Executive Summary

Article Title: Strengths and Limitations of Two Cannabis-Impaired Driving Detection Methods: A Review of the Literature

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Study Purpose or Objective(s):

The purpose of this study was to assess the pros and cons of two types of assessments that are used in detecting alcohol impaired driving and how those methods address cannabis impairment and driving.

Key Findings:

THC and Blood Toxicology

- The author suggests that many studies have failed to observe cannabis concentration dependent effects on crash rates and on driver impairment. He further suggests that there is no clear relationship between blood THC concentration and crash odds ratios.
- Plasma THC concentrations observed after cannabis use are highly variable across individuals whether they smoke to effect or to a controlled dose level.
- The amount of THC consumed to achieve a desired effect varies across individuals. There is little evidence that the dose of THC that is consumed correlates with the peak plasma concentration between individual users. The variance is likely the result of a poor scientific understanding of diet, exercise, and cannabis use experience on the drugs influence.
- Khiabani examined police physicians who assessed cannabis impaired individuals. Their interpretation of intoxication shortly after the suspect was arrested presented a THC concentration significantly greater than those deemed to be unimpaired. The relatively small difference in medians and large overlapping ranges between the two groups suggests a limited influence of THC concentration at < 25 ng/mL.
- Oral testing saliva as a matrix was found to be best at 71% which means that 29% of the test results are inaccurate. Oral fluid as a test matrix is valid for detecting the presence of THC but cannot be used to accurately estimate blood cannabis concentration.

Standardized Field Sobriety Testing

- The author suggests that driving under the influence laws around the world are diversified by the imposition of secondary methods of drug driving detection such as drug recognition experts, field sobriety tests, by the arresting officer and through biological analysis. However, he asserts that the strategies are difficult to measure due to limited evidence, varying methods, differences in cultural acceptance and prevalence of cannabis use, and diverse cannabis use patterns among the general public.
- Cannabis use can demonstrate impaired performance on several behavioral tasks such as working memory and psycho-motor reaction time. However, the author suggests that validation of currently used field sobriety tests for cannabis impaired driving have largely

failed. Furthermore, the author indicates that SFSTs have not been validated to detect cannabis impaired driving and appear inadequate at doing so. The SFSTs are unable to discern among those with THC concentrations above or below the current legal thresholds in several states.

- The author suggests that chronic marijuana users exhibits deficits in nystagmus and the walk and turn test. However, the results were not correlated to blood THC levels which may not be generalizable to all cannabis users. This suggests that current field sobriety tests might also be poorly suited to detect other drugs that impair driving.
- The author suggests that evidence that supports the utility of standardized field sobriety tests are limited. While the SFSTs are successful for alcohol impairment, the results show poor accuracy at detecting cannabis use.

  Contrary to this finding, Papafotiou discovered that SFSTs conducted 55 minutes after low and high dose cannabis consumption resulted in the evaluators correctly identifying 88.5% and 92% of subjects with impaired simulated driving. However, the evaluators correctly evaluated only 38.5% and 15.4% of the unimpaired drivers in the same conditions.

  The author suggests that bias toward impairment among the examiners diminishes confidence in effectiveness of SFSTs to correctly identify cannabis impaired drivers.

- The author suggests that distracted driving would not be detected using biological testing or field sobriety tests. Instead, when officers observe and collect evidence of driving, the driver should be detained regardless of cause. However, the observations would be better served if additional evidence was captured using surveillance cameras on roadways, in vehicles, and on officers. The evidence would then be able to be used for independent assessment of driving behavior that prompted the traffic stop.

Driver Impairment

Driving Impairment

- Driving impairment after cannabis use is not always apparent. The author suggests that several studies provide evidence of little to no adverse effects of cannabis post consumption on driving.

  Liguori reported that there were no significant impairment during the first hour after consuming cannabis. Lane positioning and braking of the dosed drivers were found to be unaffected. Another study suggested that there was no adverse effect on occasional cannabis users under uneventful conditions nor in unexpected events during simulated driving 30-60 minutes post dosing.

- The author suggests that tolerance occurs in frequent users which complicates the relationship between THC levels and driving performance. Heavy users were found to be less impaired despite having higher THC concentrations while occasional users were found to be impaired despite having lower blood THC concentrations.

This suggests that two people can exhibit different degrees of impairment with similar blood levels of THC depending on the frequency of their current use history. Thus, the degree of tolerance developed to THC presents a challenge to associating dose or concentration to driving impairment.

- Verster and Roth, examined the relationship between cannabis impairment on lab and actual driving performance and found the relationship weak. Tracking and divided attention was most predictive of lane positioning however, this condition was relatively weak accounting for only 22% of the variance. The author concludes that impairment on commonly used lab metrics are poor indicators of actual driving performance.

Detection

- The legal availability of cannabis increases the prevalence of THC positive drivers detected in traffic stops. Imposing a per se threshold or liberalization of cannabis use laws appears to result in increased detection of THC positive drivers.
- Standard deviation of lane position , speed variability, and following distance all increase after cannabis use. However, maximum driving speed, reaction time, and braking were generally not affected in laboratory studies. The author suggests that cannabis use can impair some aspects of driving performance shortly after consumption.
- The effects of cannabis consumption with on-road driving are similar to those found in simulator studies. Standard deviation of lane position was observed to increase post cannabis use to twice the level for on-road.

  However, the author indicates that functional effects of THC are prominent in lab studies, decrease in on-road driving and decrease further when drivers are in real world driving situations. In addition, it is suggested that the relationship between impaired performance on lab tasks and impaired performance while driving is weak.

Crash Risk

- Drivers with detectable blood levels of THC are at a greater risk for crashing. The authors cites three studies where the crash risk of cannabis impaired drivers equates to twice that of non-impaired drivers. This risk is comparable to driving with a blood alcohol level of 0.05 g/dl or to distracted driving.
- Overall crash frequency in Washington State was increased by 5% over similar states without legal cannabis.
- THC only drivers were only a small proportion of vehicular assault and vehicular homicide cases in Colorado. The primary concern stems not from cannabis use alone but from combined alcohol and cannabis use and other poly drug use. The finding suggests that considering cannabis use and driving alone, evaluators could be missing mixtures of drugs.
- NHTSA evaluated the impact of drugs on crash risk and discovered an unadjusted odds ratio for those with THC. When the data was adjusted for other factors the presence of THC was no longer associated with an elevated crash risk.

The author concluded that other variables are highly correlated with cannabis use and account for much of the risk associated with cannabis use previously reported. He further suggests that factors such as performing impulsive driving activities while experiencing positive THC effects predicts driving errors, driving lapses and driving violations. The author suggests that positive urgency represents a greater driving risk regardless of recent cannabis use. He further suggests that this highlights the importance of detecting impairment versus inadequate driver performance regardless of the underlying cause.

- The author suggests that those who are intoxicated by cannabis may adopt strategies that mask the appearance of the drug effects which cloud the relationship between lab and real-world assessment. This censors observable effects when THC concentrations are at their highest. By overestimating their impairment, cannabis users reduce their driving speed and following distance and in many instances, delay driving during the first hour after use. This indicates a decreased willingness to drive.

Study Strengths: The strengths of this article lies within the authors ability to contrast and compare strengths and limitations of other contributing author viewpoints. The depth of information pulled from other authors studies/papers makes this review of literature appropriate for the authors needs. However, the author may use or omit findings of studies and research to support the position they have on any particular topic. While the author does input his findings and conclusions within the introduction and summary of the paper, he uses the findings of other works to support his points throughout the document. While his positions appear to lean more toward the limitations of present day biological and human testing techniques, he does use other works to support his conclusions.

Study Weaknesses: Based upon this review, much of the authors writing seems to be more centered on the challenges and short falls of current cannabis impaired driving detection methods. While there are several illustrations of how current evaluation methods are improving traffic safety, many of those same strengths are characterized as having a weak relationship between crash risk and cannabis consumption. The author concludes:

- The relationship between the amount of cannabis consumed and crash risk are weak
- There is evidence that cannabis use impairs driving but it is weakly linked to the dose consumed
- Impairment of cannabis at maximum degree of impairment is similar to impairment produced at 0.05 g/dl of blood alcohol concentration
- Blood concentration of THC is a poor index of driving related risk or impairment
- SFSTs have not been validated to detect cannabis induced driving impairment and appear inadequate at doing so.
- SFSTs are unable to discern among those with THC concentrations above or below the current legal thresholds in some states.
- SFSTs are oiir at detecting recent cannabis use, especially among frequent users.
- There is a high variability among THC blood concentrations across individuals that do not reflect brain THC concentrations. Tolerance or other behavioral adaptations that effect THC and driving performance obscure dose or concentration dependent effects.

- The poor relationship between blood and other peripheral measures of THC concentration and driver impairment or crash risk make enforcement of cannabis laws tenuous.
- Cannabis drivers have no guidance about when they are fit to drive and law enforcement have no valid way to address the extent of impairment they suspect.
- Subjective feelings of cannabis intoxication or fitness to drive do not predict driving impairment. The lack of THC concentration or a valid subjective assessment to determine fitness to drive after consumption of cannabis leaves users without clear guidance on when they are fit to drive.
- The use of ubiquitous surveillance cameras on roadways, in vehicles and on the person of traffic safety professionals provides a means for independent assessment (by judge or jury) of driving behavior that prompted the traffic stop. This is a potentially more effective means so determining traffic risk across all dangerous situations.

Study Limitations: The information pulled from other authors studies/papers makes this review of literature slant toward a weak view of current biological and psychophysical testing methods used to detect cannabis impairment. The author appeared to use or omit findings of studies and research to support his position on the topic of cannabis use and impairment. The author uses the findings of other works to support his points throughout the document which appear to lean toward limitations of present day biological and human testing techniques.

Additionally, there are no recommendations made to improve upon the limitations outlined in the authors paper. While the author points out limitations, he does not suggest or comment on other studies or papers that address the shortcomings the he infers in his paper. There are a rare few illustrations or literary citations that point to successes of current biological, psychophysical, and driving behavioral testing methods. This suggests that there may be bias on the part of the author toward a more relaxed position on cannabis use and its relationship to traffic safety.

Overall, the papers intent was to assess the pros and cons of two types of assessments that are used in detecting alcohol impaired driving and how those methods address cannabis impairment and driving. In the opinion of this evaluator, there was little focus on assessing current biological and field testing methods that support or show promise for identifying impairment from cannabis. Instead, the authors assessment focused on limitations and weaknesses which limits the impact of the papers findings.

Subcommittee Commentary

Prosecutorial Perspective:

- This study seems ripe for use/misuse/abuse by the defense bar with lots of lines they could pull out of context to cross examine a toxicologist on if they aren't familiar with it and don't know how to respond to the limitations of it. Specifically, the section "Evidence limiting the use of functional tests for cannabis-impaired driving" is full of lines that I can see defense attorneys use to try to convince a judge to exclude the results of the SFSTs in a case where the person is impaired on THC.
- The section about "Kinetics of cannabinoids in blood..." seems to be the type of information that more prosecutors need to be aware of so they understand the limits/issues of blood tox results for THC impaired cases.
- The section titled "Adaptive driving strategies..." has some good information and quotes for prosecutors and law enforcement regarding the time that most people are impaired after consuming THC. This is the type of information that when known can be used to develop evidence of the defendant driving within the normal timeframe so that an expert can then testify about the timeframe of impairment.
- Researchers equated drivers that did not have lane departures as “unimpaired.” This is simply bad science and methodology. Cannabis impairs executive function far more than balance or even concentration. Having seen hundreds of car crashes being able to keep in your lane does not a sober driver make.
- The study fails to really get into alternatives or improvements but makes two things very clear. #1 Per se levels are a bad idea #2 Cannabis impairment is very difficult.

Enforcement Perspective:

- The literature review by the authors appears to make it more difficult to enforce cannabis only impaired driving cases. If law enforcement and prosecutors cannot show that cannabis has caused someone to lose the normal use of their faculties etc., how can we get a conviction for DWI? Even if they show there is a loss of faculties due to THC, if it is at the level of a 0.5 BAC alcohol or distracted driving will it play well enough with the jury to convince them to convict? Does it rise to the level of seriousness when jurors may look at the effects of THC on driving as the same as having drank two beers?
- Since the level of impairment is not based on the level of THC in the blood, but instead on a combination of multiple factors not related to the drug itself, the officer interview becomes more important. Adding in questions about frequency of use, how long between use and driving, prior experiences, age of first use, medical background, have they been “higher” before and operated a vehicle, etc., could provide valuable information to the prosecutor and the jury. The answers to those questions could help explain to the jury signs of impairment and relate them to the level of THC in the suspect’s system.

- The authors are correct that video evidence can be useful in documenting intoxication. Unfortunately, video cannot "see" everything that the officer observes on the side of the road. Proper use of video can make the most out of what it can document, and officers will need to try to use it to their advantage during testimony to point out impairment indicators.
- Officers will need to be aware of how other substances may change the level of impairment caused by cannabis. Documentation of both illicit and prescription drug use and inclusion with the blood sample when sent for analysis will help the lab know what substances to look for and provide information on drug interactions.

Toxicology Perspective:

- Research on cannabis use varies widely throughout the literature, and the research/studies discussed by the author offers a narrow view of current cannabis impaired driving testing methods. While research supporting limitations in cannabis testing techniques is heavily discussed, the author excludes available evidence supporting the strengths of cannabis testing. This bias leads to a misleading representation of current cannabis impaired driving testing methods.
- As with all driving under the influence cases, it is important to consider the whole picture (e.g. signs and symptoms, witness statements, combination with other drugs and/or alcohol) in conjunction with the toxicology results before determining whether an amount of any drug could have led to impairment for that individual. This is especially critical for THC and other cannabinoids.

Research and Evaluation Perspective:

- Based upon the review, much of the authors writing seems to be centered on the challenges and short falls of current cannabis impaired driving detection methods. While there are several illustrations of how current evaluation methods are improving traffic safety, many of those same strengths are characterized as having a weak relationship between crash risk and cannabis consumption.
- The information pulled from other authors studies/papers makes this review of literature gravitates toward a slanted view of current biological and psychophysical testing methods used to detect cannabis impairment. The author appeared to use or omit findings from other studies/research to support his position on the topic of cannabis use and impairment. Furthermore, he uses the findings in other works to support his position throughout the document which appears to lean toward limitations of present day biological and human testing techniques.
- Additionally, the author makes no recommendations to improve upon the limitations outlined in the paper. While the author points out limitations, he does not suggest or comment on other studies or papers that address the shortcomings the he infers. There are a rare few illustrations or literary citations that point to successes of current biological, psychophysical, and driving behavioral testing methods. This suggests that there may be partiality on the part of the author toward a more relaxed position on cannabis use and its relationship to traffic safety.

- Overall, the papers intent was to assess the pros and cons of two types of assessments that are used in detecting alcohol impaired driving and how those methods address cannabis impairment and driving. In the opinion of this evaluator, there was little focus on assessing current biological and field-testing methods that support or show promise for identifying impairment from cannabis. Instead, the authors assessment focused on limitations and weaknesses which limits the impact of the paper findings

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REVIEW

Strengths and limitations of two cannabis-impaired driving detection methods: a review of the literature

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ABSTRACT

Background: Recent cannabis use is associated with an approximate two-fold increase in automobile crash risk, but detecting cannabis-impaired driving remains a challenge.

Objectives and Methods: In this perspective, the pros and cons of two types of assessments arising from those used to detect alcohol-impaired driving are discussed in the context of cannabis-impaired driving.

Results: Some laws rely on tests to detect whether blood or breath levels exceed a legally defined (*per se*) threshold. These laws rely on clear and consistent relationships across individuals between detectable drug concentrations and the amount consumed, crash risk, or degree of driver impairment. However, unlike alcohol, there is poor correspondence between detected levels of the primary active constituent of cannabis or its metabolites and the amount consumed or its behavioral effects. Field sobriety tests assess impairment on functional tests calibrated to reflect actual driving-impairment and validated to predict traffic safety risk. However, functional tests for cannabis-impaired driving have not been developed or validated, and the degree of impairment resulting from recent cannabis use is difficult to distinguish from other conditions such as advancing age or use of certain medications.

Conclusions: Although standard field sobriety tests have advantages over *per se* tests for cannabis-impaired driving, limitations of both leave cannabis users and law enforcement officials little guidance in assessing an individual's driving fitness after recent cannabis use. General strategies for detecting and preventing impaired driving regardless of the cause would be preferable to establishing specific methods for every situation or substance that could impair driving.

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Marijuana; sobriety test; SFST; SDLP; drugged driving; drunk driving; per se law

Introduction

Recent legislation allowing medicinal and recreational use of cannabis has potential for both positive and negative impacts on traffic safety. On one hand, there is evidence that relaxation of cannabis laws may reduce the use of other substances which can impair driving or impairment caused by conditions cannabis is used to treat. For example, recent research has indicated that, when legally available, patients report substituting cannabis for opioids and benzodiazepines (1,2), and this finding is supported by evidence of lower opioid prescription rates in states with legal medical cannabis (3). Opioids and benzodiazepines appear to pose greater traffic safety threats than cannabis (4–6), so cannabis substitution could reduce the risks associated with these medications. Similarly, a recent systematic review by the National Academies of Sciences found substantial evidence that cannabis is beneficial for managing chronic pain (7), a condition which causes substantial driving impairment, and this impairment is not reversed by stable opioid therapy (8,9). Thus, from a harm-reduction perspective, liberalization of cannabis use might improve traffic safety by reducing the use of other impairing substances or the impact of conditions cannabis is used to treat.

However, liberalization of cannabis laws results in a higher frequency of drivers with detectable blood levels of the primary psychoactive ingredient in cannabis (10–12). This has raised concerns about the impact of increased cannabis use on traffic safety and prompted discussions on implementing effective laws related to driving under the influence of cannabis. Effective laws must permit lawful cannabis use while also preserving public safety. However, several aspects of cannabis complicate implementation of effective laws. First, effects of recent cannabis use on driving are relatively subtle. Recent cannabis use is associated with a 1–2 fold increase in the likelihood of a traffic collision (13). This is a lower likelihood than is seen

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among drivers with blood alcohol levels above common legal limits, and is similar to the risk determined among drivers with detectable levels of benzodiazepine (4). Further, the impact of recent cannabis use on driving performance can be difficult to detect. The most robust effects include decreased reaction time, particularly in situations that require sudden braking, and increased movement within a traffic lane (14,15). Effects on reaction time appear to be somewhat offset by a concomitant increase in following distance and reduced average speed (16,17). The most consistent effect, movement within the traffic lane, is maximal at a standard deviation of 6-8 cm greater than placebo (Figure 1). However, this represents only a doubling of normal lane position variance (standard deviation of 3–4 cm). Further, lane widths of roads in the United States range from 560 to 720 cm, so maximal cannabis-induced lateral movement only constitutes about 2% of the total lane width (23). Thus, the ability of an observer to detect this effect for drivers under the influence of cannabis remains unclear. Second, levels of the primary active ingredient in cannabis, Δ^9-tetra-hydrocannabinol (THC), detected in blood or saliva are only weakly correlated with impairment (24). This complicates the use of threshold levels for impairment the way laws for alcohol-impaired driving have been applied. Third, standardized field sobriety tests have not yet been validated to detect cannabis-impaired driving. There are some behavioral assays which may correlate with cannabis-impaired driving performance, including nystagmus (involuntary eye movement) and finger-tapping assays (25,26). However, cannabis is just one of perhaps hundreds of medicinal or recreational drugs which can impair driving performance (e.g. 27). Adding new blood or field sobriety tests to detect each of these, or their interactions, is neither feasible nor efficient. Instead, functional assessments which can detect inadequate driver performance, regardless of the underlying cause, would be more efficient and effective at improving traffic safety.

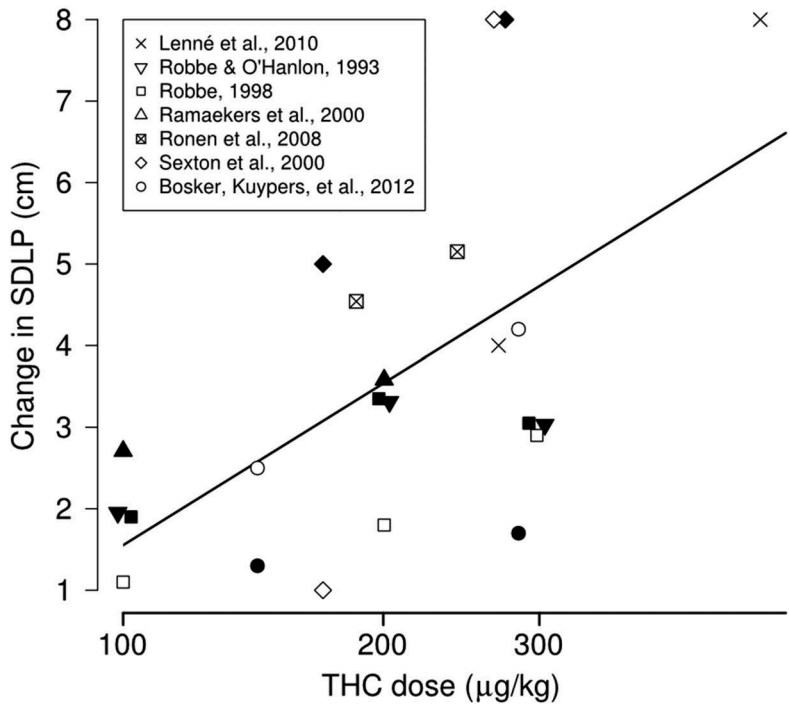

Figure 1. Change in standard deviation of lane position (SDLP, in cm) from placebo as a function of THC dose across several studies. Note that THC dose is plotted on a Log_{10} scale. Doses from Lenné et al. (18) were estimated by dividing the amount of THC present in each condition (19 mg or 38 mg) by an average weight of 70 kg. THC amounts were estimated at 19 mg (8 puffs on one cigarette) and 38 mg (8 puffs each on two cigarettes) because 8 puffs results in consumption of an entire cigarette, based on the report from which the smoking procedure was adopted (19). Doses for the Bosker, et al. (20) and Ronen et al. (16), studies were estimated by dividing the amount of dronabinol administered (10 or 20 mg) by an estimated 70 kg weight. Different colors represent performance on a closed (filled) or open (open) road in the study by Robbe (21), occasional (open) or heavy (filled) users in the study by Bosker, et al. (20), or performance on the right-hand (open) or left-hand (filled) portion of a figure eight curve in the study by Sexton et al. (22). Some points have been nudged leftward or rightward for clarity. The line represents a linear regression through all of the points. The slope of this line was positive and significantly different from 0 ($F[1, 21] = 11.8$, $p < .002$).

Methodology

A search of the literature using the search phrase: (THC OR marijuana OR cannabis) AND ((“blood level” OR “per se” OR “sobriety test” OR SFST) OR (driving AND (impairment OR performance))) was performed using the United States National Library of Medicine database through April 2019. Because the most prominent observable sign of cannabis use prior to driving is an increase in deviation of lane position, a secondary search using the phrase: ((THC OR marijuana OR cannabis) AND (SDLP OR “lane position”)) was conducted to verify the original phrase returned all relevant results. The primary search phrase returned 331 reports. Of these, 53 were reviews and 28 were pre-clinical (animal) studies. This left 221 primary reports to consider. Of those 172 were ultimately determined to be relevant to the present work and were considered in the production of the work.

Per se cannabis-impaired driving laws

Per se laws in various localities

The global popularity of cannabis has resulted in various localities imposing laws which prohibit driving with detectable levels of THC or its metabolites, also called “per se” laws. Some of these impose “zero-tolerance”, with any detectable amount prohibited, the limitation being solely the lower limit of detection of the detection method (28). Others allow for some threshold, similar to alcohol laws in which levels above a particular blood concentration are prohibited. Driving under the influence laws around the world are further diversified by imposition of secondary methods of drugged driving detection in some places, such as drug recognition experts, field sobriety tests by the arresting officer, or secondary biological analyses (28).

The impact of these various strategies is difficult to ascertain, due to limited evidence, varying methodologies, differences in cultural acceptance and prevalence of cannabis use, and diverse cannabis use patterns among the general population in different cultures (29). Still, some trends are apparent. For example, in Denmark, the prevalence of THC in blood among those suspected of driving under the influence of drugs or alcohol increased from 27% to 41% after a 1 ng/ml limit was imposed, replacing evaluation of impairment by a medical examiner (30). Similarly, the legal availability of cannabis increases the prevalence of THC-positive drivers detected in traffic stops. In Washington State, legalization of cannabis use coincided with a significant increase in THC-positive drivers from 19.1% to 24.9% (10). Thus, imposing a per se threshold or liberalization of cannabis use laws appears to result in increased detection of THC-positive drivers.

Evidence supporting implementation of per se cannabis-impaired driving laws

Drivers with detectable blood levels of THC are at greater crash risk

Results of several meta-analyses indicate that drivers with THC present in their blood are at an approximate two-fold greater risk of crash involvement; this increase in risk is comparable to that posed by driving with a blood alcohol concentration of 0.05 g/dl or by distracted driving (13,31–34). Asbridge et al. (32) performed a meta-analysis of reported odds ratios for cannabis-related auto crashes, selecting high-quality studies that considered drivers with cannabis alone (no other drugs) present in their blood and adjusted the odds ratios for factors such as age, driving experience, and miles driven. The pooled odds ratio across these selected nine studies was 1.9 [1.4–2.7] (mean [95% confidence interval]). Another meta-analysis by Li (35) sampled studies which were mostly non-overlapping with those used by Asbridge et al., and found a comparable odds ratio of 2.6 [2.1–3.4], before adjusting for confounding factors such as alcohol use. Though they do not provide the data, the authors report that adjusting for confounding variables reduced the sampled odds ratios, but odds ratios for all except one study remained statistically significant (35). More recently, Rogeberg (34) reported an adjusted odds ratio of 1.3 [1.1–1.6]. Together, these studies indicate an elevated odds ratio for crashes involving drivers with THC present in their blood, with the actual ratio falling between 1.1 and 3.4. This represents a significantly elevated (by about two-fold) risk for THC-positive drivers compared to drug-free drivers.

Recent data from states that have liberalized cannabis laws suggest greater frequency of cannabis-related traffic stops and crashes (36,37). For example, when compared with a cohort state which does not allow cannabis use, Colorado and Washington had elevated rates of insurance claims, though Oregon showed little change. Overall, the crash frequency was increased by approximately 5% over similar states without legal cannabis (37). Similarly, a report by the Colorado Department of Public Safety evaluated impacts associated with cannabis

legalization in the state across a variety of measures, including traffic safety. The study revealed steady increases in cannabis-related traffic stops, although DUI citations by the Highway Patrol and fatalities with driver THC levels ≥5 ng/ml (the legal limit in Colorado) *decreased* over this time period (36). Further analysis of these data indicate that THC alone (absent other psychotropic drugs) only accounted for a small proportion of vehicular assault or vehicular homicide cases (38). The data reveal clear cause for concern about impairment from combining alcohol and cannabis, and about the impact of polysubstance use in general (the most prevalent use pattern), on traffic safety (36,38). This suggests that cannabis-specific assays could miss more problematic mixtures of other drugs or medications.

Recent cannabis use produces some signs of driving impairment under some conditions

Driving simulators. Studies of cannabis effects on driving have been conducted in the laboratory using driving simulators. Generally, lateral movement within the lane expressed as the standard deviation of lane position, or SDLP (see Figure 1), speed variability, and following distance all increase after cannabis use (16,18,22). Other aspects of driving performance including maximum driving speed, reaction time to a car entering the driver's lane, or to an event requiring sudden braking were generally not affected in these studies. Thus, cannabis use can impair some aspects of driving performance, particularly in lane tracking shortly after consumption.

On-road driving. Because driving simulators only approximate the experience of driving, the effects of cannabis consumption on actual (on-road) driving have also been assessed (Figure 1). SDLP generally appears to increase with THC dose, although as noted below, most studies have failed to observe significant differences between dose conditions. This increase appears maximal at twice the SDLP for on-road, unimpaired driving, which is typically observed at 2.5 cm (39). This degree of cannabis-induced increased SDLP is similar to that produced by other activities associated with a two-fold increase in crash risk, including driving with a blood alcohol concentration of 0.05 g/dl and distracted driving (31,33,40,41). Clearly, lane weaving that exceeds 8 cm (2 standard deviations above normal variation) would be reason to suspect impairment, regardless of the cause.

Evidence limiting the effectiveness and use of per se cannabis-impaired driving laws

The relationship between blood levels of THC and crash risk is not completely clear

Many studies have failed to observe concentration-dependent effects of THC on crash rates or driver impairment. No clear relationship between blood THC concentration and the odds ratio for crash culpability was found among 2500 drivers involved in non-fatal crashes (42), nor among 1800 French drivers injured in road crashes (43). Ramaekers et al. (44), note that THC administration of up to 300 µg/kg are associated with crash risk comparable to blood alcohol concentrations of 0.05 g/dl and that "*higher doses … can be predicted to produce even larger impairment*" but provide no data demonstrating greater crash risk or impairment at higher doses or blood concentrations.

Plasma THC levels achieved after cannabis use are variable

Plasma THC concentrations observed after cannabis use are highly variable across individuals, whether they smoke to effect or consume a controlled dose. In general, frequent smokers achieve higher blood concentrations of THC and its metabolites, and eliminate them more slowly than occasional smokers (45). THC is sequestered in fatty tissues and slowly re-released into the blood, resulting in a long terminal half-life (46). Thus, chronic cannabis users can have detectable blood THC concentrations days after drug discontinuation (47,48), and some may have >5 ng/ml THC, the current threshold sufficient to demonstrate driving under the influence of cannabis in several localities (36), in their blood over 24 h after smoking (49).

The amount of THC consumed to achieve the desired drug effect varies across individuals. Robbe and O'Hanlon (50) allowed cannabis users (average 6 uses per month) to smoke as much as desired and found the dose of THC they consumed ranged from 194 to 524 µg/kg. This resulted in peak plasma concentrations ranging from 3.3 to 45.9 ng/ml. There was little evidence that the dose of THC consumed was correlated with the peak plasma THC concentration.

Even controlled cannabis administration produces highly variable peak blood THC concentrations (51). Kauert et al. (52) had 10 cannabis users (reporting cannabis use >5 times per month, but less than daily and without THC present in their blood prior to smoking) smoke cannabis cigarettes containing 250 or 500 µg/kg THC using a fixed smoking procedure over a 10-min period. The maximal blood concentration of THC achieved ranged from 9.2 to 110.0 ng/ml and 25.0–134.0 ng/ml for the

low and high dose conditions, respectively. This variance likely results from the still poorly understood influence of factors such as diet, exercise, or experience (45,53,54).

Driving impairment after cannabis use is not always apparent

In a driving simulator study by Liguori et al. (55), there was no significant impairment during the hour after consuming cannabis cigarettes (placebo, 1.8%, or 3.9% THC, approximately 0, 15, or 32 mg, respectively) when subjects were forced to suddenly brake from 55 mph to prevent collision with an unexpected barrier across the road. The authors also found no impairment when the subjects had to choose the widest of three available lanes while maintaining a speed of 30 mph. Another study found no effect on simulated driving among "occasional" cannabis users under uneventful conditions nor when unexpected events (a dog in the road or an emergency vehicle) occurred when driving 30–60 min after consumption of cannabis cigarettes containing 0% or 2.9% (approximately 23 mg) THC (56).

In Norway, drivers suspected of driving under the influence of drugs must submit a blood sample for subsequent analysis and are examined by a police physician using a battery of observations and tests shortly after apprehension. The physician then made a subjective rating of driver impairment (or not), regardless of the absolute scores on the tests. Khiabani et al. (57) examined records from 456 such cases in which drivers had THC and no other drug present in their blood. The median THC concentration was significantly greater among those deemed impaired (2.5 ng/ml) versus those deemed unimpaired (1.9 ng/ml). However, the relatively small difference in medians and largely overlapping ranges between the two groups ([0.3–45.3] vs [0.3–24.8] for impaired vs. unimpaired groups, respectively) suggest a limited influence of THC concentration on the subjective rating of impairment, at least at concentrations <25 ng/ml. THC concentrations >25 ng/ml were only observed among those classified as impaired, though the number of individuals this result represents was not reported.

Tolerance occurs, especially in frequent users, complicating the relationship between THC levels and driving performance

Tolerance develops to many effects of cannabis, including mood changes, brain activity, cardiovascular effects, and psychomotor task performance (58,59). Tolerance to effects on driving performance has also been observed in on-road driving. In one study 12 occasional (5–36 uses per year) and 12 frequent (>160 uses per year) cannabis users took oral THC (0, 10, or 20 mg) in a double-blind design (20). Compared to placebo, SDLP increased by about 2.5 cm in 5 of the occasional users and in 3 of the heavy users after both doses, yet still remained with the range others have reported among unimpaired drivers (40). Whole blood concentrations (determined before and after the driving test) ranged from 0.9–3.1 and 2.3–5.1 ng/ml in the occasional and heavy users, respectively. There was no evidence of any dose-dependence of behavioral or biochemical measures, and group means revealed little difference between the groups. However, the authors concluded that heavy users were less impaired, despite having higher blood THC concentrations. Further, some occasional users were impaired despite having relatively low blood THC concentrations (20). Together, these data suggest that two individuals can exhibit different degrees of impairment with similar blood levels of THC, depending on their recent use history. The degree of tolerance that develops to THC effects thus presents a challenge to associating dose or concentration to driving impairment.

Per se laws targeting specific substances may miss traffic safety risks due to other vulnerability factors

The authors of the recent Colorado Department of Public Safety report (36) caution that other factors such as heightened law enforcement awareness and more widespread toxicological assessments can increase drug detection rates and the interpretation of the relationship between detectable levels of THC in blood and driving impairment or crash risk. Indeed, the National Highway Traffic Safety Administration reported the first large-scale case-control study to evaluate the impact of drugs other than alcohol on crash risk and found an unadjusted odds ratio for crash risk among those with THC present significantly elevated to 1.25 (60). Yet, when the data were adjusted for other factors that may be involved in the crash (e.g. age, sex, ethnicity, alcohol use), the presence of THC was no longer associated with elevated crash risk (OR: 1.0 [0.9–1.3]). From these data, the authors conclude that other variables are highly correlated with cannabis use and account for much of the risk associated with cannabis use that has been previously reported.

This conclusion highlights an important limitation in epidemiological studies; this correlational approach does not directly address any causal role of THC in crashes (61). For example, Positive Urgency (i.e. undertaking impulsive actions when experiencing positive affect) predicts both problematic cannabis use and driving errors, driving lapses, and driving violations among college students (62,63). Thus, those high in "Positive Urgency" represent a greater driving risk regardless of recent cannabis use (when *per se* laws for cannabis are effective) or not (when cannabis or alcohol per se laws are ineffective).

This highlights the importance of detecting impaired or inadequate driver performance regardless of the underlying cause in order to improve traffic safety.

Kinetics of cannabinoids in blood and other body fluids complicate detection of recent cannabis use

Analysis of blood or urine samples requires that the individual be moved to an appropriate facility to obtain the sample and then that the sample be transported to a forensic laboratory. One study revealed that the average time from dispatch to sample collection in suspected drug-impaired driving stops in Colorado was 2.5 h (38). This introduces legal concerns as well as analytic complications as such delays can have a profound effect on subsequent quantification (64).

Upon ingestion, THC rapidly enters the blood, and then rapidly exits as it moves to more lipophilic compartments in the body (65,66). However, THC pharmacokinetics exhibit a great deal of individual variability, depending on a variety of factors (67). Thus, any delay between observation of potentially impaired driving and blood or urine sampling can introduce uncertainty which complicates interpretations of assay results (68). Additionally, THC is subject to oxidative degradation and to degradation by exposure to light, and thus the time between obtaining and analyzing a sample and how the sample is handled can influence the apparent THC content (69). Refrigerating the sample can reduce this variability, but again, this may be difficult to accomplish in the field (70). On-site sampling and analysis of saliva, breath, or sweat overcomes some of these limitations (71,72). Of these, salivary sampling has shown the most promise as a rapid on-site field test for recent cannabis use, and observed THC levels may correlate with observed signs of impairment (73).

However, as shown in Table 1, to date, commercially available salivary assays remain unsuitable for forensic work. THC levels detected in saliva were compared against simultaneously collected blood samples to determine sensitivity and specificity of commercial products. Sensitivity is the ratio of true positive detection divided by the sum of the true positive and false negative outcomes. However, specificity, the ratio of false negatives divided by the sum of false negatives and true positives, is arguably the more important measure. Low specificity indicates that a test will incorrectly identify drivers as being above the THC threshold when they actually are not, resulting in improper convictions and sanctions. Sensitivity and specificity of at least 80% has been proposed as the minimal performance required of such field tests, to ensure correct identification of drivers with levels of THC present above the threshold (74). Even the best product exhibits only about 71% specificity, meaning that over 25% of the positive outcomes are inaccurate. This may result from the highly variable ratio of THC in saliva versus blood (52). Even normalizing observed THC levels in blood and saliva only accounted for about 30% of the variability (75). Based on their results, these authors concluded that oral fluid is valid for detecting the presence of THC in the blood, but cannot be used to accurately estimate the blood concentration.

A study conducted in Belgium suggested that combining specific observable signs of recent substance use might improve the false-positive rate for oral fluid testing and supports further research into how to improve this method of detection (64,76).

Table 1. Published sensitivity and specificity of several commercially available oral fluid assays for THC.

Report	Test kit	Sensitivity (%)	Specificity (%)
Tang et al., 2018	Ora-Check	0.0	100.0
	Drug-Wipe	*22.0*	*100.0*
	Saliva Screen	0.0	100.0
Logan et al., 2014	Drug-Wipe	43.5	100.0
	DraegerDrugTest5000	58.3	98.5
Toennes et al., 2013	*Drug-Wipe (cheek swab)*	*87.8*	*93.8*
	Drug-Wipe (tongue swab)	*89.1*	*93.8*
	DraegerDrugTest5000	94.4	15.4
Desrosiers et al., 2012	DraegerDrugTest5000	90.7	75.0
Stano-Rossi et al., 2012	Concateno-DDS	37.8	100.0
	DraegerDrugTest5000	92.3	96.7
	RapidSTAT	72.0	97.0
	Drug-Wipe	*46.6*	*98.9*
Pehrsson et al., 2011	*Drug-Wipe*	*43.0*	*87.0*
Pehrsson et al., 2008	*Drug-Wipe*	*52.2*	*91.2*
Combined average	**Drug-Wipe**	**56.8**	**94.1**
	DraegerDrugTest5000	**83.9**	**71.4**

Sensitivity: True positive/(True positive + False Negative).
Specificity: False positive/(True negative + False positive).

Functional (field) tests of cannabis-impaired driving

Evidence supporting the use of functional field sobriety tests

Field sobriety tests have been in use to detect alcohol-impaired drivers for over 30 years (77). This battery of tests includes evaluation of nystagmus (involuntary eye movements), walk and turn coordination, and balance on one leg, and has been validated to detect alcohol-impaired driving performance at common legal intoxication thresholds (77,78). Cannabis use can demonstrably impair performance of several

laboratory behavioral tasks, including those involving working memory and psychomotor reaction time. However, attempts to validate the currently used field sobriety test for cannabis-impaired driving have largely failed (20,79). Although the field sobriety test typically requires failure on all three tasks, a recent study suggests that chronic marijuana users exhibit deficits in nystagmus and the walk and turn test which might be useful in detecting recent cannabis use (80). However, it is important to note that these results were not clearly correlated to blood THC levels, and might not generalize to all cannabis users. This complicates the use of current standardized field sobriety tests for cannabis, and suggests the current battery might also be poorly suited to detect other forms of impaired driving.

Field sobriety testing is familiar and well validated for ethanol-impaired driving

When impairment is suspected, law enforcement officials often use standardized field sobriety tests to detect and prove driver impairment (81). Depending on the number of signs observed, blood alcohol concentrations ≥0.08 g/dL can be distinguished from lower blood alcohol concentrations with this procedure. As shown in Table 2, Stuster et al. (78) showed the standard field sobriety test correctly identified 98% of individuals with blood alcohol concentrations ≥0.08 g/dl. Further, the test also correctly identified 71.1% of the subjects who had alcohol concentrations below the 0.08 g/dl threshold. Thus, the standard field sobriety test provides a reasonable level of accuracy that maximizes identification of drivers with blood alcohol concentrations above the legal threshold and minimizes false positives for drivers with blood alcohol concentrations below the legal threshold in much of the United States. This has led numerous researchers and policymakers to explore similar strategies for detecting cannabis-impaired driving (20,79,82).

Evidence limiting the use of functional tests for cannabis-impaired driving

Evidence supporting the utility of current standard field sobriety tests is limited

The success of standard field sobriety tests to detect alcohol impairment contrasts with the poor accuracy of these tests at detecting cannabis impairment. One study assessed driving performance in a simulator after participants consumed a cannabis cigarette containing 1.7% or 2.9% (approximately 14 or 23 mg) THC (79). Lane departures along with other objective ratings were used to classify impaired drivers. As shown in Table 2, a standard field sobriety test conducted 55 min after smoking correctly identified 88.5% and 92% of subjects with impaired simulated driving 80 min after smoking the low and high dose, respectively. However, the test only correctly identified 38.5% and 15.4% of the *unimpaired* drivers in the low and high dose conditions, respectively; clearly an unacceptably high false-positive rate. This suggests a bias toward demonstrating impairment among the examiners and diminishes confidence in the effectiveness of the standard field sobriety test to correctly identify cannabis-impaired drivers.

Table 2. Detection of impaired simulated driving or blood alcohol levels by the standard field sobriety test.

Low dose (1.74% THC)

		Standard field sobriety test (55-min after smoking)	
		Unimpaired	**Impaired**
Driving simulator (80-min after smoking)	**Unimpaired** (*n = 14*)	**38.5**	61.5
	Impaired (*n = 26*)	11.5	**88.5**

High dose (2.93% THC)

		Standard field sobriety test (55-min after smoking)	
		Unimpaired	**Impaired**
Driving simulator (80-min after smoking)	**Unimpaired** (*n not reported*)	**15.4**	84.6
	Impaired (*n not reported*)	8	**92**

Alcohol

		Standard Field Sobriety Test	
		<0.08 g/dl	**≥ 0.08 g/dl**
Blood alcohol concentration (actual)	**< 0.08 g/dl** (*n = 214*)	**71.1**	28.9
	≥ 0.08 g/dl (*n = 83*)	1.9	**98.1**

THC data are from Papafotiou et al., 2005 and show impaired simulated driving (judged on composite score across 33 performance measures) versus impairment on standard field sobriety tests (judged by showing 4 signs of nystagmus, or 2 signs on the walk and turn or one leg stand tests)
Alcohol data are from Stuster and Burns, 1998 and represent actual blood alcohol concentration versus predicted blood alcohol concentration based on standard field sobriety test outcomes (judgment based on composite score across nystagmus, walk and turn and one leg stand tests)
Bold values are correct detections.

Additional studies reveal potential limitations of standard field sobriety test for THC impairment. Forensic medical examiners examined experienced cannabis users (use at least once per week) after they had smoked placebo, 1.7% (11.9 mg) or 2.7% (19 mg) THC containing cannabis cigarettes using a standardized smoking procedure (22). Examiners were more likely to rate subjects as impaired after higher doses of THC, and those ratings were related to subjects' self-reported rating of the intensity of the drug effect, suggesting field ratings are sensitive to THC dose. However, examiners only made this assessment in 11 of 42 cases where cannabis had been consumed. This indicates limited sensitivity of field tests to detect cannabis use. In other studies, standardized field testing after smoked cannabis or an oral THC formulation was relatively insensitive at detecting driving impairment, determined by increased SDLP in on-road driving, especially among frequent (>160 uses per year) users (20,82,83). Together, the available evidence suggests that the standard field sobriety test has limited sensitivity to detect THC dose, and is not highly effective at detecting recent cannabis use or any driving impairment it might produce.

Behavioral effects of cannabis are not clearly dose-dependent

Behavioral effects of cannabis on functional tests are not clearly dose-dependent (19,84–87), especially in tasks that are most relevant to driver performance (31). Indeed, a meta-analysis that included 165 studies that met criteria found that only heart rate and subjective rating of "high" consistently increased with THC dose across the studies (88). Functional effects of THC are most prominent in the laboratory, decrease in on-road driving, and decrease further when drivers are assessed in real-world traffic situations (50). Further, the relationship between impaired performance on laboratory tasks and impaired performance while driving is weak (89).

Ramaekers et al. (90) selected three laboratory tests, a perceptual-motor control task (Critical tracking), motor impulsivity task (Stop signal) and cognitive function task (Tower of London), which they considered most relevant to driving impairment and report a significant correlation between blood THC concentration and impairment on each measure. Effects of 250 μg/kg or 500 μg/kg THC in subjects reporting cannabis use >5 times per month, but less than daily, on each measure were apparent within the first hour and persisted throughout the entire 6 h assessment period. However, several caveats should be considered. First, participants consumed varying mixtures of tobacco and cannabis, so effects may reflect an interaction between the two drugs. More importantly, blood THC concentrations only account for 3% of the variance in critical tracking impairment (the task the authors consider most relevant to driving) and 10% of the variance in both reaction time and executive function impairment (90,91).

The relationship between laboratory tasks which show cannabis-impairment and actual driving performance is weak

The relationship between cannabis impairment on laboratory tasks and actual driving performance appears weak. Verster and Roth (89) compared performance on laboratory tasks and on-road driving performance following 14 different psychoactive drugs (though THC was not included). The laboratory tasks included measures of tracking and reaction time in a divided attention task, as well as working memory, digit spanning, and continuous tracking. On-road driving performance was quantified using lane weaving (SDLP). The authors found that tracking in the divided attention task was most predictive of SDLP performance. However, this correlation was relatively weak, accounting for only 22% of the variance. A composite score that incorporated all 5 laboratory measures increased the predictive validity, but only to 33.4%. The authors conclude that impairment on these commonly used laboratory measures is a poor predictor of on-road driving performance.

Adaptive driving strategies after cannabis consumption

Those intoxicated by cannabis may adopt several strategies that can obscure the appearance of performance-impairing drug effects and cloud the relationship between laboratory and real-world assessments, especially shortly after consumption. This may, in turn, obscure concentration-dependent effects on crash risk by censoring observable effects when blood concentrations are highest. Drivers tend to overestimate their impairment due to cannabis, and reduce their driving speed and following distance (50,92). Further, cannabis users tend to report a decreased willingness to drive during the first hour after consumption (17,50), though some self-report data suggest otherwise (93). For example, Ménétrey et al. (94) found that 20 or 60 mg of THC administered orally to occasional cannabis users produced self-reports of decreased subject willingness to drive, regardless of the reason posed for driving (e.g. drive a friend to a party or drive an ill child to the hospital). This effect appeared to co-vary

with both blood THC concentration and subjective report of "high." However, there is evidence that while both the euphoric and driving performance effects may both begin within minutes of consumption, driving impairment may persist for several hours, long after subjective feelings and unwillingness to drive subside (92,95). Others have reported that most cannabis users have driven under the influence of cannabis, and in some cases with regularity, challenging the veracity of self-reports of willingness to drive (11).

Thus, cannabis users may reduce their driving speed or following distance or even limit driving altogether shortly after consumption (though this remains controversial), when blood concentrations are highest, but assume their impairment dissipates along with their experience of "high", similar to the effects of alcohol. This could explain, in part, why driving impairment appears greatest from approximately 30–150 min after cannabis use (31) when the subjective effects of cannabis begin to subside and drivers stop using these defensive strategies.

Summary

In summary, there is evidence that cannabis use is associated with an increased risk of crash involvement. However, the relationship between crash risk and the amount of cannabis consumed or the blood concentrations of THC is weak (92). Similarly, there is evidence that cannabis use impairs driving performance, yet this is also only weakly related to the dose consumed (92). Impairment appears maximal at a similar degree of impairment produced by 0.05 g/dl blood alcohol concentration, at least up to common recreational doses (50). Together, these data indicate that blood concentration of THC is a poor index of driving-related risk or impairment (83). Standard field sobriety tests have not been validated to detect cannabis-induced driving impairment, and appear inadequate at doing so (83). Further, these field tests are unable to discern among those with THC concentrations above or below the current legal threshold (≥5 ng/ml) in several states (80).

There are several potential reasons for the poor relationship between either THC dose or blood concentration and crash risk, driving impairment, laboratory measures, or field sobriety tests. These include highly variable blood concentrations across individuals (even after controlled administration) that likely do not reflect brain THC concentrations. Tolerance, or other behavioral adaptations to the effects of THC may also obscure dose or concentration-dependent effects of THC on driving performance.

Implications

There are two critical implications of the poor relationship between blood (or other peripheral) measures of THC or of standard field sobriety tests and driver impairment after recent cannabis use. First, cannabis users have no guidance about when they are again fit to drive. Second, law enforcement have no valid way to assess the extent of impairment in someone they suspect has recently used cannabis.

Drivers have several means of determining when they are likely to fit to drive after consuming alcohol. Convenient "rule of thumb" charts and calculators are available and posted in many bars and provide guidance about how long one should wait before driving, based on one's weight, amount consumed, and drinking duration. Recently, low-cost, portable, personal breathalyzers became widely available. These devices promise to help reduce drunk driving by allowing self-monitoring of blood alcohol concentrations, though data on their effectiveness are lacking. Because blood or other peripheral concentrations of THC (or its metabolites) are poorly related to driving impairment, similar tools would not be helpful for cannabis users, except in locales where legal thresholds have been established.

Recent public service messages have increased awareness that "buzzed" driving is drunk driving. The implication of this is that if one feels intoxicated by alcohol, one should not drive. Alternatively, if enough time has passed for the "buzz" to pass, one is more likely to be fit to drive. However, subjective feelings of intoxication or self-perceived fitness to drive after cannabis use do not predict driving impairment (94,95). Together, the lack of biomarkers (i.e. THC concentration) or a valid subjective assessment to determine fitness to drive after cannabis consumption leaves cannabis users without clear guidance on when or if they are fit to drive.

These same issues impact law enforcement officers trying to prevent cannabis-impaired driving. The lack of a validated field test makes roadside assessment of impairment due to cannabis use difficult. In fact, field tests are poor at detecting recent cannabis use, especially among frequent users (83). Similarly, the poor relationship between blood or other peripheral measures of THC (or metabolite) concentration and driver impairment (92) or crash risk (31) make enforcement of such laws tenuous. Further, developing specific assessments for each impairing substance a driver might have recently used is inefficient and unlikely to be broadly effective as new medications and recreational drugs become available. Indeed, many situations that increase traffic safety risks can not be assessed biologically, or perhaps even with a field sobriety test. For example, older drivers are at higher crash risk than younger

drivers, and may show field sobriety task impairment (96). Similarly, distracted driving threatens traffic safety, but would not be detected using biological tests or perhaps field sobriety tests. Instead, in instances when officers observe and collect compelling evidence of driving that threatens public safety, the driver should be detained regardless of the cause (33). The advent of ubiquitous surveillance cameras on roadways, in vehicles, and on the person of traffic safety officials provides a means for independent assessment (by a judge or jury) of driving behavior that prompted a traffic stop. This is a potentially more effective means of determining traffic risk, across all dangerous situations (97).

Declaration of Interest

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