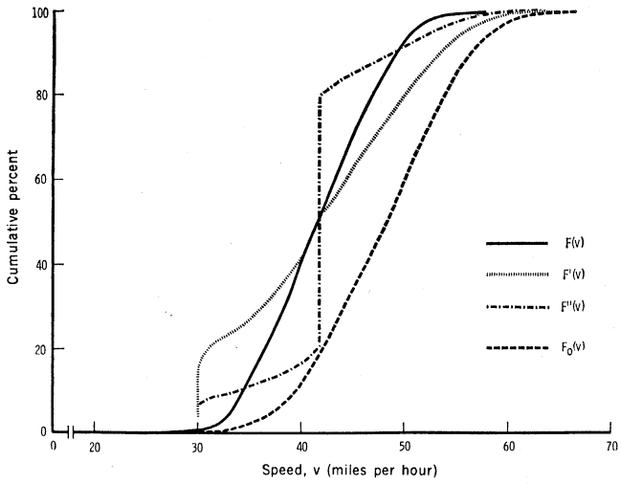

Fig. 1. The two theoretically determined cumulative speed distributions, $F'(v)$ and $F''(v)$, for the concentration of 88.4 vehicles per mile are shown in conjunction with the observed speed distribution, $F(v)$, from the SDC data (*4*) at the same concentration. Also shown is the cumulative desired speed distribution, $F_0(v)$, employed in the theoretical calculations.

bridge than over the more extended length of a freeway.

Let us now discuss some of the overall features of the speed distribution function. As we mentioned before (*3*) the comparison between theory and experiment has to be made on the basis of some integral form, since Eq. 2 involves a Dirac delta function, which is only meaningful in conjunction with integration. We shall therefore consider here the cumulative distribution function.

A specific example corresponding to the SDC data at the concentration of 88.4 vehicles per mile is considered, as the effects we wish to discuss are less marked in the more dilute traffic. In Fig. 1 we have plotted the observed cumulative speed distribution, $F(v)$, as well as two calculated distributions $F'(v)$ and $F''(v)$, for the same concentration. The cumulative distribution of the desired speeds, $F_0(v)$, employed for the calculations is also shown. The distribution $F_0(v)$ was determined from observations at a lower concentration. The parameter γ was estimated by method 1 (see Table 1). In the case of $F'(v)$, λ is assumed to be zero. For $F''(v)$ we use $\lambda = 7.04$, which was estimated from Δ and the second moment (see Table 1). As can be seen in Fig. 1, if we neglect the adjustment term by setting $\lambda = 0$ as in the case of $F'(v)$, the distribution would start too rapidly as compared to $F(v)$ and then approach unity at a higher speed than does $F(v)$. In other words, by ignoring the adjustment term the theory predicts too many cars at the very high and the very low speeds. If we take $\lambda = 7.04$ we overestimate the cooperative character of the drivers. The distribution $F''(v)$ thus shows too many cars in the neighborhood of the mean speed. The fact that the observed distribution lies between the two predictions indicates the essential role of the adjustment process, which is in agreement with our general approach with regard to the importance of drivers adapting to changes in traffic conditions.

Because of the importance of driver adaptation, it is worthwhile to model the adjustment terms more precisely. The delta function type of adjustment in Eq. 1 is only an approximation. As various groups of drivers adjust primarily to their own local conditions and local average speeds, the distribution must have a finite spread. In accordance with this result, we see in Fig. 1 that the large deviations between $F(v)$ and $F''(v)$ around $v = \bar{v}$ take place in an interval of the order of $[(v - \bar{v})^2]^{1/2}$. The quantitative formulation of this idea requires replacing the delta function in Eq. 1 with a function having a spread of the correct order of magnitude.

In order to avoid misinterpretation, we emphasize that a theory which includes effects as complex as human adaptive behavior cannot be deduced from a priori arguments. The goal of the theory is first to describe general characteristics, and then, if possible, to compare the relative importance of the various factors and processes in order to establish a rational approach to problems such as highway design and traffic control.

It is also hoped that the relative success of the one-dimensional multilane traffic problem may stimulate the development of similar mathematical models in other disciplines where adaptive behavior is also present. In all such cases the adaptive strategy is intimately related to a self-imposed program of objectives whose realization must in turn depend on the strategy.

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Cannabis and Alcohol: Effects on Simulated Car Driving

Abstract. *The effects of cannabis and alcohol on simulated car driving were studied. Cannabis resin containing 4 percent Δ^1-tetrahydrocannabinol was administered orally in three doses equivalent to 8, 12, and 16 milligrams of that component. Alcohol was given orally in one standard dose of 70 grams. Both cannabis and alcohol increased the time required to brake and start, whereas alcohol increased while cannabis decreased the number of gear changes. An effect of dosage on response was observed with cannabis.*

Cannabis metabolites have been detected in urine after oral administration of cannabis to volunteers (*1*). The research reported here is part of a program designed to combine metabolic and psychological studies of the acute effects of cannabis on man. We have used a different type of car simulator than was used in an earlier study (*2*), and oral administration of cannabis preparations with known, adequate tetrahydrocannabinol (THC) contents. The research design included placebos, a double-blind procedure, tests for re-

producibility and dose response, and training effects; the subjects acted as their own controls. The effect of a standard dose of alcohol was also studied.

The subjects, eight volunteers from the Danish Civil Defense Corps, were healthy men, 21 to 29 years old. Three were college graduates and five were skilled workers. None were, by our definition, alcohol or cannabis abusers (that is, no one had a daily alcohol consumption exceeding four drinks; three had never tried cannabis, and five had used cannabis from 1 to 15 times, but not more than once a week).

The car simulator was a modification of an instrument (Redifon Auto-Tutor) used in driving schools. The driver had access to the steering wheel, accelerator, brake, clutch, and ordinary controls. Red and green lamps were placed directly above the windscreen. The duration of the red light signal was 10 seconds, and it was always followed by the green light signal. Gear changes were recorded electronically. A rotating cyclorama was placed above the hood. A landscape was painted on the cyclorama, and during driving the landscape was continuously projected on the windscreen. The speed of the movable landscape, and thus the apparent speed of the car, was determined by the driver's activation of the accelerator. Turning of the steering wheel resulted in a corresponding movement of the landscape on the windscreen and the supposed position of the car on the road. The car simulator was placed in a room 20 m^2 in area, with no other equipment than the simulator and the control panels. Verbal contact between the subjects and the experimenters was formal during the whole investigation.

The cannabis resin, in amounts of 200, 300, or 400 mg, was baked into small brown cakes. The analyses for cannabinoids in the cakes are shown in Table 1; determinations in different laboratories agreed on values near 4 percent Δ^1-tetrahydrocannabinol (Δ^1-THC), so that each cake contained 8, 12, or 16 mg of Δ^1-THC. The placebo was cannabis resin with a negligible amount of Δ^1-THC. Neither naive nor experienced cannabis users were able to differentiate by taste between placebo cakes and active cakes. The oral route ensured a certain standardization of dosage. None of the subjects vomited after ingestion.

Drinks with alcohol were prepared by mixing 70 g of ethanol (pure, 96 percent by volume) with fruit juice to a final volume of 500 ml. Fruit juice without alcohol was used as the placebo. It was often correctly guessed in a pretrial period whether the mixture contained ethanol or not. The dose of 70 g of ethanol was chosen so that, 1 hour after alcohol consumption, young males weighing 70 to 85 kg would have blood alcohol levels around 1 g/liter. At that point, the alcohol content in blood samples was found to range from 0.67 to 1.29 g/liter, with an average of 0.95 g/liter.

Table 1. Cannabinoids in cannabis cakes. The analyses were done by thin-layer chromatography (TLC) or gas chromatography (GC); ND means none detected. All values are in milligrams per cake. The double determinations were performed on two different cakes.

Resin		Method	Cannabinoids			
Active cake	Placebo cake		Δ^1-THC	Δ^6-THC	Cannabinol	Cannabidiol
300		TLC*	12.4, 13.3			
300		GC*	13.0			
300		GC†	12.6, 12.0			
200		GC†	8.2, 8.2	ND, ND	2.6, 2.6	13.5, 13.8
300		GC†	12.6, 12.0	ND, ND	4.3, 4.1	21.6, 20.6
400		GC†	16.4, 17.1	ND, ND	6.0, 6.5	29.3, 30.7
	300	TLC*	1.0			
	300	GC†	< 2.5, < 2.5	ND, ND	5.1, 5.6	12.8, 12.0

* Analyzed in Denmark. † Analyzed in the United States.

All the subjects were experienced drivers, but in order to minimize learning effects they were trained in the car simulator once a week during 3 weeks (for a total of ten drives) before the main research period started.

On each investigation day two subjects arrived at the hospital at 4 p.m. In the pretest period the subjects were given a battery of psychological tests (*3*); ate a small cake containing cannabis, with or without THC; simulated car driving; and, finally, were given a drink of 500 ml of fruit juice, with or without alcohol. A blood sample was drawn 150 minutes after "zero time" (about 105 minutes after cannabis intake or 75 minutes after alcohol intake), and this was immediately followed by the drug-test period.

In the drug-test period the subjects took a parallel battery of psychological tests. The degree of intoxication was estimated by the subjects and the experimenter, separately. The subjects then simulated car driving, after which they had supper and spent the night in the hospital.

In the posttest period, the next morning (16 hours from zero time), the procedure was repeated; this included the parallel battery of psychological tests, a repetition of simulated car driving, and an interview on the psychological effects of the drug (or placebo).

The simulated driving lasted 10 minutes. The subject was instructed to drive as usual, following the ordinary traffic rules. Behavioral measurements included brake time, start time, number of gear changes, and mean speed. Brake time was defined as the time interval (in 0.1-second units) from when the experimenter switched on the red light until the subject activated the brake pedal. Start time was defined as the time interval (in 0.1-second units) from when the green light appeared until the subject activated the accelerator. The red signals appeared at random time intervals. During the driving the subject was presented with ten red and ten green lights, and the brake time and start time values for each subject were the means of the ten respective observations. The number of gear changes was the total number recorded electronically during the driving period. The mean speed was calculated from the distance (in 10-m units) covered during the 10-minute drive.

Phenomenological measurements included estimation of time and distance (*4*). The subject's pulse rate (beats per minute) was checked at 0, 1, 2, 3, 4, and 16 hours from zero time.

The general research period covered 9 weeks and was subdivided into three 3-week periods or parts. Parts I and II each included a 300-mg cannabis day, a 70-g alcohol day, and a placebo day. Part III included three cannabis days of 200, 300, and 400 mg. The subjects rotated in randomized order and each completed nine research days with weekly intervals. The dosage plan for one of the subjects was:

Part I: 1) placebo day (placebo cake and placebo drink); 2) cannabis day (300-mg cannabis cake and placebo drink); 3) alcohol day (placebo cake and 70-g alcohol drink).

Part II: 4) alcohol day (placebo

Table 2. Average brake time for eight subjects during 10 minutes of simulated driving. Each driving period included ten red light signals. The drug-test and posttest changes are the percentage differences from the pretest values.

Treatment	Pretest (sec)	Drug-test change (%)	Posttest change (%)
	Parts I and II		
Placebo	0.84	− 2	2
Cannabis (300 mg)	.81	23	1
Alcohol (70 g)	.81	44*	−
	Part III		
Cannabis			
200 mg	.76	5	9
300 mg†	.76	16*	5
400 mg	.76	66*	7

* $P < .05$. † Values for seven subjects.

cake and 70-g alcohol drink); 5) cannabis day (300-mg cannabis cake and placebo drink); 6) placebo day (placebo cake and placebo drink).

Part III: 7) cannabis day (400-mg cannabis cake and placebo drink); 8) cannabis day (200-mg cannabis cake and placebo drink); 9) cannabis day (300-mg cannabis cake and placebo drink).

Nonparametric statistics in form of Wilcoxon's matched pairs signed ranks test (*5*) was used throughout the study. To counterbalance the effects of practice and variations from day to day and test to test, each subject was his own control, both on each research day and in between-days calculations. The results from parts I and II were pooled in the final analysis, as training effects were found to be minimal compared to drug-induced changes.

Both cannabis and alcohol increased brake time and start time. Table 2 shows the effect of increasing the cannabis dosage on brake time. As shown in Table 2, 70 g of alcohol is intermediate in effect between 300 and 400 mg of cannabis resin, or 12 and 16 mg of THC. The effect of both cannabis and alcohol on start time was somewhat less marked (see Table 3), and only the increase after 400 mg of cannabis resin was statistically significant. However, the pattern and the relative effects of cannabis and alcohol were similar to those observed for brake time. The pretest values for brake time and start time tended to improve as the examination progressed, indicating a moderate but continued learning effect. Tables 2 and 3 also show that the effects of both cannabis and alcohol had disappeared at the posttest the following morning.

It should be noted that the results in Table 2 for 300 mg of cannabis in Part III of the research period are for seven instead of the usual eight subjects. The reason is that on this dose one of the subjects "passed" eight out of ten red lights without activating the brake pedal, let alone making a full stop.

The total number of gear changes increased by 10 percent for subjects on alcohol, and this increase was statistically significant. On cannabis the number of gear changes tended to decrease with increasing dose, without reaching statistical significance.

Pulse rates were influenced by both cannabis and alcohol (Table 4). A dosage effect was observed for cannabis, the higher doses causing higher pulse rates for a longer duration. At posttest the following morning, the effects of both cannabis and alcohol had disappeared.

Driving a car simulator is only an approximation to real driving; on the other hand, it seems to be more complex and realistic than most of the usual laboratory situations, which have little or no appeal to fantasy and emotions. The findings of Crancer *et al.* (*2*) indicate that there is a better correlation between simulated car driving and actual driving performance than between the latter and an on-the-road driving test. The type of simulator may be quite important—for example, whether it calls for driver initiative or whether it reduces the subject to a robot, who has only to react to the stimuli of a fixed program.

Smoking is the most common way of consuming cannabis, and it would seem that this route of administration would be more realistic. However, when smoking is used there is no certainty about the quantity of the active substances absorbed by the subjects.

We assume on the basis of present knowledge that the Δ^1-THC content is an appropriate measure for active substances. It remains to be shown whether Δ^1-THC is the only or major active substance or the precursor of such a substance. The oral route of administration was chosen because it was considered more reliable and reproducible and reduced variations in dosage in and between subjects. The slower onset of psychic effects and more prolonged action were advantageous for the double-blind method and because they gave stability of intoxication during the long test procedures.

Table 3. Average start time for eight subjects during 10 minutes of simulated driving. Each driving period included ten green light signals. The drug-test and posttest changes are the percentage differences from the pretest values.

Treatment	Pretest (sec)	Drug-test change (%)	Posttest change (%)
	Parts I and II		
Placebo	1.18	1	3
Cannabis (300 mg)	1.12	16	− 1
Alcohol (70 g)	1.06	[illegible]	17
	Part III		
Cannabis			
200 mg	0.91	- 9	− 8
300 mg†	[illegible]	6	1
400 mg	.88	47*	1

* $P < .05$. † Values for seven subjects.

In a comparative study of cannabis and alcohol, it is important that the psychological peak effect of both drugs appears during the drug-test evaluation. While the effect of alcohol in the dose used peaks 1 to 2 hours after consumption, the effect of cannabis after oral administration begins within 30 to 60 minutes and culminates after 2 to 3 hours (*6*). Accordingly, our cannabis cakes were administered ½ hour before the alcohol drinks, and during that time interval the pretest driving could take place. None of our subjects reported a cannabis effect during the pretest driving. This is in accordance with the results of studies of ^{14}C-labeled Δ^1-THC in man (*7*), where plasma levels of total radioactivity were unmeasurable during the first 30 to 60 minutes after oral administration.

We have shown that both cannabis and alcohol exerted a considerable effect on simulated car driving with our experimental setup. The influence of alcohol on driving has been so overwhelmingly documented both practically and under laboratory conditions that it need not be elaborated here. In contrast, there have been few investigations of the effect of cannabis. The results obtained by Crancer *et al.* (*2*) showed a much smaller effect than we have found.

In the study by Crancer *et al.* cannabis was smoked, and the authors stated that the two cigarettes had a THC content of 22 mg. This was later challenged by other workers, who analyzed the same batch and suggested that the actual content was only 8 or even 3 mg (*8*). Some doubt may

therefore exist as to whether the subjects were still influenced by cannabis when they had their first driving test 30 to 60 minutes after they finished smoking. (In our study, the prolonged period of drug effect was checked by subject and observer ratings immediately before drug-test driving.)

The type of driving simulation was also basically different. In our model the subject controlled the speed and, to a certain extent, the route. When directions as to route and speed were imposed, it was up to the subject to observe these instructions or not. In the study by Crancer *et al.* the landscape simulation was a movie, which the subject passively followed, trying to escape some imminent dangers. With this experimental setup and with the problems of cannabis administration mentioned above, Crancer *et al.* found an increase in the speedometer error, but not in the accelerator, brake, signal, steering, and total errors. They investigated braking or not braking, but not brake time, which was among the most strongly influenced factors in our study. As mentioned by Carpenter (*9*), brake time is especially valuable for extrapolating from laboratory experiments to driving conduct in normal traffic.

The number of gear changes was not recorded by Crancer *et al.* However, Drew *et al.* (*10*) used the same type of car simulator as ours to study the effect of alcohol on driving, and they found no effect on the number of gear changes with blood alcohol concentrations up to 0.8 g/liter. Unfortunately, they did not correlate this finding with speed. With alcohol, we found that the number of gear changes significantly increased and with cannabis that it tended to decrease, while neither drug affected the actual mean speed. Gear changing may, therefore, reflect a change in spontaneous motor activity,

Table 4. Average pulse rate (beats per minute) for eight subjects.

Treatment	Time (hours)					
	0	1	2	3	4	16
	Parts I and II					
Placebo	77	72*	74	73	72	73
Cannabis (300 mg)	74	77	86*	84*	77	74
Alcohol (70 g)	76	76	81	83*	85*	78
	Part III					
Cannabis						
200 mg	72	76	85*	80*	77	74
300 mg†	72	76	86*	83*	82*	77
400 mg	73	75	92*	85*	82*	72

* $P < .05$. † Values for seven subjects.

increased by alcohol and decreased by cannabis.

The most marked physiological effect of cannabis on man is increased pulse rate, regardless of the type of preparation or route of dosage (*11*). We found a dosage effect of cannabis on pulse rate and could demonstrate that this effect was parallel to the effect of cannabis in the behavioral measurements.

The limited number of subjects in our study and the considerable individual variation made it impossible to obtain a significant correlation between the various steps in the dose response study. Training effects were also observed, in spite of the initial training period. Although the subjects were their own controls, the percentage effect of 300 mg of cannabis (about 12 mg of THC) was not the same in part I and part II compared with part III, as shown in Tables 2, 3, and 4. There was, however, no definite trend in these variations, which are of the same order as the day-to-day variations found in innumerable complex biological studies.

The similarities between the effects of cannabis and alcohol were, thus, more dominant than the differences, but in the phenomenological part of our study a different pattern was observed, with pronounced cannabis effects and very moderate alcohol effects (*4*). This discordance may explain much of the conflicting evidence from cannabis research, and it should be taken into account in the future (*12*).

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