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► **To cite this version:**

Pierre van Elslande, Jean-Yves Fournier, Magali Jaffard. Influence of Cannabis on Fatal Traffic Crash: A Detailed Analysis. *Transportation Research Record*, 2012, 2281, pp.43-50. hal-00851255

HAL Id: hal-00851255

<https://hal.science/hal-00851255v1>

Submitted on 13 Aug 2013

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Influence of Cannabis on Fatal Traffic Crash: A Detailed Analysis

Transportation Research Record 2281 (2012) 43-50

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ABSTRACT

The influence of cannabis on traffic crashes is a growing concern. Experimental studies provide ample evidences of cannabis influence on psychomotor and cognitive performances. Epidemiological works describe the excess crash risk that this substance causes. And yet, this psychotropic drug influence in causing crashes is still at the centre of many discussions. The present analysis consists in exploiting crash data in detail to obtain a more precise understanding of the failures that drivers are subject to when they have consumed cannabis, depending on the level of Tetrahydrocannabinol (THC) measured in blood samples. Two groups representative of fatal crashes occurring in France were studied: the Cannabis group (n=174) and a Control group (n=174) involving neither cannabis nor alcohol. The results of this analysis notably show that cannabis consumption significantly increases the rate of "generalized failures" by the driver, reflecting an alteration of all sensorial, motor and cognitive functions, specifically for high blood levels of THC (>5 ng/mL). At lower levels of intoxication, cannabis leads to a poor diagnosis of driving difficulties.

INTRODUCTION

After alcohol, cannabis is the most frequently encountered drug in European and North America driving populations (1). Reports by the French Monitoring Centre for Drugs and Drug Addiction (OFDT) indicate that there are nearly 1.2 million regular cannabis users in France and traces of Tetrahydrocannabinol (THC) are found in 7% of drivers involved in fatal traffic crashes occurring on the French territory, up to 17% for those under 25 years old (2). As a matter of fact, this drug is mainly consumed by young people and its use increases significantly from the age of 14 (3). In France, this age is also the age of access to the first modes of motorized transportation (moped). The cannabis problem on the road is therefore a current issue that mainly concerns young people and which is progressively catching up, and may sometimes exceed, the risks related to driving under the influence of alcohol for this population (1). However, the role of cannabis on drivers' performances and risk is far from being clearly established, and existing data are often contradictory (4). Thus, the question is still open as to the real effects and consequences of cannabis behind the wheel, and notably its role in crash situations.

From a clinical point of view, delta-9 Tetrahydrocannabinol (Δ^9 THC), the active psychotropic substance in cannabis, causes moderate euphoria and a feeling of wellbeing, followed by a period of reduced vigilance, i.e. a decrease in the level of alertness. Depending on the dose ingested, the user's sensitivity and his consumption habits, disorders can be observed in psychomotor and cognitive performances: longer reaction time, changes in sensory perceptions and time perception disorders, disturbance of motor control, troubles of working memory and short-term memory, disturbance of divided attention and selective attention (5, 6, 7, 8). These reduced performances can be explained by a disturbance in brain functions, notably in the frontal and prefrontal regions, the hippocampus and the basal ganglia. All these neural structures are in charge of high-level cognitive functions and motor coordination (9). These neurological effects of cannabis are not insignificant when we consider the importance of psychomotor and cognitive functions in the driving task. Recent studies carried out on driving simulators have shown that the consumption of cannabis reduces the ability to maintain stable driving by measuring lateral deviations in the position in the lane and headway variability (10,11). And although many articles report that cannabis consumers adopt behaviors to compensate for their deficiency and reduce the effects of cannabis by driving more slowly and cautiously (11, 12, 13,14), most recent epidemiological studies appear to agree on the fact that cannabis consumption significantly increases the risk not only of being involved in an crash, but also of being responsible for one (15,16).

CRASH RISK LINKED TO CANNABIS: FROM EVALUATION TO QUALIFICATION

We will base the present paper on an important study conducted in France in order to analyze the role of cannabis and alcohol in fatal crashes: the SAM study (16). The database used for this study covered all the fatal crashes between 2001 and 2003, with systematic blood tests for drugs and alcohol, which corresponds to an overall sample of 16,705 people. The SAM study was mainly statistical, dealing with the estimation of the fatal crash risk induced by the consumption of cannabis. A second aspect, which will be developed here, concerns the precise qualification of this excess risk from the viewpoint of the driving functions altered (the "functional failures"), the different factors associated with cannabis which contribute to this alteration and the crash configurations in which they occur.

The statistical analysis of the whole SAM database showed that, all doses combined, there is an excess risk of 1.8 of being responsible for a fatal crash after consuming cannabis (16). It is also demonstrated a dose effect of cannabis in this responsibility, by showing an excess risk of 1.5 for THC blood level less than 1 ng/mL, whereas it reaches 2.12 for a THC level exceeding 5 ng/mL. This epidemiological approach allows interesting results regarding the estimated risk of being involved in a crash as a function of being intoxicated in cannabis. However, it does not allow to give an accurate view of the psychomotor and cognitive functions that are more specifically affected in drivers using cannabis under the wheel, the types of failure that affect these functions depending on the level of cannabis observed, nor of the precise circumstances characterizing crashes involving cannabis. This is the purpose of the present study.

Such aspects will be apprehended by applying a Human Factors approach to the same crash data. The aim of the present detailed crash analysis is to determine the effects of cannabis on driving failures through a comprehensive case-by-case examination of the different crash configurations encountered by drivers intoxicated with THC. This analysis was elaborated so as to:

- Isolate the effects of cannabis by considering only those drivers who did not consume any other substance (Ca Group);
- Compare this group to a matched group of drivers (same age and same sex) whose blood tests were negative for drugs (Control Group).

In brief, the purpose of the present paper consists of a detailed exploitation of crash data to gain a more precise understanding of the crashes involving drivers who had consumed cannabis, taking into account the THC levels measured in the blood tests. Such an analysis is complementary to the statistical analysis showing the level of risk induced by cannabis. The descriptive elements for various crash situations will be used to better understand the specificities of the driving difficulties encountered by drivers depending on the degree of intoxication.

HUMAN FACTORS IN CRASH RECONSTRUCTION

Detailed analysis of crashes can be viewed as a necessary complement to quantitative studies based on macroscopic national data. In this purpose, IFSTTAR Accident Mechanisms Research Unit has put forward, since 1980, in-depth research works which have led to operational models of crash cinematic reconstruction (17) and of human factors analysis in the process of crash production (18). These two models contribute together to understanding crash genesis. The reconstruction model is devoted to the sequential and material aspects involved; it allows determining the different phases characterizing each crash. The "human functional failure" (HFF) model becomes useful when considering the behavioral and cognitive aspects involved; it allows putting forward human errors and the different factors of these errors.

Human Functional Failures

The HFF model has been elaborate through a cross-referenced use of many studies of crash cases looking at the data in the literature in order to elaborate an operational grid for classifying human errors

and deficiencies that are found in deteriorated driving situations (19). This classification model has been used in different crash studies and has notably been validated in the frame of the European TRACE (Traffic Accident Causation in Europe) project (20).)

The model distinguishes five major functional categories within which can be identified the incapacity of a function (perceptive, diagnostic, prognostic, decision, motor) to overcome a difficulty encountered by the driver. A sixth heading deals more with a problem of general aptitude to drive than the specific capacity to handle a difficulty: these "generalized failures" correspond to an alteration to the entire functional chain (i.e. on the perceptive, cognitive and psychomotor levels) making the driver unable to manage the slightest difficulty encountered on his route (e.g. falling asleep). See Table 1. These different categories of failures are delineated in 20 types, which are further detailed in Table 2.

1- Perceptive failures (Per1 to Per5) cover problems of detecting and identifying certain parameters essential to the situation, depending on the reasons (see Table 2).

2- Diagnostic failures (Diag1 to Diag4) describe information processing problems which keep the driver from evaluating the physical parameters identified during the previous step in order to estimate the feasibility of the planned maneuver and from understanding the information gathered concerning the type of situation he is confronted with in his interaction with environment and traffic.

3- Prognostic failures (Pro1 to Pro3) correspond to another information processing step, characteristic of all activities with a dynamic component: applying expectations as to the potential development of a situation.

4- Decision failures (Dec1 to Dec3) correspond to an ill-suited "choice" of a maneuver by the driver from among the driving strategies he could have adopted in the situation, notably from the point of view of his safety demands.

5- Failures in the psychomotor step of Executing the action (Exe1 to Exe2) deal with weaknesses in the last link in the functional chain involved in the driving activity: action on the vehicle's controls to guide it along the trajectory followed.

6- Generalized failures (Gen1 to Gen3) are distinguished from the previous in that they deal with an alteration, not of one function, but of a large part of, up to the entire functional chain described. The problem thus is situated at the upper level of the individual's general ability to control the situations, both in terms of the information to be gathered, the processing operations to be applied, the decisions to be taken or the actions to be undertaken.

Factors of Human Functional Failures

Another point to mention is the fact that a human functional failure is only a sharp end cause which has its own causes, cannabis intoxication being one of them, most often in association with others. For this reason, once a HFF is identified in a crash process, the analysis is completed by searching for the factors of such a failure, whatever their sources: human, environmental or vehicular. Functional failures and factors of failures thus constitute two levels of parameters which must be stressed distinctly to fully understand the ins and outs of the crash process.

Different sets of overlapping factors are involved the occurrence of every driving functional failure. These factors of failures correspond to the main parameters characterizing the driving context in which the driver met a difficulty. They are relative to the road (e.g. visibility, difficulty of a bend), to the vehicle (e.g. tire pressure, light), to the driver himself (e.g. experience, vigilance), to the conditions under which the task is performed (e.g. speed, time constraint) and to the other road users involved (e.g. atypical maneuver, no signaling). By combining one with another, these factors contribute to the emergence of such or such driver's functional failure when faced with a demanding road situation. In the following study, up to 5 factors are identified for each failure. Once again, as part of the HFF model, the classification grids of these factors have been elaborated on the base of repeated crashes studies, and their full description can be found on the TRACE project website (20). The most important factors of failures acting in the frame of this study are presented in Table 3.

METHOD

This study is based on a clinical analysis of crash procedures (police reports) involving an attentive reading of the entire file explaining each crash studied to identify variables that are relevant for research.

Population Studied

Two groups of drivers were established: the cannabis group which constitutes the hard core of the present study and the control group which will serve as a comparison to better estimate the influence of cannabis in crash production. The samples were drawn using a random selection from the SAM database, reminding this database covers the 16,705 people involved in a fatal crash in France between 2001 and 2003. This period was chosen because, as part of the French Gayssot law, blood test for narcotics and alcohol were systematically performed on each person involved in a fatal traffic crash between 2001 and 2003 in France.

The "cannabis"(C) group is made up of 174 drivers involved in crashes with THC identified in the blood, to the exclusion of all other psychotropic substances and for whom the functional failure was possible to diagnose. Let us mention that THC levels in the drivers are distributed in a rather unbalanced way for the high values, so that it is more relevant to study the medians than their averages of the levels. Some very high levels of THC (sometimes greater than 150 ng/mL of blood) affect the averages upward, making them poorly representative of the real consumption by all the drivers in the sample. Out of a concern for homogeneity, we will therefore use this median indicator for cannabis in the following analysis.

This group of drivers involved in crashes under the influence of cannabis presents some specific demographic characteristics. This result is not surprising considering national data on cannabis use, as mentioned above: it is mainly young people (less 30 years) who use cannabis and boys are very much cannabis over users (1). The average age of our Cannabis group is 25 years, there are 92.5% men and 55.7% of this population are young men under 25 years. These features can have a significant impact on the crash features. To highlight only the effects of cannabis on the functional failures and not the effects that could be explained by age or gender of drivers, we formed a Control group of drivers matching the Cannabis group. This Control group was formed using the method of "individual matching", which is to select, for each case included (i.e. for each driver involved in a crash with cannabis) a "control case" with the same characteristics without cannabis. Thus, we finally obtain "case" and "control" groups strictly comparable, by construction, with regard to the confounding factors age and gender. The Control group is composed of 174 drivers involved in crashes without drugs or alcohol in their blood test.

Data Processing

The case-by-case analysis has been performed by three cognitive psychologists, expert in crash analysis and familiarized with the classification method, members of the IFSTTAR Accident Mechanisms research team, with the help of two technicians of the same team for the reconstruction parameters to consider. Crash files for which information was not sufficient enough to diagnose the human failure were rejected. Note that the data on cannabis were hidden in the files so that they could not influence the diagnostic.

In order to check the reproducibility of the inter-expert coding method used in this study, 100 crash reports were coded in parallel by two teams of coders. An analysis of the reliability rate was performed. The proportion of inter-expert agreement was measured for the categories and types of failures identified for each driver studied, and also for the factors of these failures. A Cohen's Kappa coefficient was measured for each observed proportion of agreement. We used the scale proposed by Landis and Koch (21) to test the validity of our results. Thus, for the types and categories of failures was measured a rate of agreement above 80% which corresponds to a Kappa coefficient between 0.73 and

0.86. Following the scale of Landis and Koch, the agreement can be considered "good" up to "excellent" for these variables. Regarding the factors of failures identified (from 1 to five items, depending on the case), there is an agreement rate of 94% for the first item and 70.5% for the second one with Kappa values of 0.94 and 0.67 corresponding to the agreements considered "excellent" and "good". However, the agreement tends to decrease for the following explanatory elements, which can be explained by the fact that they correspond to more secondary factors that are whether considered, depending on the coder, useful or not to explain the failure.

RESULTS OF EFFECTS OF CANNABIS ON CRASH PRODUCTION

The following results are presenting the crash characteristics of the Cannabis group compared to the matched control group.

Categories of Failure

Table 1 presents the distribution of drivers' categories of failures. Despite a certain degree of overall similarity in the distribution, the functional failure distributions for drivers in the Cannabis group (Ca group) and the Control group are significantly different. It can notably be seen that a "generalized failures" resulting from a deterioration of all driving capacities are found in 27% of the crashes involving a driver positive for THC, i.e. four times as often as for the Control group (7.5%) ($\chi^2=22.7$; $P<.01$). Conversely, in the control group, the class of failures most frequently observed in fatal traffic crashes is to be "prognosis" failure. This category of failure is significantly more represented in the control group than in group Ca (27.6% vs 11.5%, $\chi^2=12.2$, $P<.01$). The other failures categories don't stand out significantly different between the two groups, even if one can notice an increase of 6.4% in the number of "diagnosis" failures in group Ca (16.7% vs. 10.3% in the control group) and a slight decrease for the failures of perception, decision-making and implementation (see Table 1).

TABLE 1 Distribution in Percentage of Failure Categories for Cannabis and Control groups

Failures Category	Groups (%)	
	Cannabis	Control
Perception	21.8	23.6
Diagnosis	16.7	10.3
Prognosis	11.5	27.6**
Decision	8.6	11.5
Execution	14.4	19.5
Generalized	27.0**	7.5
Total (%)	100	100
Total (n)	174	174

* $p<.05$ - ** $p<.01$

Specific Types of Failures

For the two populations studied, Table 2 gives details of the distribution of the types of failures grouped into categories in the previous table. In addition to the results on functional failures, Figure 1 presents the median levels of psychotropic drugs measured, as well as the quartile deviations of these levels. In this figure, the levels are represented for the failures found in more than 5% of the cases in Ca group. Failures that are less represented are grouped under the heading "other failures" to make up a sufficiently large sample to analyze the median value. This graph enables to determine the "dose effect" of THC on the related functional failures.

Generalized alteration of sensorimotor and cognitive capacities (Gen2 failure) is the most common failure among Ca drivers. It accounts for 18.4% of the drivers involved in fatal crashes who were under the influence of THC ($\chi^2=30.0$; $p<0.01$). This type of failure is characteristic of users whose driving skills were proved to be totally overwhelmed when they encountered the slightest difficulty on their route (e.g. a slight curve), to such a degree that they lose the simple control of their vehicle. We can observe that drivers affected by a Gen2 failure have a median level of THC of 16.1ng/mL vs. a median level of 2.5 ng/mL for drivers positive for THC who commit other types of failures. Furthermore, 75% of drivers with cannabis presenting a Gen2 failure have measured levels of THC greater than 5.3 ng/mL (and 25% greater than 52.6 ng/mL). Concerning other failures, high levels of cannabis can also be observed, but above 5ng/mL, we usually observe Gen2-type generalized failures (42.4% of the drivers with a THC level greater than or equal to 5ng/mL have Gen2 failures; and 78% of drivers in this group with a failure Gen2, have a THC rate higher than 5ng/mL. In brief, the difference between the levels within this group of drivers who are positive for THC show a threshold effect for the dose of cannabis consumed which moves on from a "conventional" type of functional failure (involving only an alteration of one specific function) to an extreme failure leading to a breakdown of all the functions required for driving. The resulting breakdown of capacities will almost systematically lead to a loss of control of the vehicle being driven, showing the radical incompatibility of high levels of THC (notably above 5 ng/mL) with driving activity.

The second failure which makes the Ca group stand out the most, and most significantly from the Control group, is the "Poor evaluation of a temporary difficulty related to the road infrastructure" (Diag1 failure). This diagnostic error, which notably explains problems in evaluating the difficulty of a bend, is characteristic of 13.2% of the drivers testing positive for THC vs. 5.7% of the Control drivers ($\chi^2=5.0$; $p<0.05$). It appears that drivers under the influence of THC involved in fatal crashes have specific difficulties in assessing the problem posed by the sharpness of a bend upon approach (whether it presents particular difficulties in negotiating it or its curve differs in intensity from other bends in the same series driven) and are thus more easily taken by surprise when negotiating it. These results from crash analysis thus show a sensitivity among cannabis consumers toward failures of this type, even for relatively low doses of THC (a median of 2.6 ng/mL; 75% of drivers had a level of THC lower than 5.4 ng/mL) (see Figure 1).

TABLE 2 Distribution in Percentage of Types of Failures for Cannabis and Control Groups

<i>Failures Categories</i>	<i>Types of Failures</i>	<i>Groups</i>	
		Ca	Control
Perception	Per1: Non-detection in a situation of limited visibility	10.3	8.6
	Per2: Information acquisition focused on a partial component of the situation	1.1	3.4
	Per3: Cursory or hurried information acquisition	4.0	3.4
	Per4: Momentary interruption in information acquisition activity	1.7	1.1
	Per5: Neglect of information-seeking requirements	4.6	6.9
Diagnosis	Diag1: Poor evaluation of a temporary difficulty	13.2*	5.7
	Diag2: Erroneous evaluation of the size of a gap	2.3	1.1
	Diag3: Mistaken understanding of how a site functions	0.6	0.0
	Diag4: Mistaken understanding of another user's maneuver	0.6	2.9
Prognosis	Pro1: Expectation by default of no maneuver by another user	2.9	5.7
	Pro2: Active expectation of adjustment by another user	1.7	11.5**
	Pro3: Expectation of no obstacle	6.9	10.9
Decision	Dec1: Violation directed by the characteristics of the situation	0.6	1.1
	Dec2: Deliberate violation of safety rule	6.3	9.8
	Dec3: Violation by automatism	1.7	0.6
Execution	Exe1: Poor controllability when faced with an external disturbance	9.2	13.2
	Exe2: Guidance problem	5.2	6.3
Generalized	Gen1: Total loss of psychophysiological capacities	7.5	6.9
	Gen2: Alteration of all sensorimotor and cognitive capacities	18.4**	0.0
	Gen3: Overstretching cognitive capacities	1.1	0.6
Total (%)		100.0	100.0
Total (n)		174	174

* p<.05 - ** p<.01

Factors of Failures Co-Occurring with Cannabis

As mentioned earlier, functional failures are explained by different patterns of factors, which are developed in the present section. The element “cannabis” is not included in these results insofar as this variable is characteristics of the sample by its very construction. It is of course nonetheless an element that massively contributes to the failures produced by the drivers. The analysis therefore focuses on the factors, associated with cannabis, which co-explain the driving failures produced by the drivers. As mentioned in the “method” section, each functional failure can be explained by a combination of 1 to 5 elements, depending on the case. The results presenting the percentage of contribution for each element in the failures therefore run higher than 100%. Table 3 presents the distribution of the main explanatory elements behind the failures among drivers in the two groups, i.e. those with at least a 5% contribution to these failures in one of the groups.

Four co-occurring elements with cannabis explain most of the failures among drivers in this group.

Variables that are characteristic of the driver's condition strongly contribute to functional failures under the influence of cannabis. “Low level of vigilance” characterizes 31% of Ca group vs. 6.3% of Control group (Chi2=32.1; p<0.01). “Low level of attention” considering the demands of the situation explains 30.5% of Ca group failures vs. 8.6% for the control group (Chi2=26.3; p<0.01).

Vigilance problems correspond to a low level of arousal (psychophysiological) which can be seen in tasks that present no particular difficulties. Attention problems are linked to the capacity to allocate mental resources to the activity and are diagnosed for the more complex components of driving (identifying signals, performing a maneuver, etc.) (19). Consuming cannabis very significantly increases the involvement of vigilance and attention problems in the failures observed, and as a consequence in the crash production.

From the point of view of driving behavior, "risky driving" involving a high playful and disobedient component also strongly contributes to producing various failures by drivers under the influence of cannabis. This element is found significantly more than in the "Control group" (33.9% of cases vs. 16.7%; $\chi^2=19.3$; $p<0.001$), which presupposes that the drivers on cannabis involved in fatal crashes are particularly inclined or particularly sensitive to such behavior. It must be pointed out that this variable is characteristic of the "driving attitude" (aggressive, playful, etc.), as can be established in the data taken from the crash reports. It does not include the obvious risk-taking underlying the very fact of driving in such a state of intoxication.

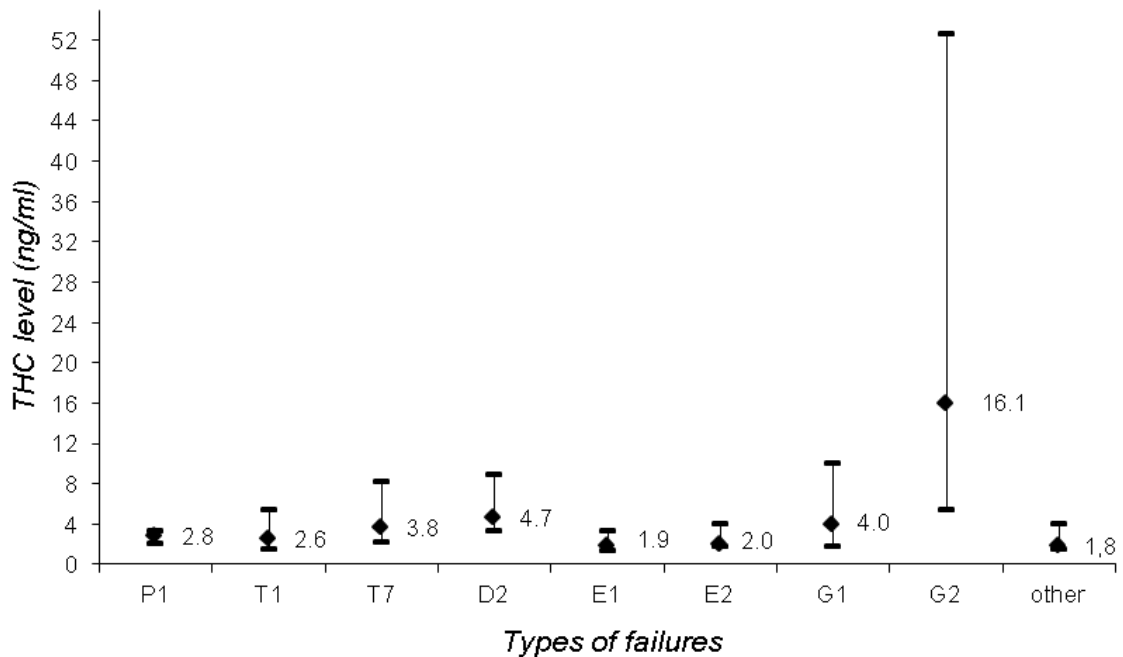
Still dealing with driving behavior, it can be noted that "excessive speed" represents a very important variable contributing to fatal crashes in the population of drivers under the influence of cannabis (42% of cases), even if this parameter is not significantly higher than in the same population of young males drivers crashed without psychotropic substance (33.3% for the Control group).

TABLE 3 Distribution in Percentage of Main Explanatory Elements for Cannabis and Control Groups

<i>Categories of Explanatory Elements</i>	<i>Explanatory Elements</i>	<i>Groups</i>	
		Ca	Control
Elements relative to the driver's condition	Falling asleep	7.5	5.7
	Low level of vigilance (in the physiological sense of the state of vigilant arousal)	31.0**	6.3
	Low level of attention (in the psychological sense of allocating cognitive resources to the driving task)	30.5**	8.6
	Distraction by an element external to driving	1.1	8.0**
Elements relative to experience	"Automatic" driving (strong knowledge of the itinerary)	10.9	17.2
	Weak driving experience	4.0	10.3*
	Weak experience with the vehicle	2.3	6.9
Elements linked to internal conditions while performing the task	Rigid attachment to right-of-way status	6.9	14.4*
	Situational time constraint	5.2	1.7
	Trivialization of the situation	3.4	10.9*
	Excessive speed	42.0	33.3
Elements linked to layouts	"Risky" driving (playful – disobedient)	33.9**	16.7
	Visibility reduced by the infrastructure	7.5	9.2
	Difficult layout	12.1	8.0
	Temporary visibility problems	6.3	6.3
	Presence of an unlit obstacle	6.3	4.0
Elements linked to driving conditions	Atypical maneuver by another user	10.3	30.5**
	Inconvenient behavior of a user ahead (e.g. low speed)	2.3	8.0*
	Reduced visibility conditions	14.4	9.8
	Loss of adherence	5.7	9.2

* $p<.05$ - ** $p<.01$

FIGURE 1 Median THC levels in ng/mL and quartile deviations for failures in cannabis group.



Type of crash

Crash data shows that drivers under cannabis influence were significantly more often involved in single vehicle crashes (corresponding to a loss of control of the vehicle) than drivers of the control group (51.1% vs. 34.5%, $\chi^2=10.5$, $p < 0.01$). This result may be connected to the overrepresentation of Cannabis group drivers for generalized failures Gen2, as noted above. Indeed, this type of failure leads mostly to a loss of control even in situations without apparent difficulty. The increase in the frequency of single vehicle crashes is also correlated to the increase in THC measured in the blood. Indeed, in group Ca, the median rate of THC measured in the case of single vehicle crash is higher than that found for other configurations (3.7 ng/mL vs 2.4 ng/mL). In addition the variability of THC is very important for single vehicle crashes with rates that can exceed 100ng/mL and 40% of these drivers have a rate higher than 5ng/mL of THC in the blood. Finally, 63% of drivers with more than 5ng/mL of THC in the blood at the time of the crash lost control of their vehicle. On the opposite, the majority of crashes (65.5%) for the control group occur in interaction with another road user (65.5% vs. 48.9% for the Ca group, $\chi^2=10.5$, $p < 0.01$).

DISCUSSION

The objective of this analysis was to clarify the role of cannabis in traffic crashes from the point of view of crash mechanisms, the human functional failures involved and the associated factors.

Concerning the distribution of functional failures categories in these fatal crashes, we found a significantly different distribution for drivers under the influence of cannabis compared with the control group. Nearly one third of crashes involving drivers under the influence of cannabis entail a generalized alteration of psychomotor and cognitive capacities. These failures are characteristic of drivers under the strongest influence of cannabis (for levels of THC greater than 5 ng/mL of blood), whereas for lower levels, less extreme failures are observed. In fact, the levels of THC measured in fatal crashes occurring after a "generalized failure" reach important values. Whereas the median level in all users under the influence of cannabis is 2.9 ng/mL, the median levels observed in the Gen2 scenarios are greater than 15 ng/mL. These results are in agreement with the effects already described in the literature according to

which, for THC levels between 14 and 60 ng/mL, performances on psychomotor tests are affected between 70 and 80% (22, 23). It is also in agreement with experimental and epidemiological studies indicating that a limit for THC in the 7 to 10 ng/mL range (measured in blood serum or plasma, equivalent to 4 to 6 ng/mL measured in whole blood) offers a reasonable separation of unimpaired from impaired drivers who may pose a higher risk of causing accidents (24). What is shown here is the fact that, for blood THC levels greater than 15ng/mL, this drop in performances is accompanied by generalized failures in the driving task leading in most cases to a loss of control of the vehicle. These results illustrate the dose effect of cannabis previously described from an epidemiological viewpoint by Laumon et al. (16): the risk of being responsible for a fatal crash increases as a function of the THC level measured in the blood. Others studies reported such a significant increase in risk associated with cannabis use. Using responsibility analysis with samples of fatally injured drivers in Australia, Drummer et al. (15) reported that drivers with any THC were 2.7 times more likely to be responsible for collisions than nonusers, and those with THC concentrations greater than 5 ng/ml were 6.6 times more likely to be responsible. Mura et al. (25) found that among hospitalized patients, the crash involved group was 2.5 times more likely to have cannabis concentrations greater than 1 ng/ml. This phenomenon can be explained from a crash analysis point of view by the increase in the number of "generalized failures" for which the intoxicated driver is considered as being at the origin of the crash.

At more moderate THC levels, failures more specifically concern certain functional steps. It is currently accepted that cannabis consumption causes a deficit in attention processes, short-term memory, executive functions and motor control (5, 6, 7, 9), these motor and cognitive functions being necessary for the proper processing of information during the driving activity. In terms of the crash implications of functional deficits, we can see that cannabis specifically affects the ability to evaluate the physical parameters useful to estimate the feasibility of a maneuver (increase in Dial type failures: "Poor evaluation of a temporary difficulty").

Numerous studies rather supported the principle of the adoption of behavioral compensation by drivers under the influence of cannabis (26, 27, 28). They are thus more considered with lower speeds and more careful driving (28) enabling them to make up for part of their reduced capacities due to this substance. On the other hand, some studies have shown that THC users were willing to take more risks in a traffic situation that could be evaluated as slightly dangerous (29). Some data in our study agreed with this notion of behavioral compensation, while demonstrating the limits of such adjustment. In configurations of interaction with traffic, we can see a very strong similarity of drivers under the influence of cannabis with those of the Control group, suggesting an absence of any substantial effect of cannabis on the driving failures produced under these conditions. Nonetheless, overall we can see that more crashed drivers adopted risky behavior (playful, disobedient or even aggressive) when they were under the influence of cannabis than when they were not, notably when it deals higher levels of THC ending up with a loss of control. It thus appears that the drivers studied, involved in fatal traffic crashes, sometimes deviate from the behavioral standards observable in the experimental situation. Such results are supported by recent data which show that drivers who declare that they drive under the influence of cannabis also declare that they engage in risky driving (30).

These results remind us that cannabis is not a unilateral variable that makes all its users identical, that there is a wide inter-individual variability in its effects which also depends on the drivers' level of intoxication and related variables (psychological, sociological and contextual) (31). The illicit character of cannabis consumption should not lead us to forget the heterogeneous component of this population, notably in terms of driving (32). There are different types of cannabis consumers, and these differences have major implications for their attitudes – notably toward risk – and for their driving behaviors (33).

In conclusion, this study provides a complement to epidemiological studies concerning driving under the influence of cannabis by demonstrating the crashes forms that the excess risk takes, as well as the driving functions that are most affected depending on the level of intoxication. It also provides a complement to the experimental work on the effects of this substance at moderate doses in a controlled experimental framework with volunteer subjects supervised by observers. It makes it possible to compare the data gathered on the effects of cannabis and to analyze their implications in the context of traffic crashes where the levels of THC are sometimes very high and behaviors sometimes extreme with

an overrepresentation of high speed and risk taking. Thus, the population studied is neither that of cannabis consumers, nor even cannabis consumers who drive cars, but rather a population of drivers under the influence of cannabis having had fatal crashes. This is not without consequences on the nature of the results that we observe, some of which deviate from what could be expected from the conclusions of studies carried out in controlled situations, but they do reflect the crash reality that causes deaths on the road.

ACKNOWLEDGEMENTS

This research was sponsored by the French Monitoring Centre for Drugs and Drug Addiction (OFDT) and the authors would like to thank the whole of the SAM group for their participation in this study.

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