measures is given in Table 2. A detailed description of the various tasks is given below.

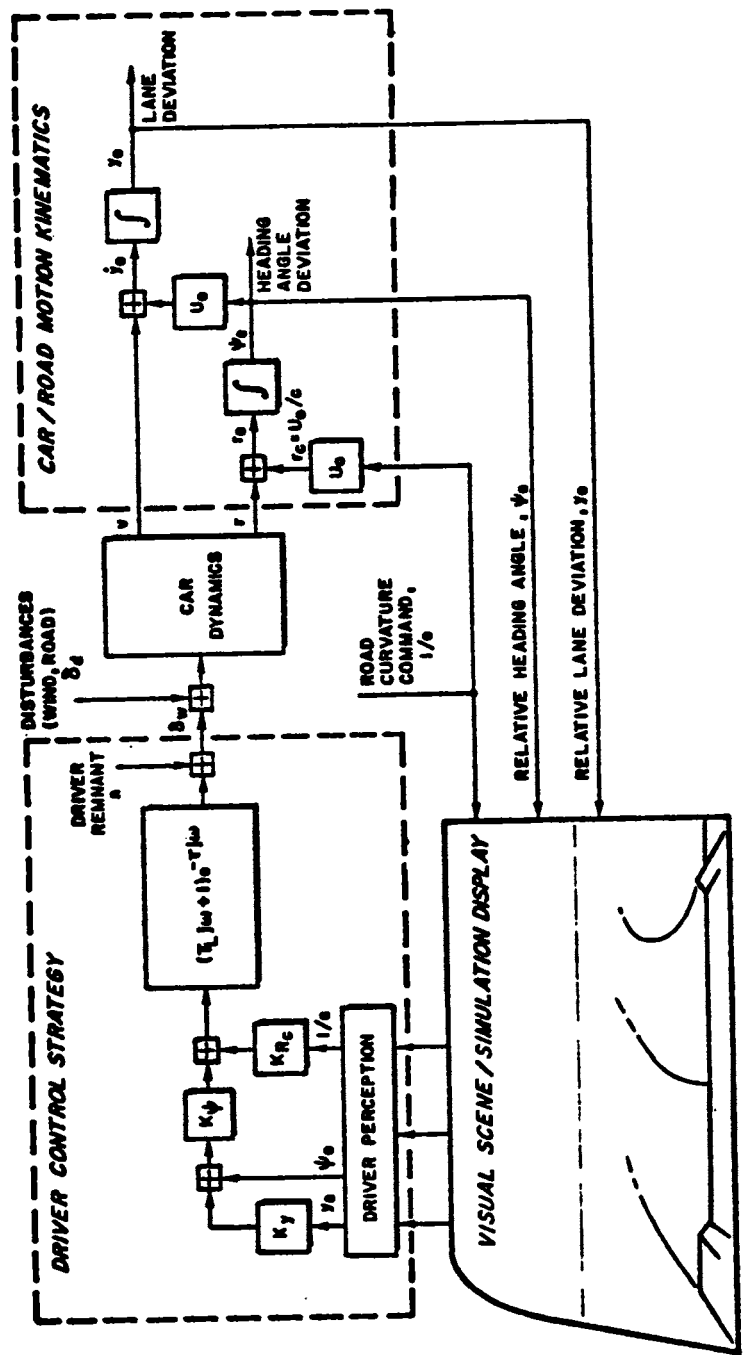
#### 4. Steering Control with Divided Attention

Steering control of car path is a psychomotor task involving both visual perception and motor control. Both driver steering behavior and lane keeping performance have previously been found to be sensitive to alcohol impairment, particularly when the driver is also distracted by a subsidiary sign recognition task (Ref. 45). Two tasks were employed, one requiring regulation against random wind gusts, the other involving following a random winding road. These tasks require two different facets of driver control behavior. The regulation task, commonly called a compensatory tracking task, requires the driver to compensate for a disturbance which is not perceived other than by its effect on the car's motion. On the other hand, steering along a winding road allows the driver to directly perceive and anticipate the required car path.

Figure 5 illustrates the driver/vehicle control structure associated with the above two steering control tasks. Using random wind disturbances or road commands we were able to measure steering performance measures such as lane deviation errors ( $y_e$ ) and heading deviation errors ( $\psi_e$ ). By cross correlation techniques we also measured the input/output response characteristics of the driver (i.e., driver describing functions in control system

TABLE 2  
SIMULATED DRIVING SCENARIO

TASK	MEASUREMENTS	NUMBER
Overall Scenario Performance	<ul style="list-style-type: none"> <li>● Number of speeding tickets (45 mph speed limit)</li> <li>● Number of crashes (hitting obstacles, exceeding road edges)</li> </ul>	<p>32 events</p> <p>32 signs</p>
Random Wind Gust and Winding Road Tracking	<ul style="list-style-type: none"> <li>● Driver dynamic response and remnant parameters</li> <li>● Lane deviation errors</li> </ul>	1 each, 100 second measurement period
Highway Sign Detection and Recognition (during above tracking tasks)	<ul style="list-style-type: none"> <li>● Response time</li> <li>● Response errors</li> </ul>	16 signs randomly presented at 4 locations
Isolated Curve Control	<ul style="list-style-type: none"> <li>● Ensemble speed response</li> <li>● Ensemble path deviations</li> </ul>	10 curves
Fixed Obstacle (double lane change) and Unexpected Obstacle	<ul style="list-style-type: none"> <li>● Time and distance to peaks and axis crossings</li> </ul>	10 each



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**Vehicle Motions and Roadway Commands:**

- $v$  = Vehicle lateral velocity normal to vehicle path
  - $r$  = Vehicle inertial heading rate
  - $rc$  = Equivalent roadway heading rate at vehicle speed  $U_0$
  - $re$  = Vehicle heading rate error with respect to the roadway
  - $\delta d$  = Equivalent disturbances to vehicle lateral motion
- Perceived Quantities:**
- $y_e$  = Lateral lane position error
  - $\psi_e$  = Vehicle heading error with respect to the roadway
  - $1/c$  = Road curvature (inverse radius of curvature)

**Driver Dynamic Behavior:**

- $K_y$  = Driver gain applied to  $y_e$
- $K_\psi$  = Driver gain applied to the composite heading error  $\psi_e + K_y y_e$
- $K_{rc}$  = Driver gain applied to road curvature perception
- $\tau_L$  = Driver lead or anticipation time constant applied to perceptually derived steering commands to counteract vehicle response lags
- $\tau$  = Driver visual/motor time delay or response time
- $\delta_{sw}$  = Resulting driver steering wheel deflection
- $n$  = Remnant (noise) or random time variations in driver steering action

Figure 5. A Driver/Vehicle Dynamic System Model for Analyzing Steering Control Behavior (Taken from Ref. 47a)

engineering terms) and various parameters associated with the driver's control process. These parameters include visual motor time delay ( $\tau_e$ ) and control gains applied to perceived lane deviations ( $K_y$ ), heading deviations ( $K_\psi$ ), and road curvature ( $K_{Rc}$ ). The control engineering approach for these measurements and their interpretation has previously been documented (Refs. 45-47a). Further detail is given in the appendix to this report.

The divided attention aspect of the random steering tasks was provided by a sign detection and recognition task. Signs were projected slightly above eye height at four locations  $\pm 20$  deg and  $\pm 40$  deg off-axis from the center of the roadway. Standard white regulatory signing formats were used (Ref. 48) and the signs read either "LEFT LANE MUST TURN LEFT" or "RIGHT LANE MUST TURN RIGHT." The driver was required to respond appropriately with the turn indicator, and response times and errors were measured on the performance computer.

## 5. Isolated Curves

This event requires the driver to control both his steering and speed in order to negotiate a 90 deg turn. A curved road display configuration is shown in Fig. 2. In this task the road curvature increased to a maximum value at curve midpoint, then decreased back again to a straight roadway. At minimum road curvature the car had to be kept below 28 mph (the speed advisory was 25 mph) or it would not maintain enough traction to negotiate the curve. Previous research (Ref. 49) has shown performance on this maneuver to be quite sensitive to alcohol, and it represents a situation which frequently leads to the single car out of control category of accidents as discussed in Section II.B.2.

The performance computer was used to sample the lane position and speed profiles incurred in this maneuver. Data from the several repeated encounters in a trial (Table 2) were also ensemble averaged at the end of the trial to give mean and variance measures for the speed and lane deviation profiles.

## 6. Obstacle Avoidance

Transient lane changes were induced by both anticipated and unexpected obstacles in the displayed roadway. The anticipated obstacles consisted of three stationary objects positioned on the roadway as shown in Fig. 6 in order to induce the driver to perform a double lane change maneuver. This maneuver tested the driver's ability to coordinate and time a relatively precognitive transient maneuver. The unexpected obstacle on the other hand was obscured until it moved unexpectedly onto the roadway. The performance computer measured the time and distance to peak amplitudes in both the steering response and lane deviation profiles. These events and measures test the driver's visual motor steering reaction time and subsequent maneuver coordination.

## C. EXPERIMENTAL DESIGN

The objectives of the experiment were to allow measurement of a marihuana dose response relationship, and test the interaction between alcohol and marihuana. The full placebo design employed is illustrated in Fig. 7. Only two alcohol levels were chosen because dose response relationships for alcohol are well established. The 0.10 BAC level is a common legal limit and is known to generally cause measurable experimental impairments. Three marihuana levels were selected to allow measurement of potential dose response effects. The 100  $\mu\text{g}/\text{kg}$  THC dose is a modest, common experimental dose.

Twelve subjects were subjected to each experimental treatment during a separate session. All subjects experienced all treatments over six different experimental sessions in order to allow written subject comparison of the treatment effects. The order of exposure to the treatments was balanced according to a 6x6 latin square design which also controlled for second order followings (Ref. 50).

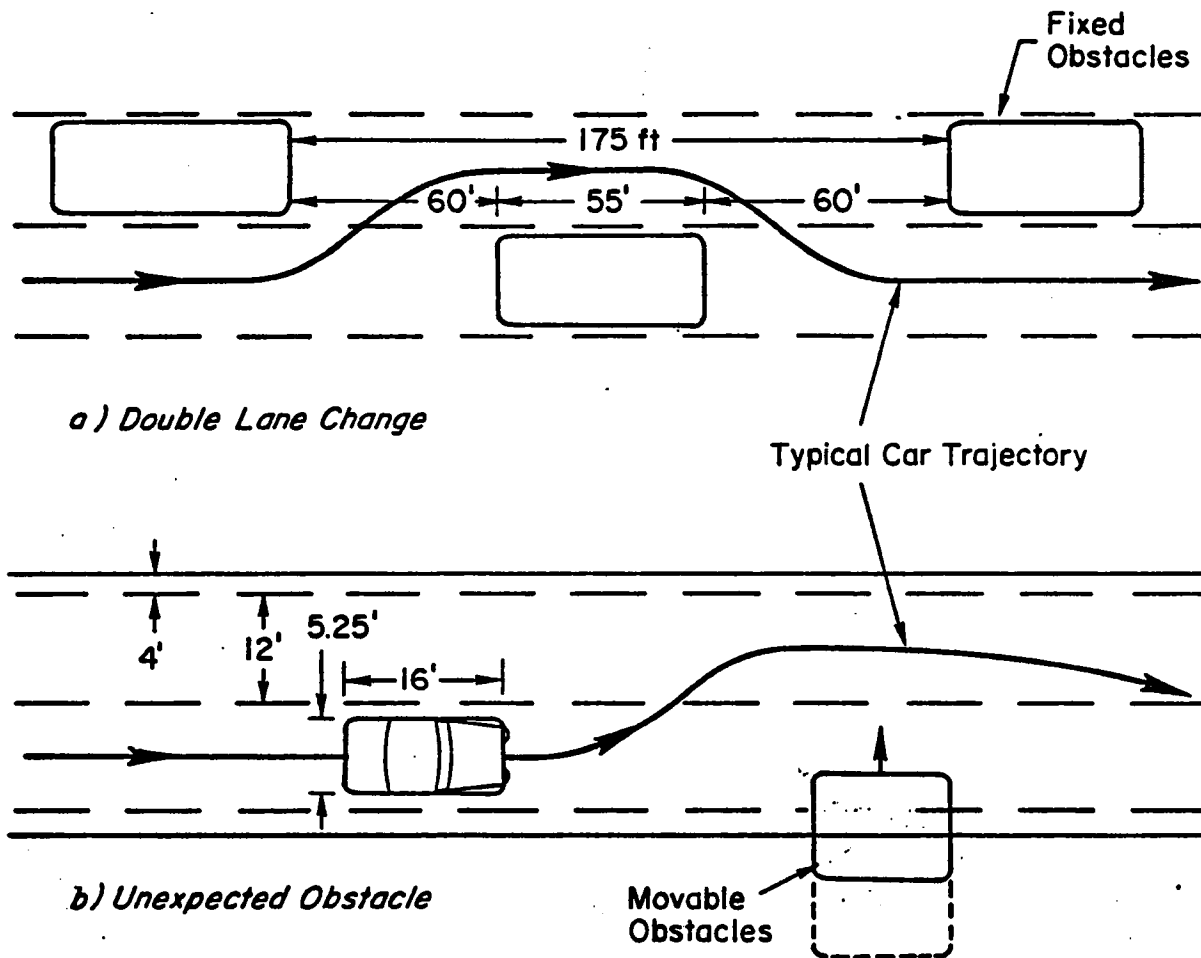


Figure 6. Ground Plane Representation of the Obstacle Avoidance Tasks

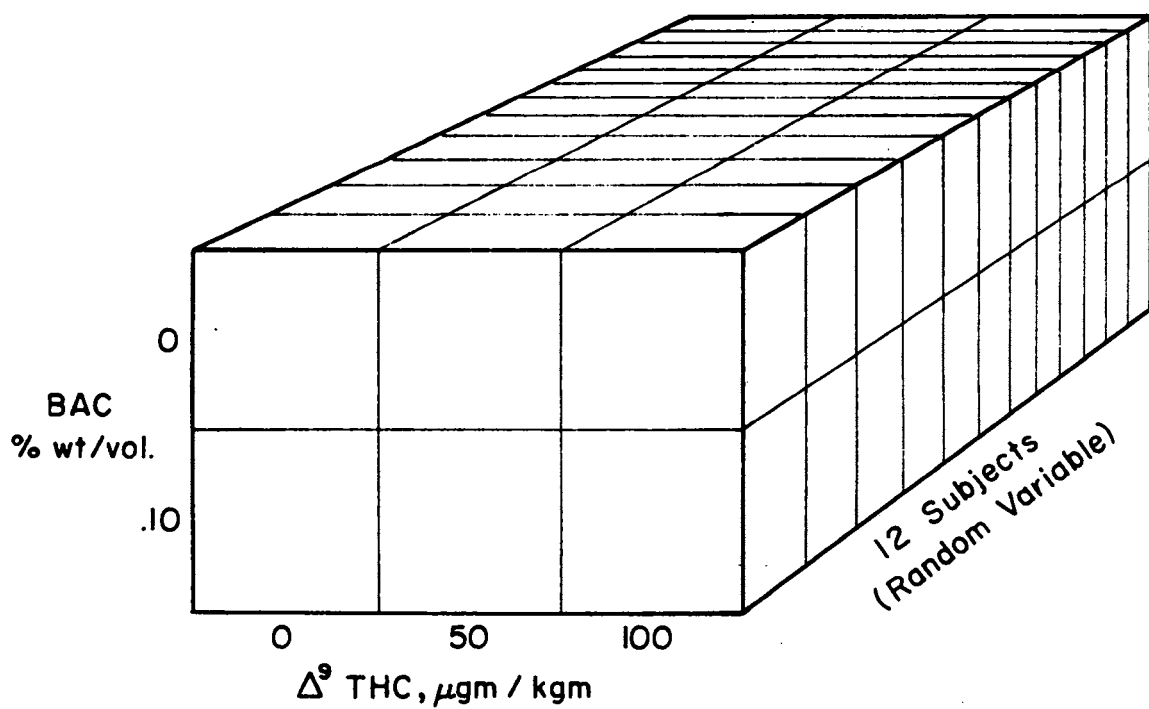


Figure 7. Three-way Experimental Design for Initial Data Analysis

## D. EXPERIMENTAL PROCEDURES

### 1. Subject Selection and Training

Rather stringent criteria were placed on subject selection in this experiment because of the illegal status of marihuana and the resultant cognizance of Federal and State agencies over subject welfare considerations. All subjects were required to pass a complete medical examination including the laboratory tests given in Table 3 and a physical examination by the project physician. The blood tests in Table 3 screen for tissue damage, which is somewhat incompatible with our other requirement, that subjects be relatively heavy drinkers. However, the population at risk in alcohol involved accidents are males with BAC's in the range of 0.10 and above (Ref. 1) and past experience has shown that subjects must be fairly habituated to alcohol in order to reach this BAC.

A summary of our subject screening experience is given in Table 4. The selection process was initiated by placing advertisements in local newspapers, shopping flyers, college newspapers, and on laundromat bulletin boards. From this extensive advertising campaign just over 500 phone calls were received. After an initial description of the project, and a "rough" screening procedure designed to eliminate women, light drinkers, non-marihuana users, and non-drivers, applications were taken for approximately 50% of the calls. Rejection at this stage was due to a combination of the above criteria.

The above applications were then carefully screened to select those meeting our general subject criteria: male; 21-65 years of age; in good health; moderate to heavy drinkers; marihuana users; and non-drug abusers. This screening procedure eliminated 56% of the applicants. The two major reasons for rejection at this stage were excessive use of other drugs and/or inability to meet heavy drinking criteria (i.e., marihuana users tend not to be heavy drinkers). The remaining 44% were invited to come in for an orientation session. At this session the project was described in detail. After the description the applicants took the Minnesota Multiphasic Personality Inventory (MMPI), and filled out a comprehensive health history. The MMPI was scored, and those with clinically abnormal personalities, or

TABLE 3

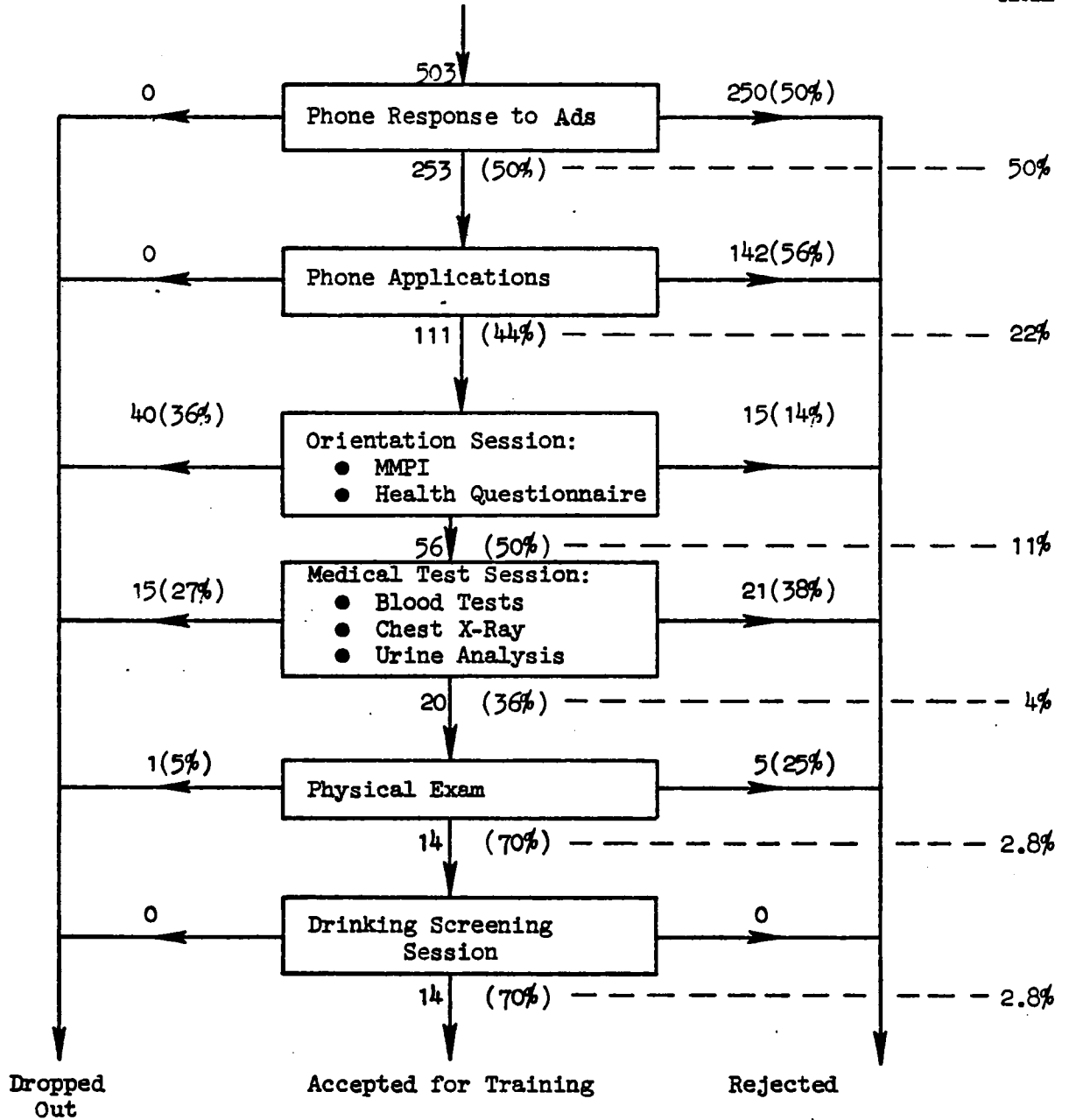
LABORATORY TESTING PROCEDURES

1. Hepatic group
  - a. SGOT
  - b. SGPT
  - c. GGTP
  - d. Alkaline Phosphotase
  - e. Billirubin Total
  - f. Total Protein
  - g. Albumen
  - h. AG Ratio
2. Fasting Sugar
3. 2 Hour Post-prandial Sugar
4. CBC - Sed. Rate
5. Complete Urinalysis
6. VDRL
7. ZSR
8. Complete Chest X-Ray

TABLE 4

SUBJECT SOLICITATION AND SCREENING SUMMARY

DROP OUTS (VOLUNTARY, NO SHOWS, ETC.)      SCREENING STAGES AND NUMBER ACCEPTED      REJECTIONS BASED ON SCREENING CRITERIA      ACCUMULATED ACCEPTANCE RATE



with personality types that have a high correlation with violence under alcohol were eliminated from further consideration. The health histories were also thoroughly screened, and applicants indicating present substance abuse, or general poor health were eliminated. Of those completing the orientation session 40% had acceptable profiles (although some were clinically abnormal) and were asked to return for laboratory tests.

The laboratory tests included a complete blood work up, a chest X-ray, and complete urine analysis (Table 3). Only 30% of those screened passed this phase of screening even though we allowed a 10% leeway outside the normal range. The majority of those dropped from consideration had either diabetes, hypoglycemia, or abnormally high trygliceride levels; all common problems with a heavy drinking population.

Out of 20 subjects passing the laboratory test screening, 14 were accepted as fit by the physician. All 14 subsequently passed a preliminary drinking test to make sure they could reach 0.10 BAC before investing any further time in training or formal data sessions.

The subjects surviving the screening process were then given two training sessions. The subjects had previously received an orientation and initial exposure to the driving simulator during the drinking screening session. The first training session was used to familiarize the subjects with the driving scenario and reward/penalty structure using points rather than actual money. The second session served as additional practice with the subjects making two drives under the reward/penalty structure.

## **2. Formal Data Session Procedures**

Subjects were nominally run four at a time for efficiency during the formal data trials. Subjects were picked up in the morning and given a BAC check before beginning the session (heavy drinkers have occasionally shown up with non-zero BACs in the morning even though they are instructed otherwise). Following a negative BAC reading the subjects were then taken through the drug administration profile shown in Fig. 8.

The sessions started with a sober baseline experimental trial. Two drinks, calibrated by body weight to result in a maximum BAC of 0.10, were

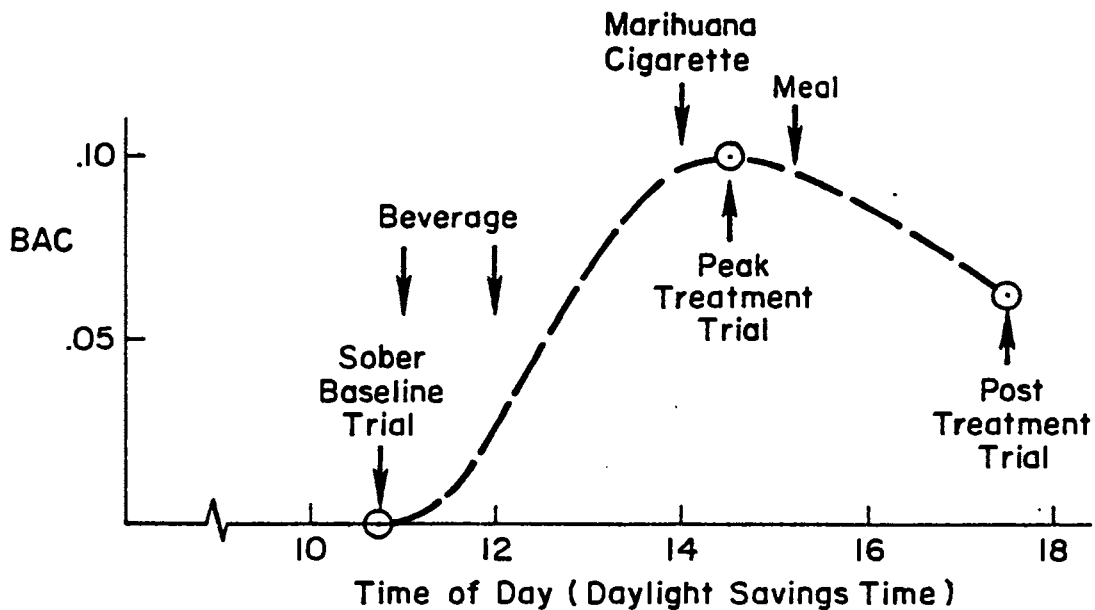


Figure 8. Drug Administration Protocol

then given to the subject roughly one half hour apart. The subject's BAC was then monitored, and when it neared the peak they were given a marihuana cigarette to smoke. By the time a subject was administered his second driving trial of the day he was near both peak BAC and peak marihuana high. Subjects were then given a meal and tested on one final trial in the late afternoon when their BAC had declined to the region of 0.06-0.07. Finally subjects were driven home when their BAC declined below 0.05.

Subject heart rate was measured before each experimental trial, which resulted in one reading immediately after the smoking procedure. At this point subjects were also asked to rate their level of alcoholic intoxication and the quality of the marihuana smoked using a scale marking technique.

Double blind procedures were maintained throughout the experiment. One experimenter was in charge of bartending and BAC measurement, and another responsible for smoking procedures and heart rate measurement. Marihuana cigarettes were prepared ahead of time and given to the appropriate experimenter on the day of the test in envelopes marked only with the subjects code number. Finally, a third experimenter administered the simulator driving trials.

**Alcohol Treatment** — The alcohol drinks consisted of each subject's favorite beverage and mixer. This was done to maintain high motivation and adequate social ambience. The alcohol beverage quantity was adjusted according to body weight in order to achieve the desired peak alcohol treatment of 0.10 BAC. Placebos were concocted by substituting water for the alcoholic beverage, and floating a quarter ounce of the requested alcoholic beverage on the top of the drink. Drink requests that would not allow credible placebos were tactfully avoided. Subjects were not aware that only two alcohol conditions were employed and were told that they would be served varying amounts of alcohol throughout the six experimental sessions. BACs were measured with a gas chromatograph breath analyzer.

**Marihuana Treatment** — Subjects smoked nominally 5 g cigarettes formulated to administer the desired 0, 50, and 100  $\mu\text{g}$  THC/kg body weight treatments. Detoxified and 2%  $\Delta^9$  THC marihuana was obtained from the University of Mississippi under the auspices of the National Institute on Drug Abuse. Cigarettes were rolled from either the 0%, 2% or a combination 1% material and adjusted by body weight for each individual subject. Cigarettes were administered under double blind conditions and smoked using a standard inhaling/exhaling procedure monitored by an experimenter. A glass tube was used to allow the entire cigarette to be consumed.

## **E. DATA ANALYSIS**

At the conclusion of the experiment, the data was then transferred from our laboratory minicomputer to a large time sharing computer system which allowed the data to be efficiently analyzed with standard statistical analysis programs. The data was arranged according to the experimental design and edited to remove errors, obvious outliers, and fill-in occasional missing cells. Over 50 dependent variables describing driver/vehicle performance and driver behavior were available for analysis. However, due to occasional unusual behavior, it was impossible to achieve perfect data for every trial. Procedures were set up to ensure that editing would have minimal biasing effect on the data, and that any possible biasing effects would be conservative (i.e., they would reduce rather than emphasize the effect of the treatments). In the end, conclusions are drawn from the totality of measures to avoid any biasing effect due to editing procedures.

Three classes of data were analyzed for each task (Table 2) as follows:

- Overall scenario performance including tickets, accidents, drive completion time, and overall reward/penalty payoff.
- Driver/vehicle performance for each task including lateral lane position, probability of lane exceedence, and speed regulation.
- Driver behavior for each task including dynamic control response measures (gains, transport delays, etc.), and transient control measures such as steering and sign response times and speed profiles.

These data were analyzed according to the basic experimental design shown in Fig. 9 using Analysis of Variance (ANOV) procedures. The objective of the analysis was to look for basic alcohol and marihuana effects, treatment

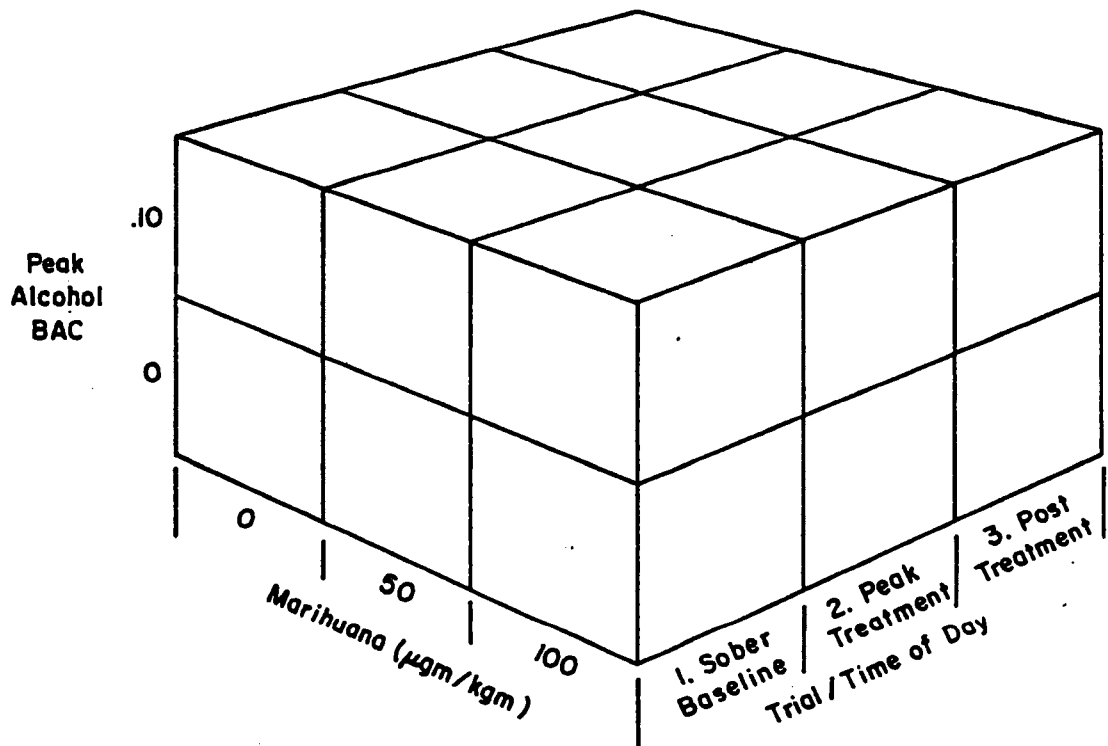


Figure 9. Data Analysis Experimental Design

combination effects, and time (carryover) effects between the peak and post treatment trials. All effects were tested against between subject interaction terms, and subjects were treated as a random effects variable so that the results can be extrapolated to the heavy drinking male driver population in general.

The basic statistical analysis procedure involved consideration of the peak treatment data only. In various instances where peak effects were statistically unreliable but potentially present we included trials as an additional variable and analyzed the second and third and/or all three trials within the day long experimental session.

## SECTION IV

### RESULTS

This section begins by presenting the performance effects found in the overall driving scenario. These results directly relate to traffic safety and are compared with some real world accident statistics. Subsequent articles then present the performance and behavioral effects found for each of the events within the driving scenario. This section is then concluded with an article summarizing and comparing the various results in terms of the experimental treatment effects. The reliability of the following experimental results was tested with Analysis of Variance procedures (ANOV). Type I error probabilities are stated for statistically significant findings.

#### A. OVERALL SCENARIO PERFORMANCE (TRAFFIC SAFETY)

Accidents were recorded throughout the driving scenario. In Fig. 10 we show the total accidents as a function of the various experimental treatments. Analysis of Variance procedures showed alcohol to have a statistically significant effect on accidents ( $p = 0.04$ ). The effects of the marihuana and the alcohol/marihuana interaction were not significant.

In Fig. 11 the relative increase in accident rate is compared with previous experimental results and real world accident statistics. In this experiment the descending BAC level (0.06 on trial 3) showed no increase in accident rate, while the peak BAC measurement (0.10 on trial 2) showed an increase of about 6 times. The sober accident rate for this experiment was small and was averaged over all sober runs in order to obtain a reliable denominator for computing the relative increase in accidents with BAC. The data from this experiment are consistent with the real world data. In Fig. 12 accidents are broken down according to driving events. Accidents primarily occurred on the curve and double lane change tasks, and only on the curve task was the change in accidents with experimental treatment reliable ( $p = 0.03$ ).

Treatment effects on speeding tickets are illustrated in Fig. 13. The alcohol effect was marginally significant ( $p = 0.02$ ). It would appear as though marihuana tends to reduce the alcohol effect, but this

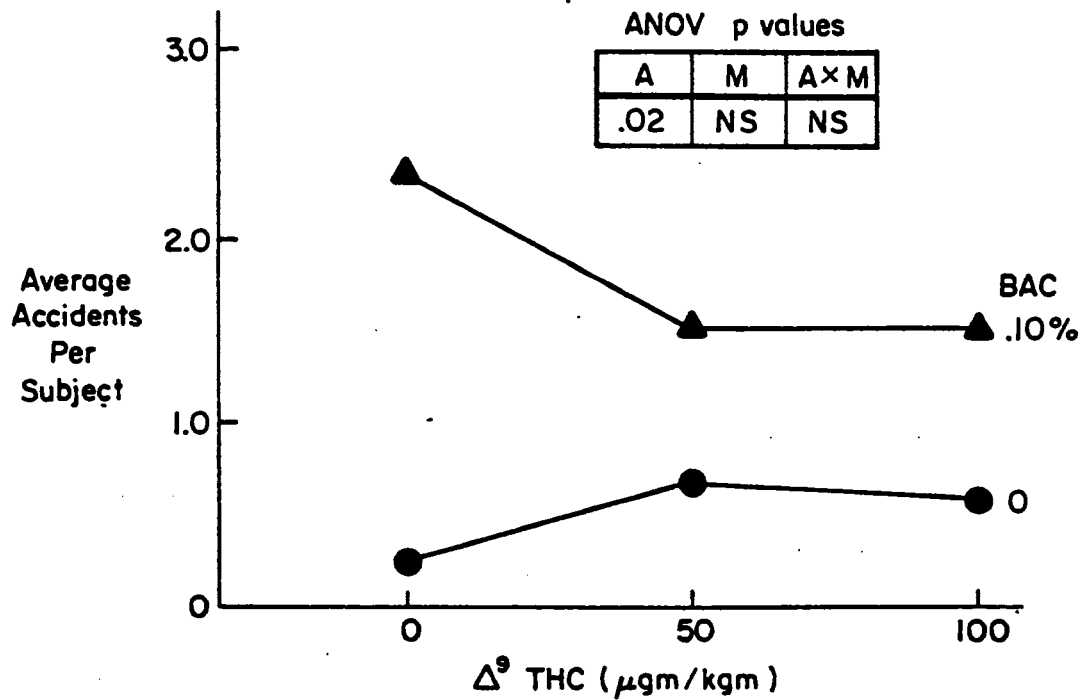


Figure 10. Combined Accidents During Driving Scenario as a Function of Experimental Treatments

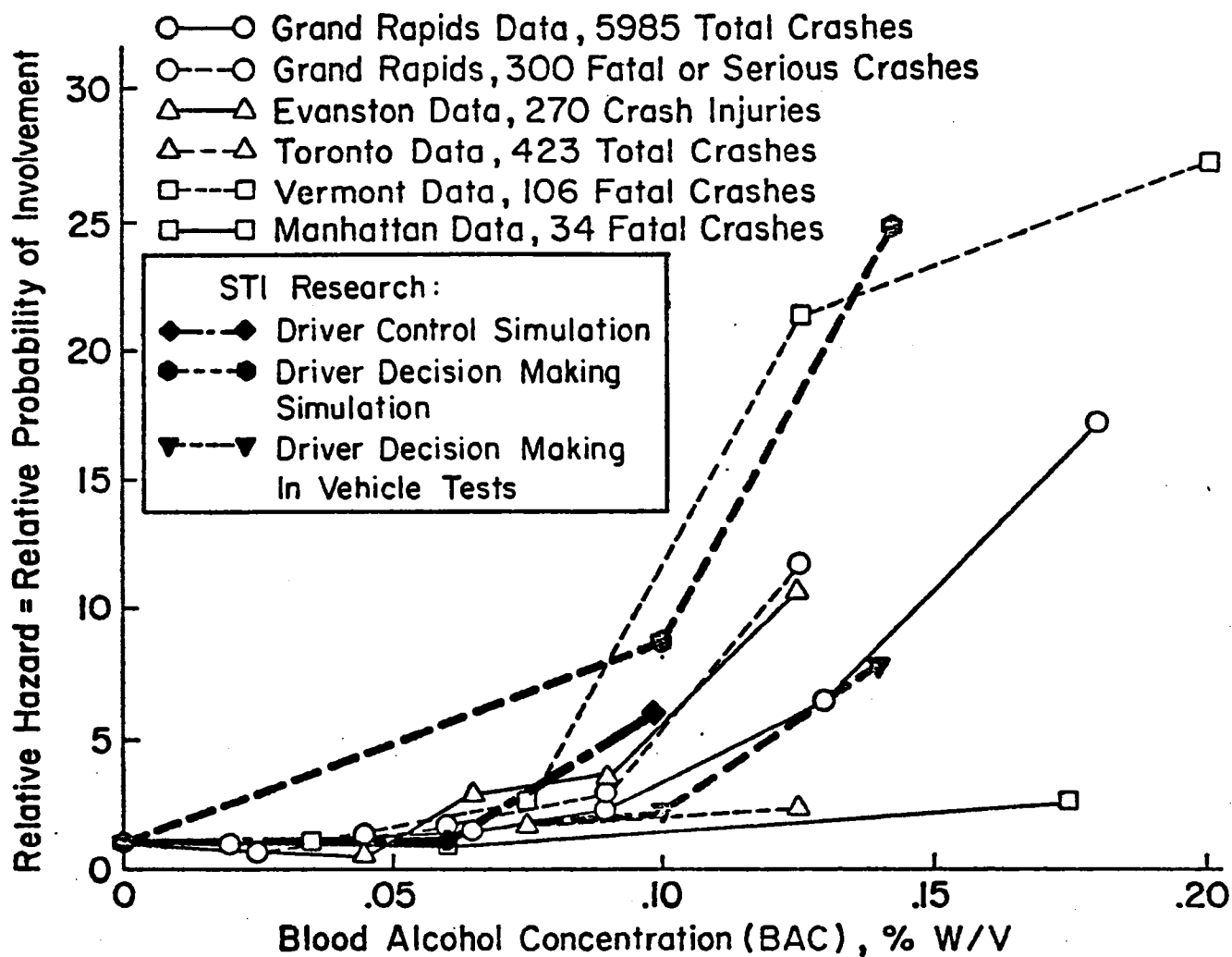


Figure 11. Relative Probability of Crash Involvement as a Function of BAC Where 1.0 = Relative Probability at Zero Alcohol. Comparison of Real World Data (After Hurst, Ref. 3), Current STI Driver Control Study, and Past STI Driver Decision Making Studies (Allen, et al., Ref. 45)

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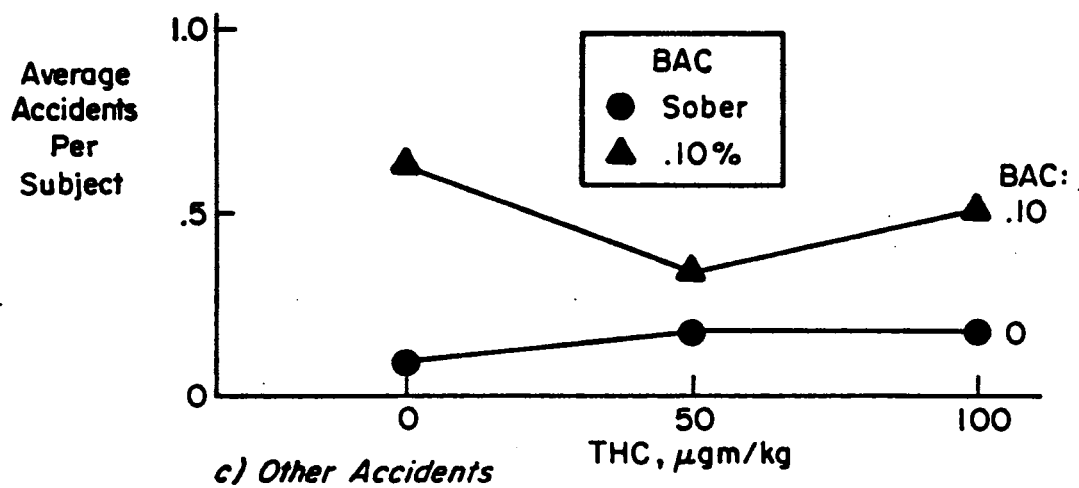
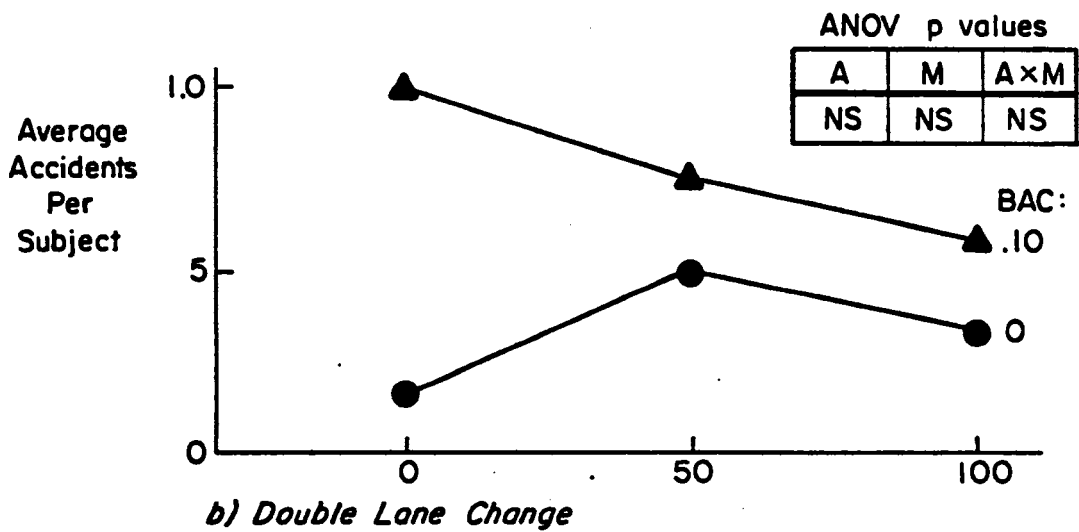
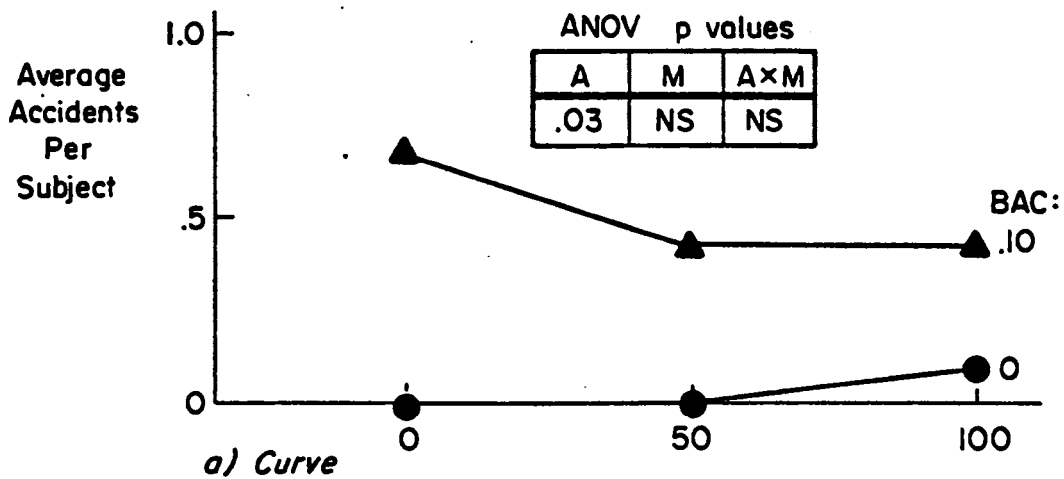


Figure 12. Accidents Partitioned as a Function of Driving Events

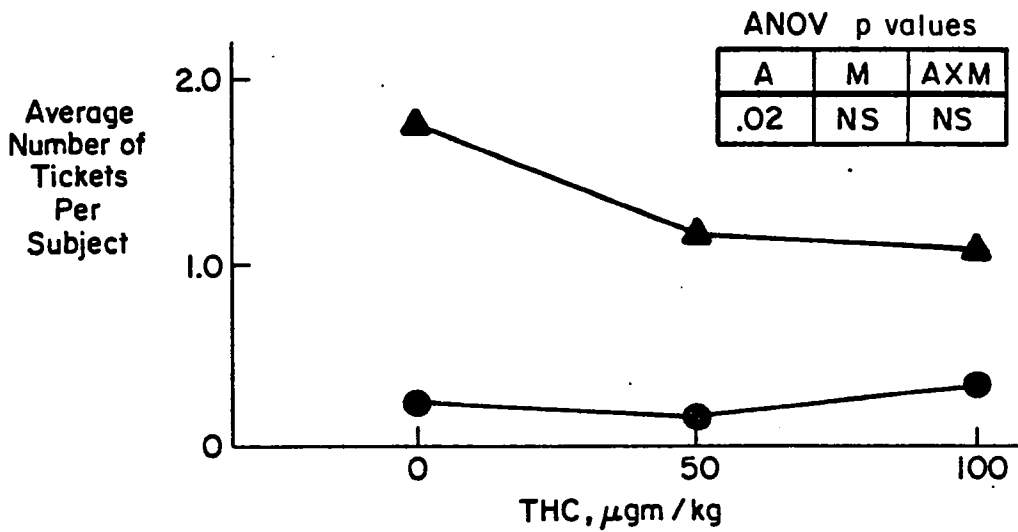


Figure 13. Average Speeding Tickets Per Trial in Driving Scenario

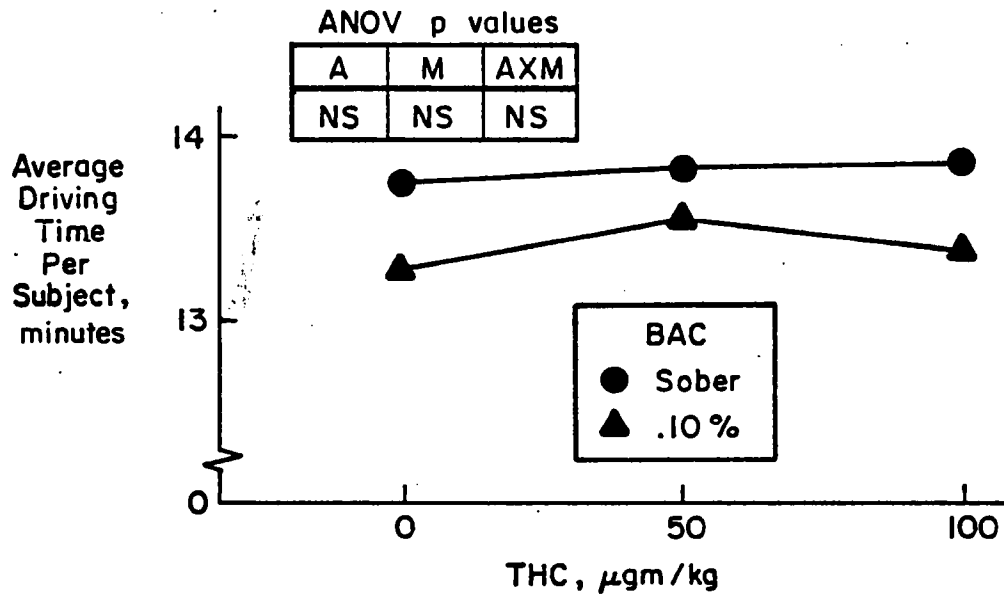


Figure 14. Average Driving Scenario Completion Time Per Trial

trend was not statistically significant. Even though there was some alcohol effect on speeding tickets, total driving time in the scenario was not significantly affected. In Fig. 14 we see how remarkably consistent the driving times were for all treatments. There appears to be a slight tendency for the times to be lower under alcohol. This could be in response to receiving tickets. The trend was not significant, however.

Overall it appears that the alcohol treatment had some effect on traffic safety related variables, while possible marihuana trends were not statistically reliable. As evidenced by the remarkable constant driving times, drivers were apparently not taking any overt additional risk under any of the treatment combinations. The increased incidence of speeding tickets under alcohol would suggest more variable speed keeping, however. This result is similar to our findings on a previous related driving experiment (Ref. 49).

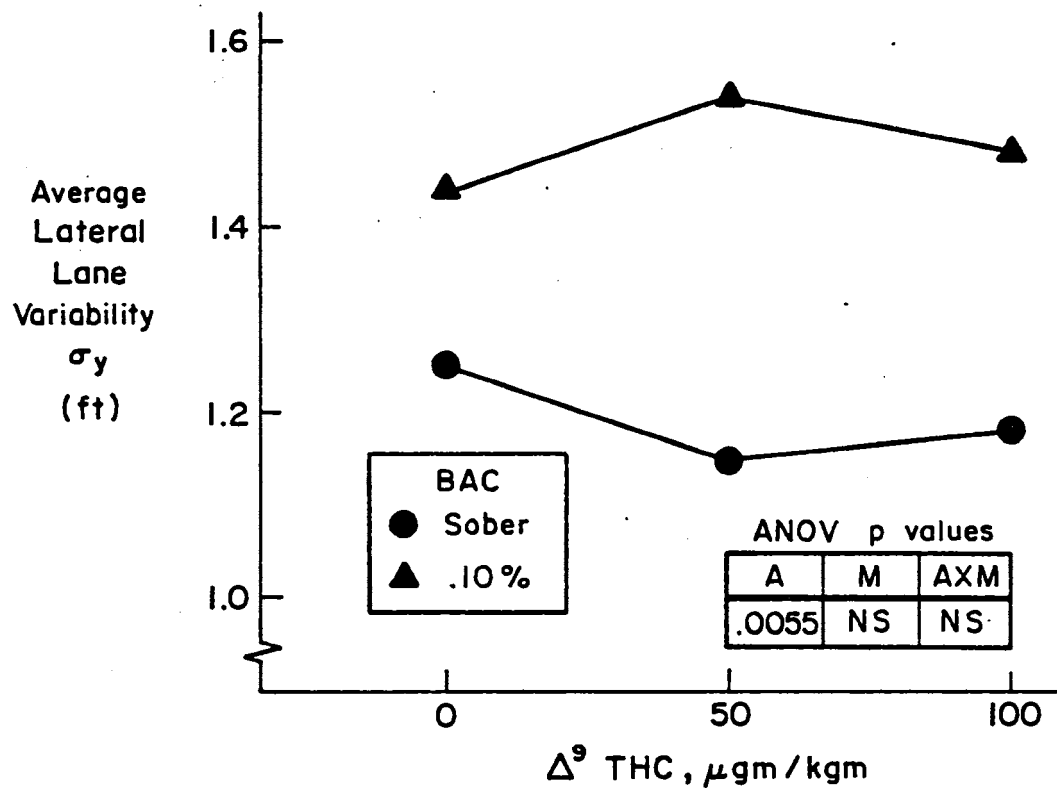
Given the above results on the overall driving scenario, let us now consider driver/vehicle performance on some of the scenario events.

## **B. STEERING CONTROL WITH DIVIDED ATTENTION**

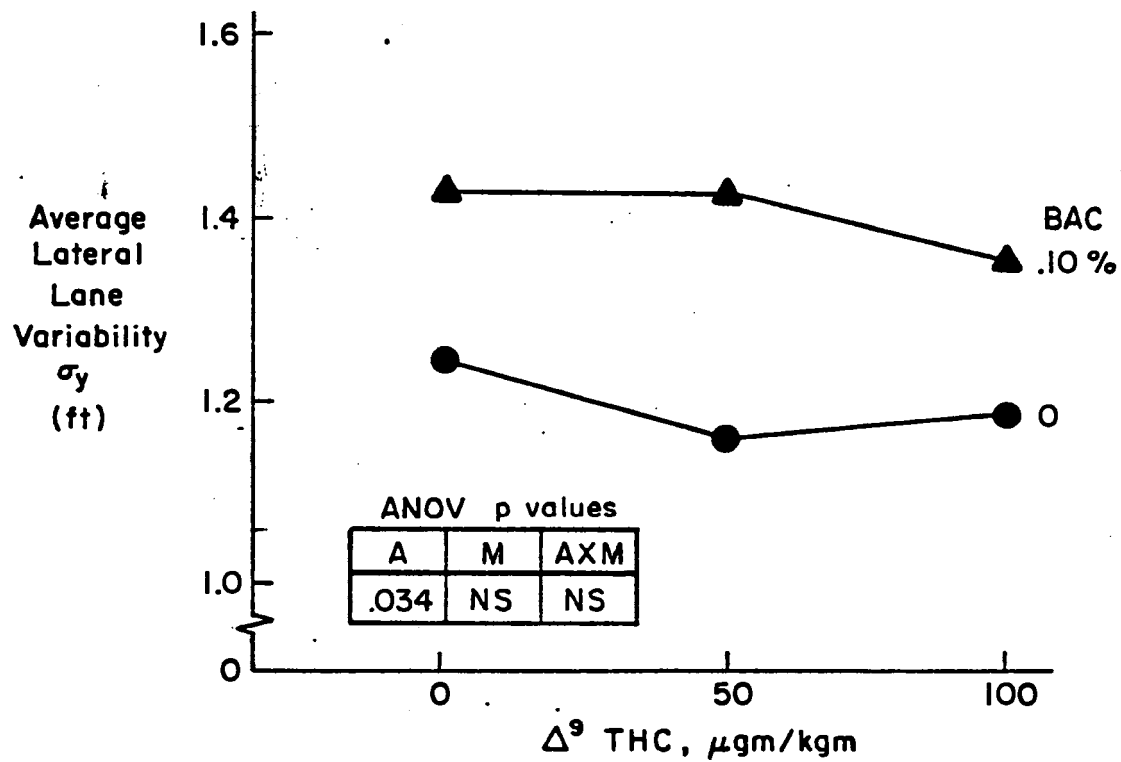
### **1. Random Input Steering Task**

Performance effects, in terms of lateral lane variability, are illustrated in Fig. 15. The alcohol effect was significant and statistically reliable for both the wind gust and winding road tasks. No marihuana effect was in evidence for performance on these tasks. The increased lane deviations with alcohol are consistent with past interactive driving simulation tests (Refs. 11, 45).

The probability of lane exceedence was computed by combining measures of the mean and standard deviation of lane position and assuming a Gaussian distribution. Lane exceedence probability was found to be significantly affected by alcohol, but not by marihuana or any interaction between the two variables. In Fig. 16 we show the relative increase in lane exceedence probability for two BAC levels (the lower BAC measurements were obtained on the descending side of the BAC/time curve). These data are also compared



a) Wind Gust



b) Winding Road

Figure 15. Steering Performance on the Random Steering Tasks

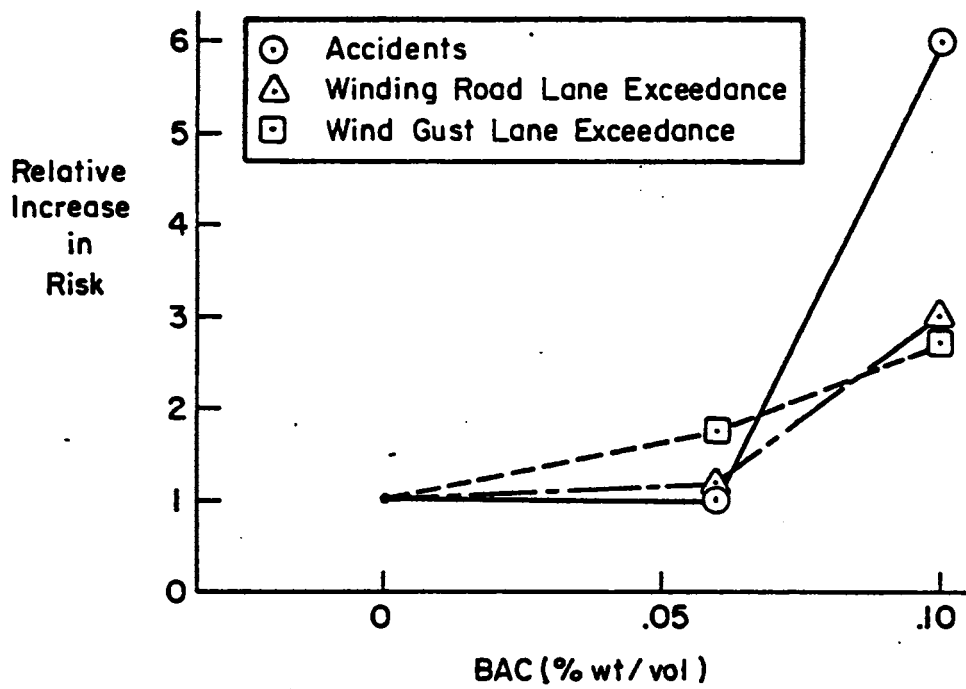


Figure 16. Effects of BAC on Traffic Safety

with the relative increase in accident rate. The accident rate shows a sixfold increase at 0.10 BAC, while lane exceedence shows about a factor of 3 increase. As discussed previously, the accident rate increase agrees with real world data, and the increased lane exceedence probability data show a consistent trend.

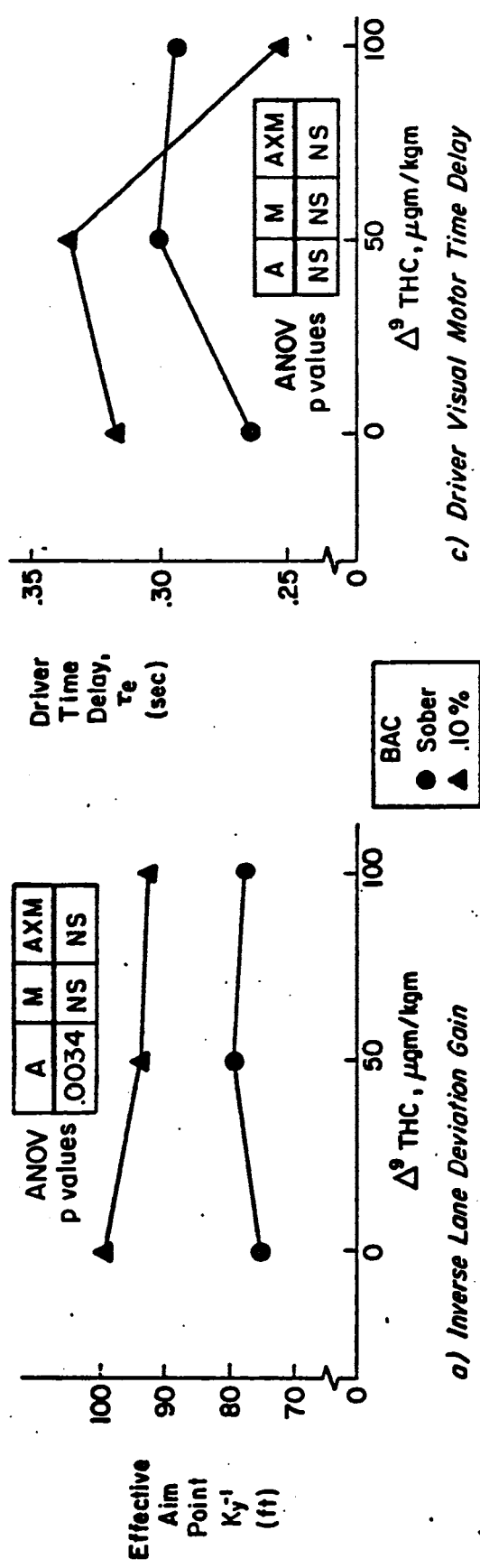
Alcohol and marihuana effects on driver control behavior in the random wind gust steering task are illustrated in Fig. 17. A detailed description and interpretation of the various control parameters is given in the Appendix. At the top of the figure the inverse of the lane deviation gain is plotted ( $K_y^{-1}$ , see Fig. 5). The inverse gain can actually be interpreted as the aim point of the car, the point at which the driver would steer to when he is off from his desired lane position (Ref. 46). Here we see the aim point ahead of the car increases with BAC, which implies a lower lane deviation gain, with resultant increased lane deviations as shown previously in Fig. 17. The decreased lane deviation gain under alcohol might also be interpreted as an increase in the driver's threshold for acceptable lane deviations (Ref. 45). Marihuana or interaction effects on  $K_y^{-1}$  were not significant.

In Fig. 17b we see that both alcohol and marihuana have affected the driver's heading gain,  $K_\psi$ . Heading gain decreases under alcohol while marihuana provides a counteracting increase. Analysis of the second trial (peak drug effect) data only shows the marihuana effect to be statistically significant. Analysis of all three trials per day shows both the alcohol and marihuana effects to be statistically reliable.

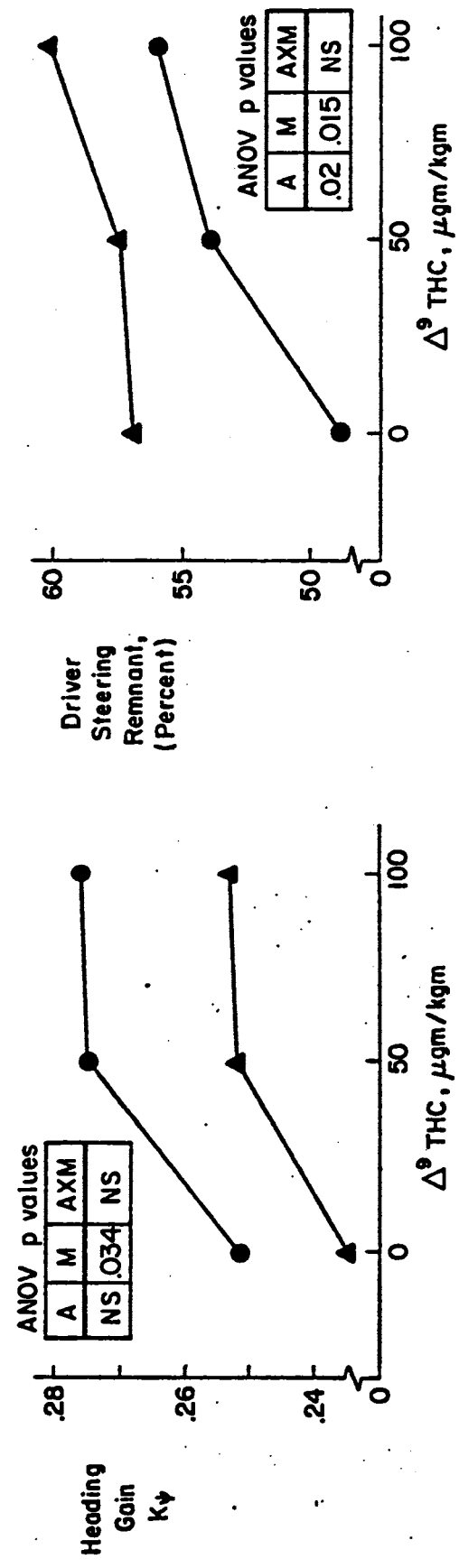
Effects on driver time delay are shown in Fig. 17c. There is some indication of alcohol and marihuana interaction on time delay. The statistical analysis of the peak treatment data only showed  $\tau_e$  results to be unreliable. Combined analysis of the peak and descending trial data gave some indication of reliable interaction, however ( $p = 0.034$ ).

Finally in Fig. 17d the treatment effects on driver steering remnant or noise are illustrated. The driver's noise output represents steering actions uncorrelated with the original wind disturbance. Both the alcohol and marihuana effects are statistically reliable and show the same trend, i.e., increasing steering response noise with drug dose.

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a) Inverse Lane Deviation Gain



b) Heading Gain

d) Remnant (Noise)

c) Driver Visual Motor Time Delay

Figure 17. Driving Steering Behavior Effects During the Random Wind Gust Task

## 2. Speed Regulation

Speed regulation served as one subsidiary task during the random steering tasks. In order to optimize performance the subjects best strategy would be to drive as near to the speed limit as possible in order to minimize driving time, and maintain speed as constant as possible in order to avoid excursions beyond the speed limit.

Speed control performance is plotted in Fig. 18. The mean speed was held quite close to the speed limit (i.e., 45 mph with the speed violation detector set at 48 mph). There was a tendency for alcohol to cause higher average speed while marihuana lead to reduced speeds, a counteracting effect between the two drugs. However, only the marihuana effect for the winding road mean speeds proved to be statistically significant ( $p = 0.015$ ).

In Fig. 18 speed variability tended to increase with both alcohol and marihuana dose. The speed variability results were generally significant for alcohol ( $p = 0.006$ ), but unreliable for marihuana. The increased speed variability under alcohol intoxication is consistent with the increase in speeding tickets.

## 3. Sign Detection and Recognition

The sign detection and recognition task served as a second subsidiary task during the random steering sequences. Response time was employed as a measure of behavior and some effects on mean response time are illustrated in Fig. 19. Alcohol generally increased response time and the effects were statistically significant ( $p = 0.042$ ). This result is consistent with past driving simulator research (Refs. 45, 51). The variability of response time was also tested but showed no change with drug treatment.

Sign response errors are also shown in Fig. 19. A marginally significant marihuana effect was noted for the wind gust tests.

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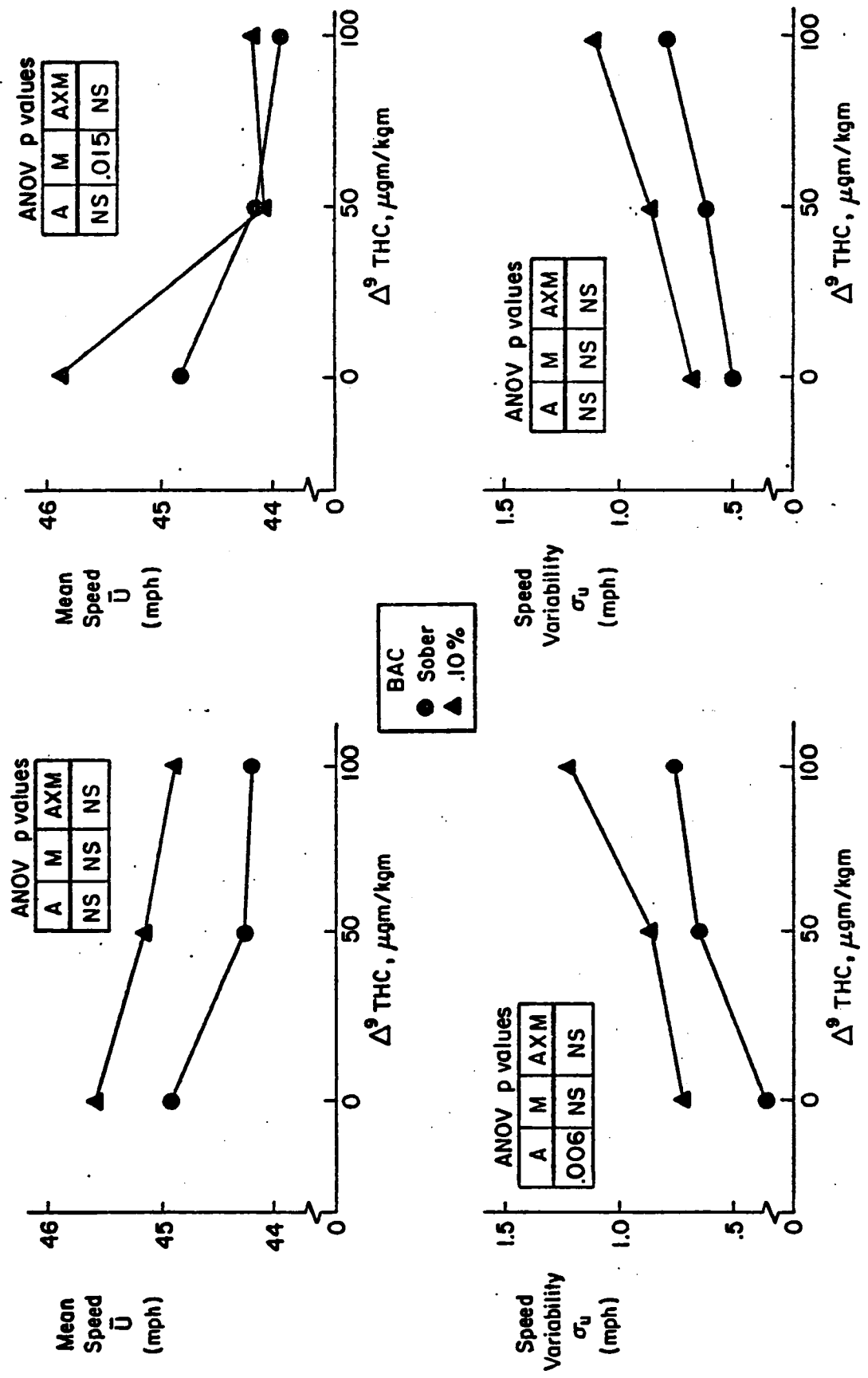
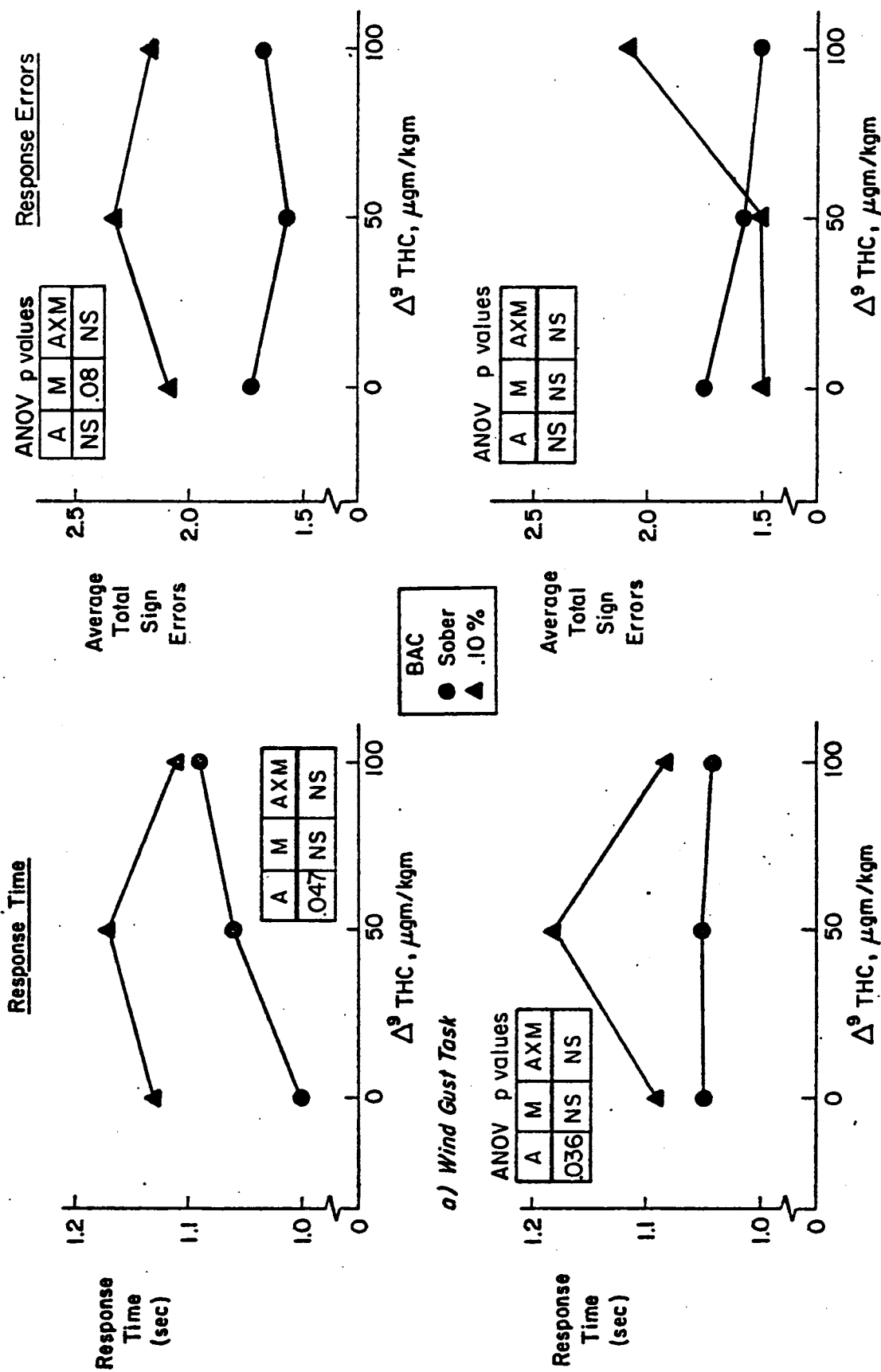


Figure 18. Alcohol and Marihuana Effects on Speed Regulation Performance During the Random Steering Tasks



a) Wind Gust Task

b) Winding Road Task

Figure 19. Effects on Sign Response Time and Error During the Random Steering Tasks

### C. ISOLATED CURVES

This situation required simultaneous steering and speed control to safely negotiate the curve. We have previously noted that the experimental treatments caused increased accidents, and here we analyze control performance during the curve encounter to determine causal factors. In Fig. 20a mean and standard deviation of ensembled speed profiles are plotted as a function of distance through the curve. The road curvature and car equations of motion were arranged such that the driver had to reduce his speed below the critical limit for loss of control illustrated in Fig. 20. Both alcohol and marihuana lead to reliable increases in speed variability ( $p = 0.006$  and  $p = 0.016$  respectively). Differences in mean speeds were not reliable.

In Fig. 20b the mean and standard deviation of lateral lane position is illustrated for alcohol only. The variability of lane position increased under alcohol and this result was marginally statistically significant ( $p = 0.075$ ). Marihuana effects on lane position were not significant.

In Fig. 21 the speed and lane position variability results are averaged over the 8 time epochs of Fig. 20 in order to clarify the basic alcohol and marihuana effects. The reliable alcohol and marihuana trends are apparent for speed variability. The marginally significant alcohol effect on lane position variability is also evident, while marihuana has an inconsistent effect between the two alcohol conditions. The alcohol effect on both speed and lane position variability is consistent with the increase in curve accidents under alcohol.

### D. OBSTACLE AVOIDANCE

Accidents on the obstacle avoidance tasks were not sensitive to the drug treatments, but the double lane change event did show some driving behavior sensitivity. Typical behavior on the double lane change task measured in a preliminary experiment is illustrated in Fig. 22. Because of the nature of car dynamics, to a first approximation lane position is the second integral of steering wheel position (Ref. 52). The characteristic "w" shaped steering response is required to achieve the double lane change

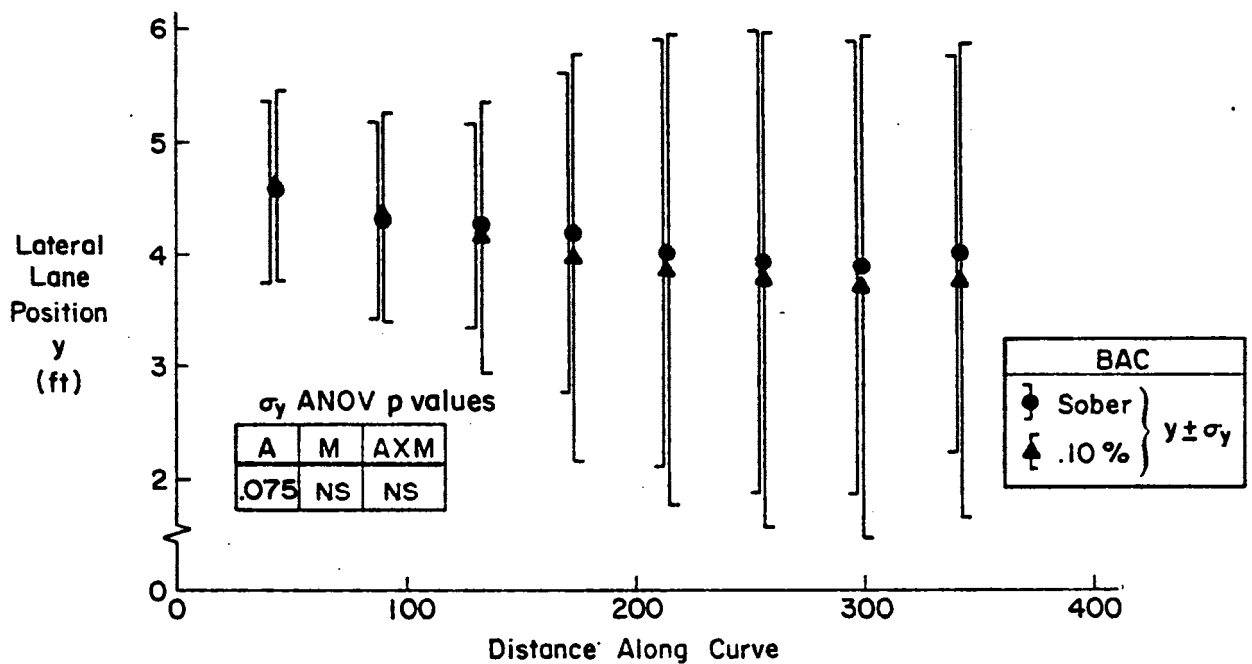
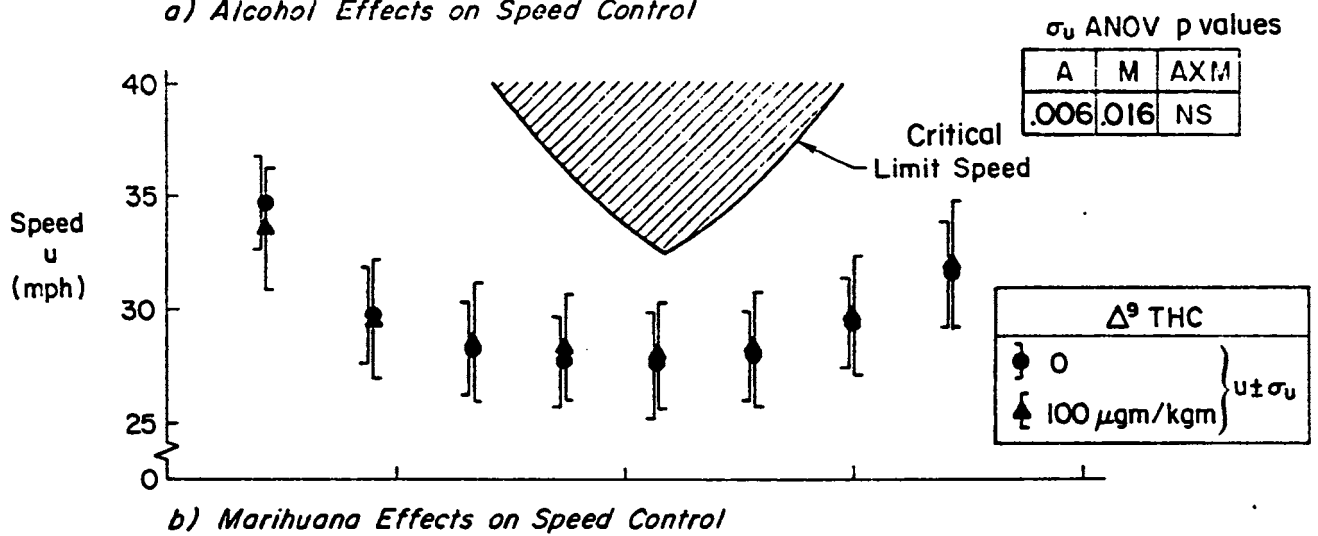
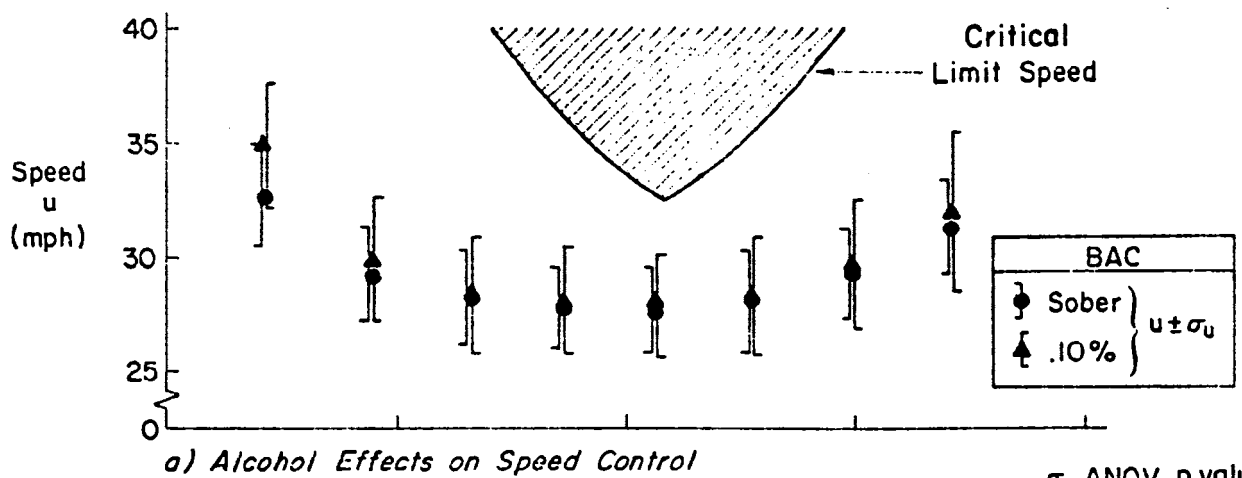
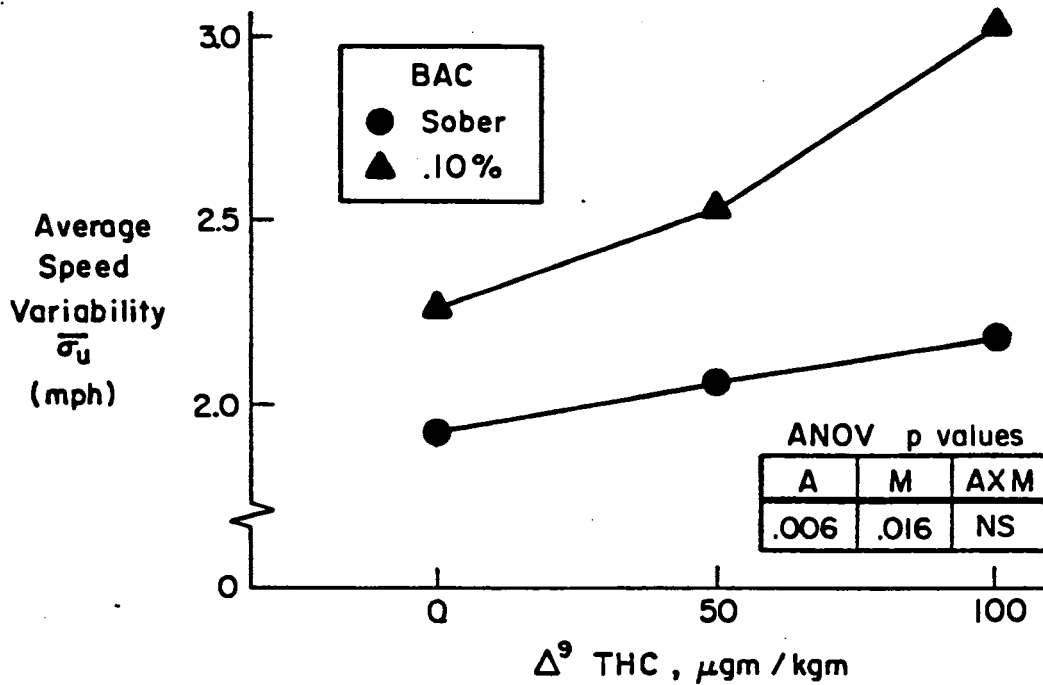
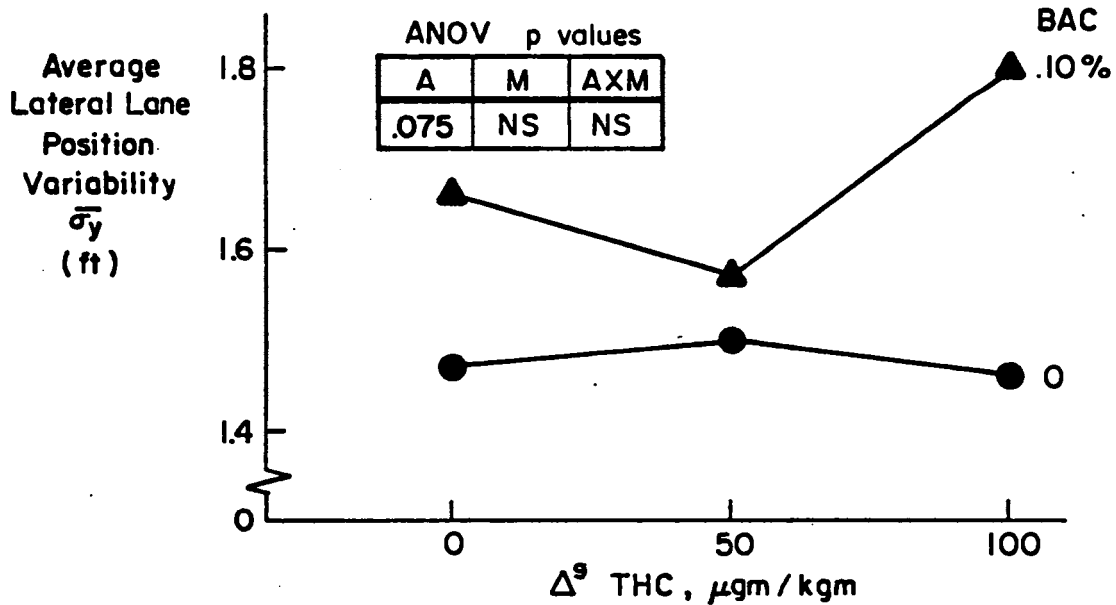


Figure 20. Ensemble Speed Profiles Throughout the Curve Task as a Function of Drug Treatment



a) Speed Variability



b) Lane Position Variability

Figure 21. Effects on Speed and Lateral Lane Deviation Variability Data Averaged Over 8 Time Epochs in Fig. 19

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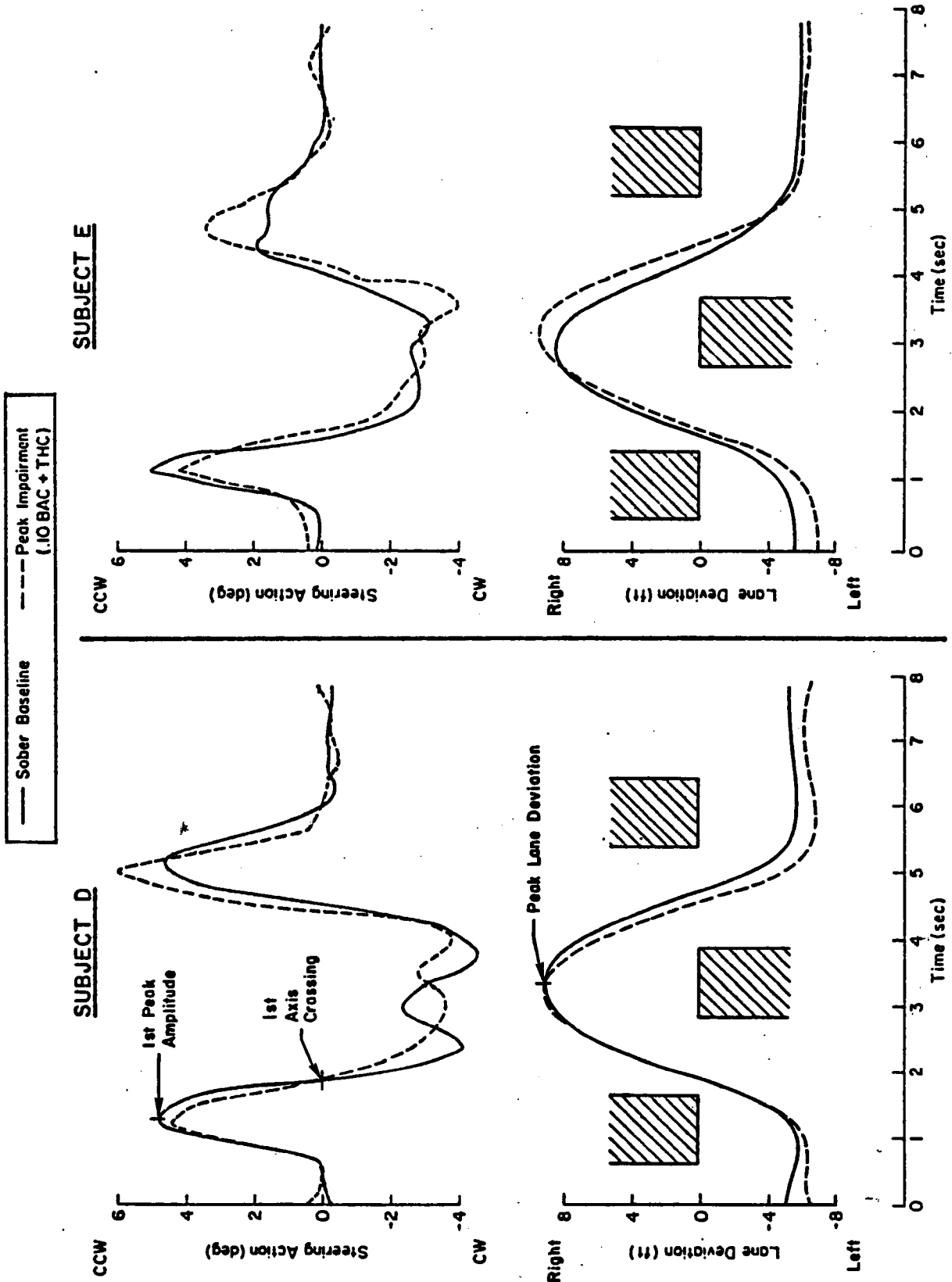


Figure 22. Ensemble Average Time Responses for Double Lane Change Maneuver

path illustrated. Based on the Fig. 22 data it was decided to measure characteristic peaks and axis crossings of the steering and path profiles rather than attempting to work with the detail of the complex profile shapes.

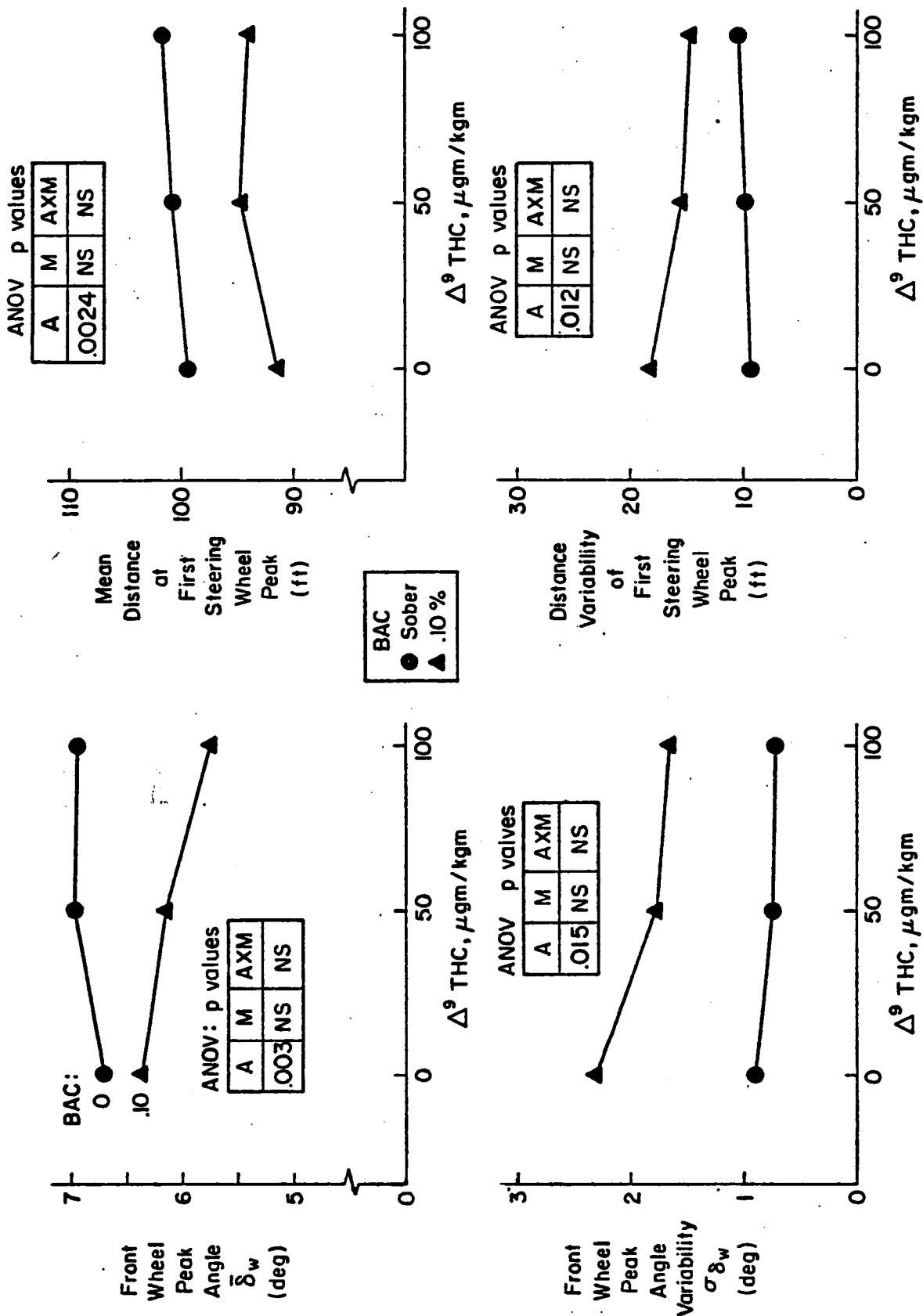
In Fig. 23 the drug effects on the distance down the road and amplitude of first steering wheel peak are illustrated. The alcohol effect on all Fig. 23 variables was reliable. The marihuana effects are small, however, and not statistically significant.

In Fig. 24 the drug effects on the first steering wheel axis crossing and the peak lane deviation are illustrated. As noted in Fig. 22 the steering axis crossing corresponds approximately to the lane edge crossing. Under alcohol the axis crossing occurred sooner and this effect was reliable. The peak lane deviation shows a counteracting effect between alcohol and marihuana which was marginally statistically significant.

Overall the double lane change task was not very sensitive to the drug treatments from a traffic safety point of view. It did demonstrate impairment in the driver's psychomotor capability, however, in terms of the amplitude and timing precision of a required transient steering maneuver.

The unexpected obstacle event showed even less sensitivity than the double lane change maneuver. It is interesting to note that both of these tasks are somewhat insensitive to alcohol and marihuana impairment compared to the random steering and isolated curve tasks. These latter two tasks require divided attention, however, (i.e., sign response in the case of the random steering task and a definite speed control profile throughout the isolated curve) while the obstacle task primarily required steering control only. Moskowitz (Ref. 6) has found divided attention situations to be more sensitive to alcohol impairment, and this may account for the results here.

Another interesting corollary to the above discussion is the fact that in our previous decision making research (Ref. 49) the unexpected obstacle task combined with possible adjacent traffic had provided a traffic situation sensitive to alcohol impairment. In that case when an adjacent car was observed the subject had to stop rather than go around in order to avoid



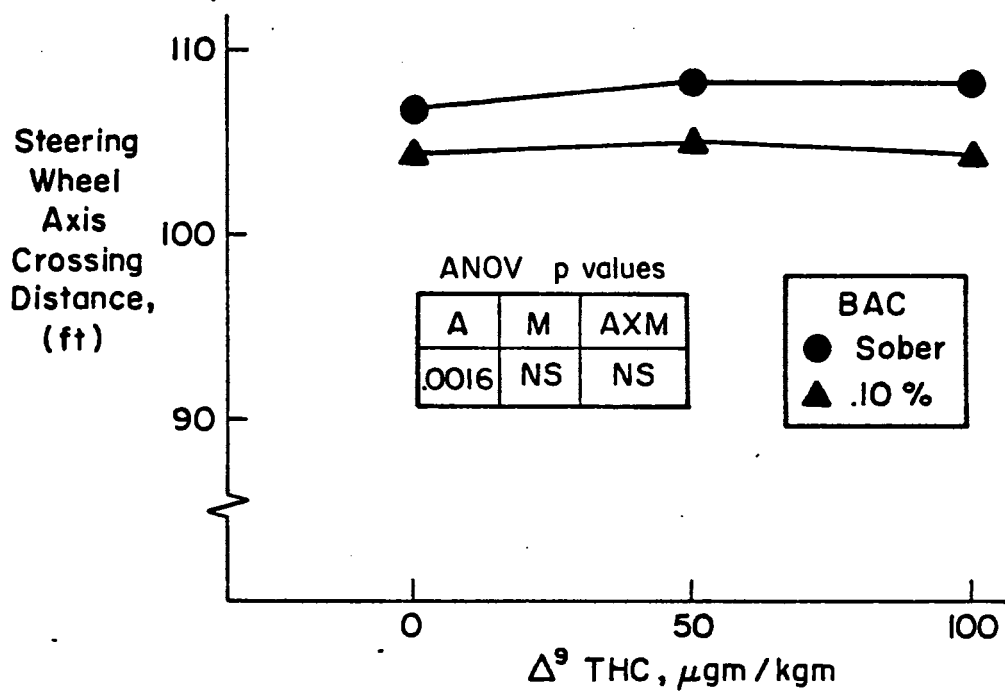
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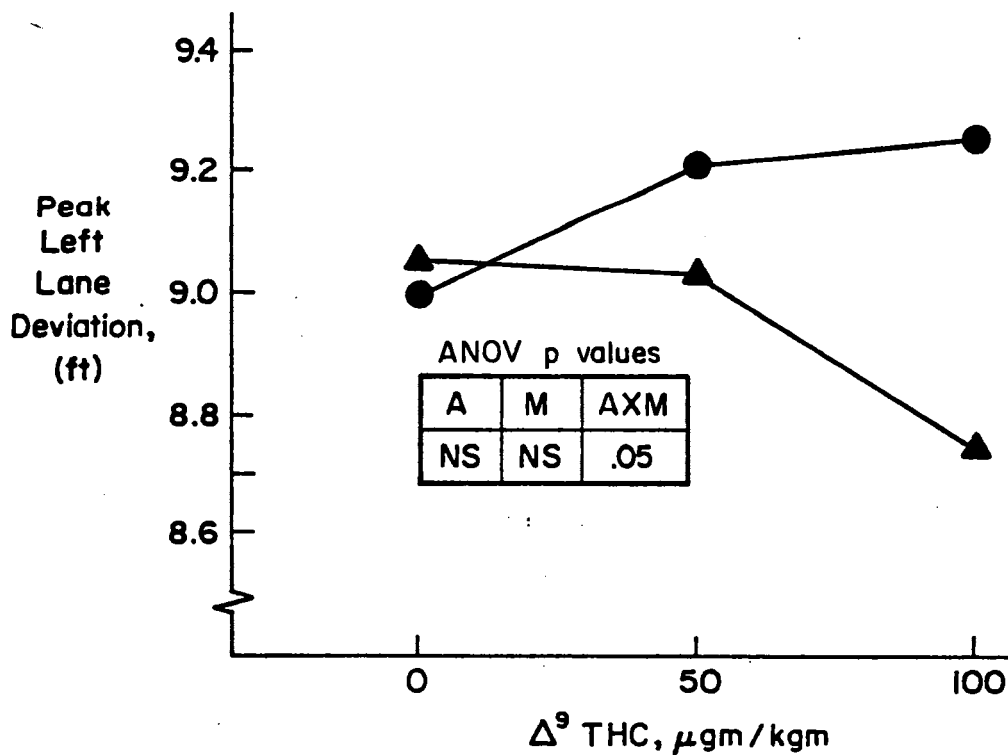
b) Distance to First Steering Wheel Peak Amplitude

a) Steering Wheel First Peak Amplitude

Figure 23. Steering Behavior Effects on the Double Lane Change Maneuver



a) Axis Crossing



b) Peak Lane Deviation

Figure 24. Steering Performance Effects on the Double Lane Change Maneuver

hitting the adjacent car, and a frequent number of adjacent traffic was included in the driving scenario. In this current experiment we were primarily interested in driver steering control, so that only two adjacent cars were included in the entire scenario, and the task otherwise amounted to a rather mundane steering maneuver.

#### E. SUBJECTIVE RATINGS AND PHYSIOLOGICAL RESPONSE

Further insight into the strength of the drug treatments was obtained from subject ratings and heart rate measurements. After the smoking episode in the daily session procedure, subjects were asked to rate the intoxicating value of the marihuana and alcohol treatment by indicating their subjective impression on the Fig. 25 scales. Heart rate was also obtained before each simulator trial which gave one measure immediately following the smoking episode.

The treatment ratings averaged across subjects are shown in Fig. 26. The alcohol rating gave a clear cut differentiation between the two alcohol treatments and was not influenced by the marihuana treatments. Statistical analysis showed the variability between subjects to be less than one scale unit, while the interaction with the alcohol treatment was on the order of one and a half scale units. This latter result presumably reflects a varying reaction to the alcohol between subjects.

The marihuana ratings in Fig. 26b show a weak dose response relationship and a potential accentuation with alcohol. The marihuana differences were reliable but alcohol effects were not. Both the alcohol and marihuana treatments elicited similar peak and placebo ratings in comparing parts a and b of Fig. 26. To the extent this indicates equivalent social levels of alcohol and marihuana, the previously discussed results would indicate that alcohol has the more consistent and pervasive effect of the two drugs.

Heart rate measurements are shown in Fig. 27. Both alcohol and marihuana affected heart rate, with the expected marihuana dose response relationship. The marihuana effect seems to have died out by the post treatment measurement (1-1/2 hours post smoking), while some alcohol effect is still in evidence. Statistical analysis showed the alcohol

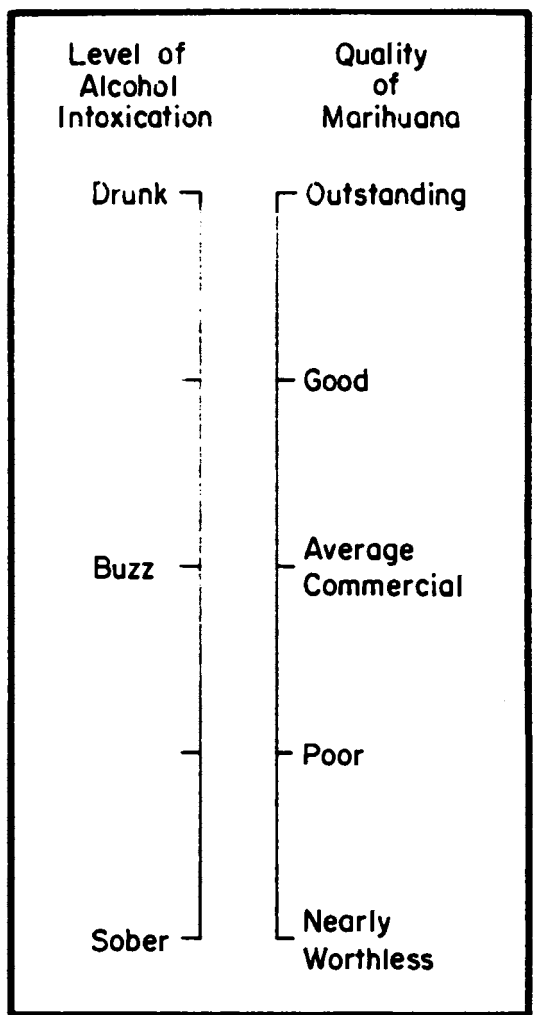
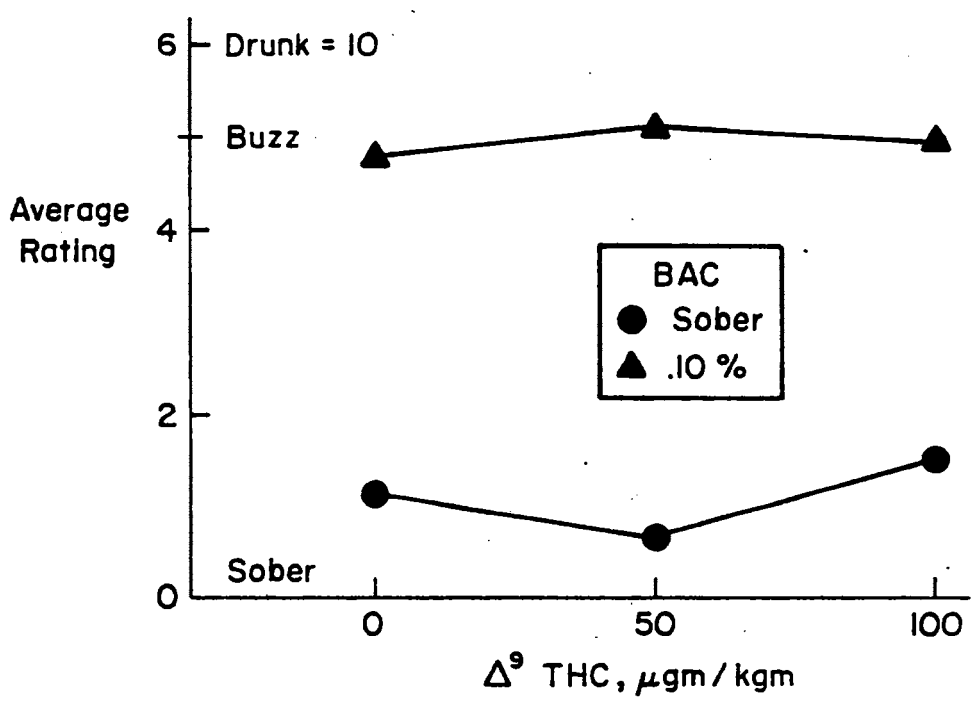
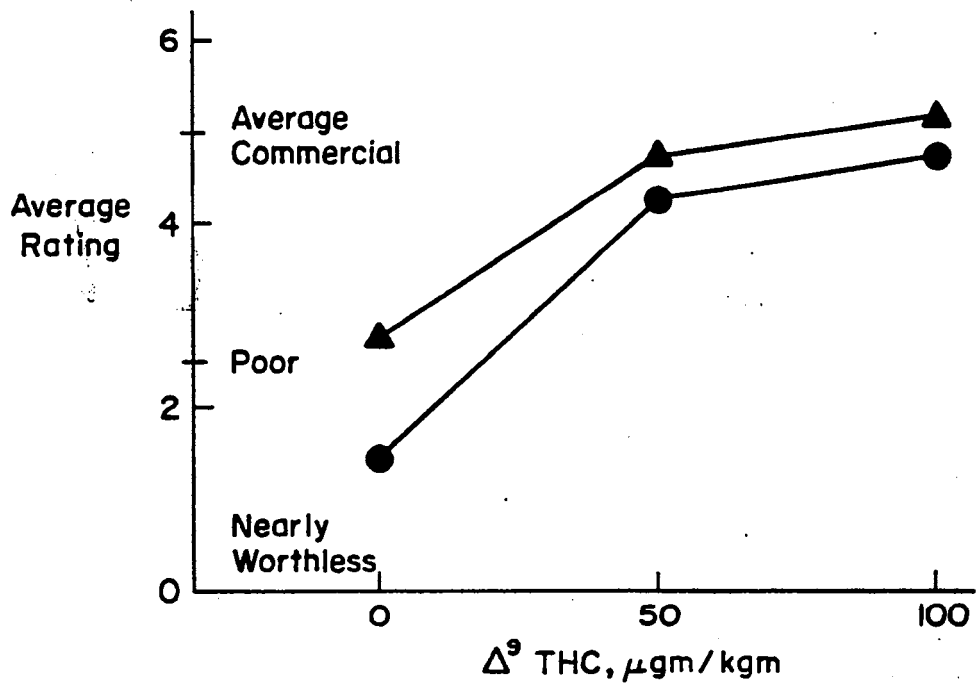


Figure 25. Rating Scales for Alcohol Intoxication and Marihuana Potency



a) Alcohol Ratings



b) Marijuana Ratings

Figure 26. Average Ratings for Alcohol and Marijuana Treatments

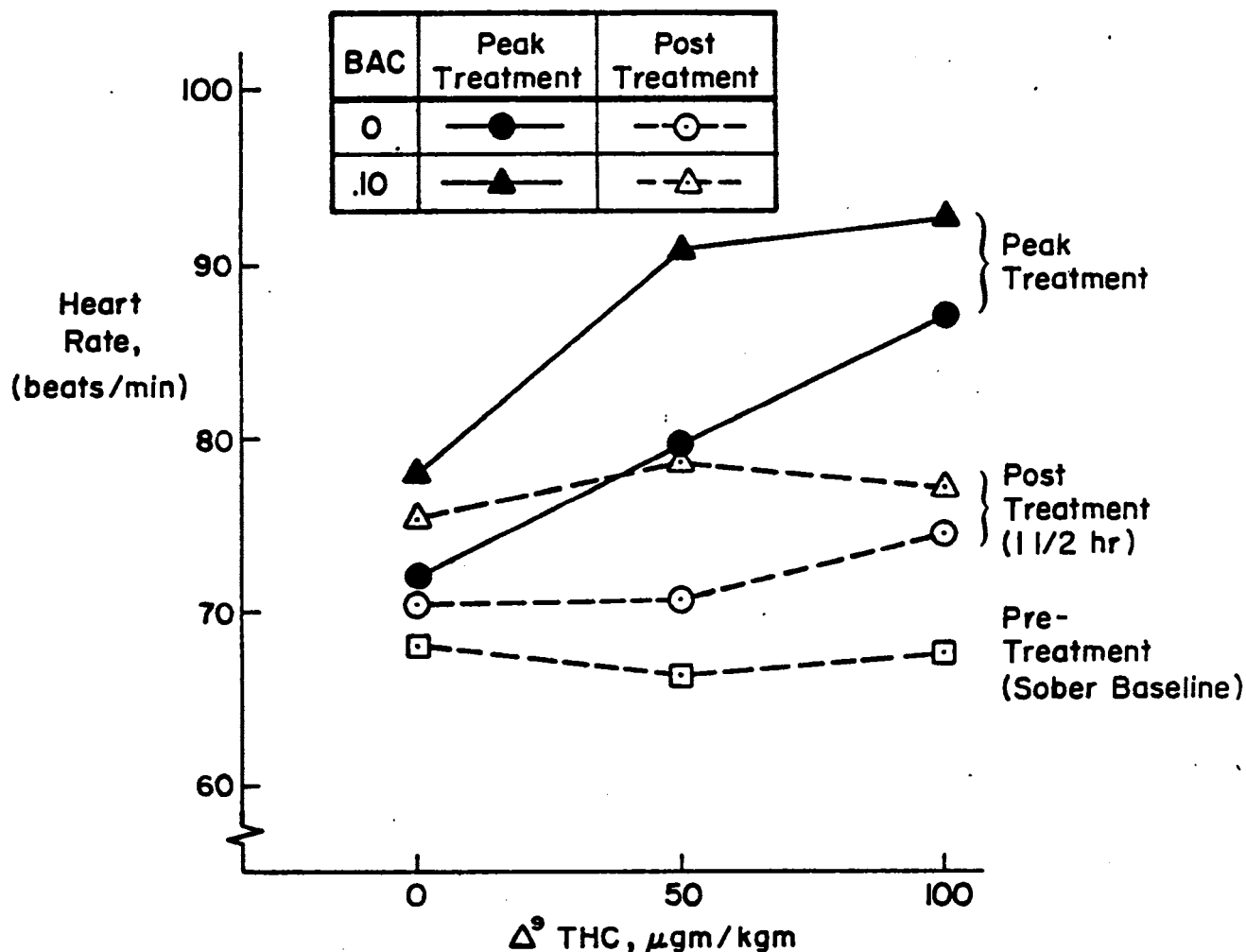


Figure 27. Treatment Effects on Heart Rate

and marihuana effects to be reliable, ( $p = 0.011$ ,  $p = 0.005$ , respectively). Between-subject variability was about 7 beats/min on the average, and differential response to the drug treatments amounted to another 4 beats/min.

No unusual or otherwise unexpected reactions were elicited due to the combined administration of alcohol and marihuana. The doses administered here appear to be safe, and not unusual based on informal subject comments. The marihuana dose of 100  $\mu\text{g}/\text{kg}$  was modest according to subject comments and could probably be increased by 50 percent or more in the future without undue hazard to subjects.

## F. BETWEEN-SUBJECT VARIABILITY

Information on qualitative effects and variability of results is summarized in Table 5. The most obvious result from Table 5 is that alcohol routinely affected behavior and performance and the results were quite reliable. Marihuana on the other hand only showed reliable effects in a few instances. Alcohol impairments in speed and steering regulation would seem to relate to reliable increases in accidents and tickets. In the case of marihuana, steering and speed control were not routinely affected and traffic safety effects were not in evidence. Differential effects between alcohol and marihuana were virtually non-existent.

One possibility for the lack of statistically significant marihuana effects is a masking effect due to between-subject variability. Some past studies have found that marihuana effects vary appreciably between subjects. This effect can be assessed by comparing estimated variance components for between-subject variability derived from the analysis of variance procedures applied to all our data. This analysis is summarized in the last two columns of Table 5. Here we have taken ratios of the between-subject variances for marihuana and alcohol ( $\sigma_{MS}^2/\sigma_{AS}^2$ ), and the alcohol/marihuana interaction and alcohol ( $\sigma_{AMS}^2/\sigma_{AS}^2$ ). These quantities are F ratios, and we are able to use standard statistical tables to determine if the marihuana treatments cause a statistically significant increase in between-subject variability over that due to the alcohol treatment.

As noted in Table 5 marihuana alone showed increased variability over the alcohol treatment in only a few instances, and in one or two cases alcohol actually shows a significantly greater between-subject variance if we would invert the  $\sigma_{MS}^2/\sigma_{AS}^2$  ratio and refer to an F table under the appropriate degrees of freedom. The interacting effects of alcohol and marihuana ( $\sigma_{AMS}^2/\sigma_{AS}^2$ ) show a definite trend towards greater between-subject variability than alcohol effects alone, however, which of course makes it difficult to identify interaction effects.

TABLE 5. SUMMARY AND RELIABILITY OF TREATMENT EFFECTS AND ANALYSIS OF BETWEEN-SUBJECT VARIABILITY

CLASS	MEASUREMENT	ALCOHOL EFFECTS	MARIHUANA EFFECTS	AxM	$\sigma_{MS}^2 / \sigma_{AS}^2$ <sup>c</sup>	$\sigma_{AMS}^2 / \sigma_{AS}^2$ <sup>c</sup>
Scenario Performance (Traffic Safety)	Accidents	↑**	NS	NS	1.03	1.29
	Tickets	↑†	NS	NS	0.58	0.48
	Driving Time	NS	NS	NS	1.51	3.62*
Steering Regulation <sup>a</sup>	Lane Deviations	↑***	NS	NS	0.28	0.71
	Effective Aim Point, K <sub>y</sub>	↑***	NS	NS	4.02*	6.65**
	Heading Gain, K <sub>ψ</sub>	NS	↓*	NS	0.53	0.58
	Time Delay	NS	NS	NS	2.26†	3.95*
Speed Regulation	Remnant (Noise)	↑*	↑*	NS	0.68	1.68
	Mean <sup>b</sup>	NS	↓*	NS	0.55	2.07
Sign Detection and Recognition <sup>b</sup>	Variability <sup>a</sup>	↑***	NS	NS	4.79**	3.86*
	Mean Response Time	↑*	NS	NS	0.42	0.36
Curve Control	Errors	↑*	NS	NS	1.24	2.84*
	Speed Variability	↑***	↑*	NS	0.99	2.22†
	Lane Position Variability	↑†	NS	NS	1.05	2.84*

Level of Statistical Significance: \*p < 0.05; \*\*p < 0.01; \*\*\*p < 0.001; †p < 0.10; NS p > 0.10.

Treatment Effect: ↑ increased; ↓ decreased; ↑ ↓ counteracting.

<sup>a</sup>Wind Gust Task.

<sup>b</sup>Winding Road Task.

<sup>c</sup> $\sigma_{AS}^2$  = between subject variance over alcohol conditions, 11 degrees of freedom.

$\sigma_{MS}^2$  = between subject variance over marihuana condition, 22 degrees of freedom.

$\sigma_{AMS}^2$  = between subject variance over interactions between alcohol and marihuana, 22 degrees of freedom.

(Concluded on following page)

TABLE 5 (Concluded)

CLASS	MEASUREMENT	ALCOHOL EFFECTS	MARIHUANA EFFECTS	AxM	$\sigma_{MS}^2/\sigma_{AS}^2$ <sup>c</sup>	$\sigma_{AMS}^2/\sigma_{AS}^2$ <sup>c</sup>
Double Lane Change Task	Mean Steering Peak	↓***	NS	NS	2.40 <sup>†</sup>	6.08**
	Steering Peak Variability	↑*	NS	NS	0.45	0.79
	Mean Distance at Steering Peak	↓***	NS	NS	1.10	5.31**
	Distance Variability at Steering Peak	↑*	NS	NS	1.40	1.57
	Steering Axis Crossing Distance	↓***	NS	NS	1.76	5.38**
	Peak Lane Deviation	NS	NS	↑ ↓ <sup>†</sup>	0.85	1.51
	Driver Reaction	Alcohol Rating	↑***	NS	NS	0.28
Marihuana Rating		NS	↑***	NS	1.05	1.21
Heart Rate		↑***	↑***	NS	0.76	1.59

Level of Statistical Significance: \*p < 0.05; \*\*p < 0.01; \*\*\*p < 0.001; †p < 0.10; NS p > 0.10.

Treatment Effect: ↑ increased; ↓ decreased; ↑ ↓ counteracting.

<sup>a</sup>Wind Gust Task.

<sup>b</sup>Winding Road Task.

<sup>c</sup> $\sigma_{AS}^2$  = between subject variance over alcohol conditions, 11 degrees of freedom.

$\sigma_{MS}^2$  = between subject variance over marihuana condition, 22 degrees of freedom.

$\sigma_{AMS}^2$  = between subject variance over interactions between alcohol and marihuana, 22 degrees of freedom.

## G. SUMMARY

In presentation of the results thus far we began with the ultimate traffic safety consequences of driver impairment, accidents and tickets, then proceeded to the underlying behavioral causes. In summary let us now start with the basic behavioral effects of alcohol intoxication then trace their contribution effect to traffic safety.

The driver dynamic response measures in the wind gust steering regulation task provide the best indications of drug impairment. Driver gain applied to lane position errors ( $K_y$ ) was depressed by alcohol (i.e., the inverse of this gain, or look ahead distance, increased) with no effect of marihuana. Driver gain applied to heading errors ( $K_\psi$ ) was elevated by marihuana and depressed by alcohol, although only the marihuana effect was reliable. No effects were noted on driver time delay but both marihuana and alcohol elevated the amount of remnant or portion of the driver's response uncorrelated with the original system wind disturbance.

The above results seem consistent with the alcohol effect on steering performance in the wind gust task as measured by lane position variability. Decreased gain levels and increased remnant would tend to increase lane deviations in the case of alcohol impairment. In previous research (Ref. 45) the decreased effect of alcohol on control gains has been interpreted as a possible decrease in sensitivity to lane errors or increased indifference threshold. The effects of marihuana in the wind gust steering task were counteractive, however. There was no effect on lane position gain, and increased heading gain under marihuana would act to offset the increased remnant level. The net consequence is consistent with the lack of a marihuana effect on lane position deviations.

The treatment effects were similar on lane deviations in the wind gust and winding road tasks. There were other detailed describing function effects which were similar between the two tasks and we would infer that the same conclusions can be drawn for both situations.

Behavior in the double lane change task seems consistent with the random steering tasks. Alcohol depressed the peak steering amplitude which is consistent with the decreased gains in the wind gust task.

Alcohol also increased variability in the peak amplitude and in the timing (distance) of the peak which corresponds to the remnant increase in the wind gust task. No marihuana effects were found in the double lane change task except for a marginal interaction between alcohol and marihuana on the peak lane deviation.

Direct behavioral measures were not made on the isolated curve control task but we infer that the same dynamic response effects were at work here as measured in the wind gust task, i.e., decreased gains and increased remnant under alcohol.

Speed control capability showed increased variability under alcohol on the curve and random steering tasks. Although behavioral measures were not obtained for speed regulation, control processes similar to steering regulation are involved here, and we would infer that increased remnant and decreased gain are responsible for the alcohol effects. Marihuana also increased speed variability in the curve task, but reduced mean speed during the wind gust task.

The net system performance result of alcohol induced decreased gain and increased remnant or noise is reduced speed and accuracy of response. Reduced speed and accuracy under alcohol also showed up directly in the secondary sign detection and recognition task. These effects combined significantly and consistently throughout all the tasks and measurements. The net result was a significant increase in accident rate, which was most sensitive in the isolated curve control task. In the curve task situation the drivers were close to performance limits anyway as represented by mean speeds close to the limit out-of-control speed, and the consequence of control performance variability under alcohol was to increase the probability of loss of control.

Marihuana did not show consistent effects on behavior or performance deterioration, or related deterioration in traffic safety measures. There is some evidence for counteracting marihuana effects on driver control processes which may explain the lack of performance effects. Also, only average subject ratings were obtained for the marihuana treatments and the dose levels employed here may not have been large enough to consistently affect driver behavior.

## SECTION V

### CONCLUSIONS AND RECOMMENDATIONS

The results have been presented, discussed and summarized in the last section. Here we give a succinct listing of conclusions on alcohol and marihuana effects on driving safety and recommendations for a field validation study and potential impaired driving countermeasures.

#### A. CONCLUSIONS

- Alcohol at a BAC of 0.10 percent impairs driver control behavior significantly and consistently as evidenced in a wide range of measurements. These effects lead directly to degraded traffic safety as measured in terms of accidents and speeding violations.
- The alcohol impaired driver control behavior consists of reduced control gains (with the possible interpretation of increased indifference thresholds) and increased remnant or noise (i.e., steering actions uncorrelated with task demands).
- In terms of driver/system performance, alcohol impairment amounts to reduced response speed and accuracy which is also consistent with results obtained on a secondary sign detection and recognition task.
- Marihuana doses of 50 and 100  $\mu\text{g } \Delta^9 \text{THC/kg}$  body weight do not lead to consistent impairment of driver control processes.
- The effects of combined alcohol and marihuana are not as consistent between subjects as are the effects of alcohol or marihuana considered separately.

#### B. RECOMMENDATIONS

- Marihuana effects were inconsistent at the dosage levels employed here. The combined alcohol and marihuana conditions employed did not lead to any adverse or unexpected reactions from subjects, and higher marihuana dosages should be considered in a Phase II simulator experiment.

- The major driver/vehicle control performance effects observed in this experiment were reduced response speed and accuracy as discussed above. Countermeasures should address these impairments. Road and vehicle designs should minimize requirements for driver response speed and accuracy. The trend toward smaller, more agile cars should help in this regard. Also through driver education and public information motorists should be made aware of the inevitable reduction in their vehicle control capabilities with alcohol impairment in order to discourage drinking and driving.

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## APPENDIX

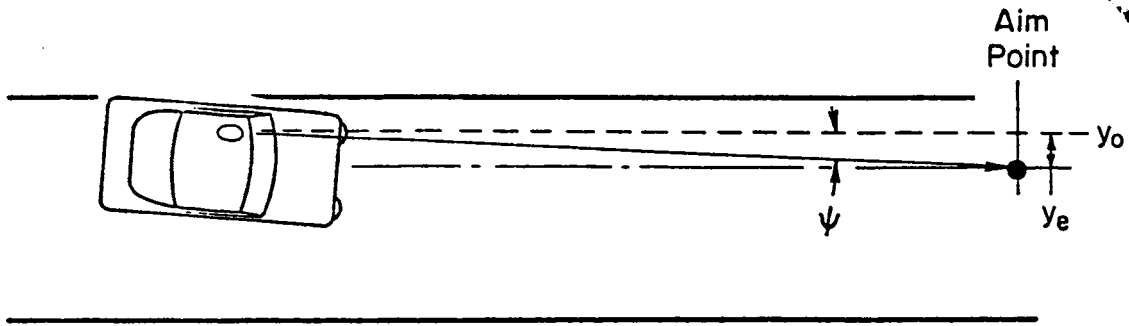
### DRIVER CONTROL MODEL AND MEASUREMENTS

A control feedback model of driver steering behavior is shown in the main text in Fig. 5. This model relates primarily to the "control level" of driver steering performance. The Fig. 5 model was actually developed for an FHWA delineation research program (Ref. 47a) and has more recently been shown to agree with field test data (Ref. 52). This model can give some insight into the effect of alcohol on driver control behavior that is required for maintaining lane position as discussed below.

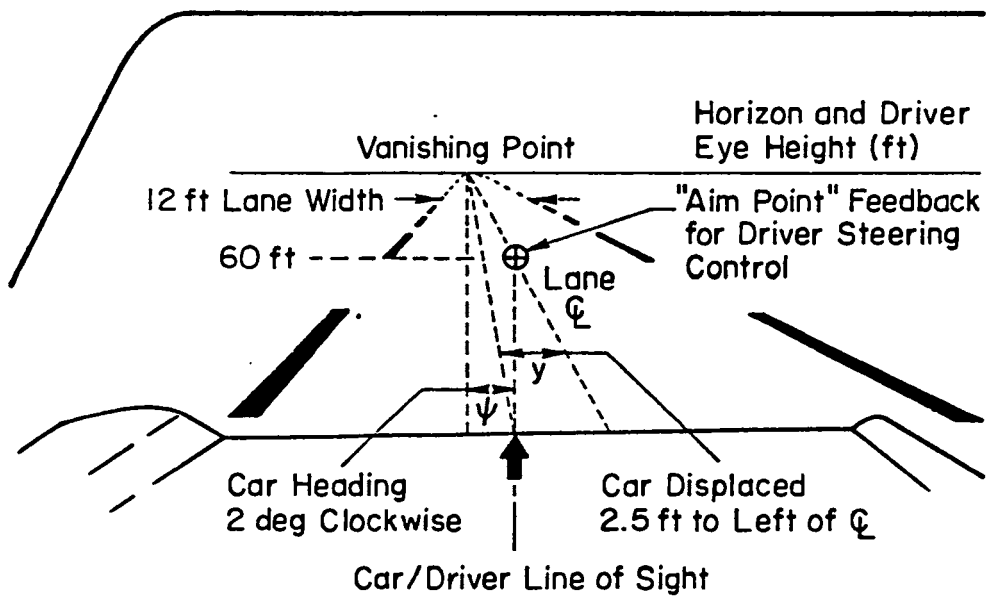
In the Fig. 5 model the driver bases his steering action ( $\delta_{sw}$ ) on his perception of lateral lane position ( $y$ ), heading error ( $\psi_e$ ) relative to the road alignment, and commanded curvature,  $C_c$ . Also, the model judges lane position error ( $y_e$ ) from a nominal desired lane position  $y_o$ . Adequate perception of lane position, heading and road curvature are important, and past delineation research (Ref. 47a) has shown that steering performance deteriorates when delineation visibility recedes much below 100 feet.

A further perceptual interpretation of the Fig. 5 model is illustrated in Fig. A-1. Here we show the driver controlling to an aimpoint down the road. The aimpoint concept requires the driver to perceive only a single quantity, aimpoint error ( $\psi_L$ ), which replaces the separate perceptions of lane position and heading errors. The "aimpoint control" concept thus allows perceptual economy for the driver. A review of past driver control studies has shown measured equivalent aimpoint look-ahead distances within the range of 60-120 feet (Refs. 47a, 53, 54). This range is consistent with past driver eye movement research that shows the driver looks down the road 100 feet or more (Ref. 54) and is also consistent with the delineation visibility work mentioned above that shown deteriorated steering performance for visibility ranges much below 100 feet (Ref. 47a).

Using the steering disturbance signal shown in Fig. 5 as a system stimulus ( $\delta_d$ ), the driver's compensatory control behavior can be measured by describing function techniques described in Ref. 46. The describing



a) Plan View



b) Perspective View

Figure A-1. Aimpoint Control Law with Car Orientation  
Such That  $\psi_L = 0$

function can be fit with model parameters as discussed in Ref: 52. In the time domain these model parameters describe driver control actions as a delayed sum of two components:

$$\delta_w(t) = [y_e(t - \tau)K_y + \psi_e(t - \tau)]K_\psi$$

where

$$\delta_w(t) = \text{driver's wheel response}$$

$y_e(t - \tau); \psi_e(t - \tau)$  = time delayed lane position error and heading angle error respectively

$\tau$  = driver's visual motor time delay

$K_y$  = driver gain or control weighting applied to lane position errors

$K_\psi$  = driver gain or control weighting applied to angular errors with respect to an aim point ahead of the car

The gain  $K_y$  can actually be interpreted perceptually as the reciprocal of the distance to the effective control aimpoint as discussed above (Ref. 47a). Thus  $K_y^{-1}$  is the distance to the aimpoint as illustrated in Fig. A-1, and  $K_\psi$  is the gain or control weighting the driver applies to these aimpoint errors.

Normally, increasing  $K_y$  and  $K_\psi$  would imply better driver tracking performance. There is a limit to this effect, however, as the closed loop stability limit of the control system is approached. The system can then become quite oscillatory, with performance deterioration and potential loss of control.

A final control parameter that is of use in describing driver steering behavior is the percentage of remnant or noise in the driver's steering actions. Remnant is defined as the proportion of steering action that is



linearly uncorrelated with the original system disturbance (in this case  $\delta_d$ ). Then by definition the remnant does not act to reduce the effect of the disturbance on system error performance, and in fact adds to the magnitude of system error. Impairments to driver behavior such as intoxication and reduced visibility have been shown to increase driver steering remnant in past studies (Refs. 45 and 47a respectively).



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