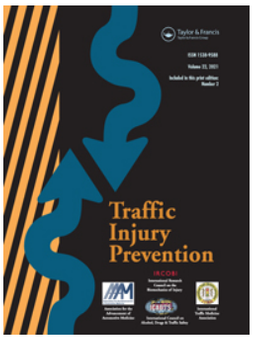

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The failings of *per se* limits to detect cannabis-induced driving impairment: Results from a simulated driving study

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ABSTRACT

Objective: Many jurisdictions use *per se* limits to define cannabis-impaired driving. Previous studies, however, suggest that THC concentrations in biological matrices do not reliably reflect cannabis dose and are poorly correlated with magnitude of driving impairment. Here, we first review a range of concerns associated with *per se* limits for THC. We then use data from a recent clinical trial to test the validity of a range of extant blood and oral fluid THC *per se* limits in predicting driving impairment during a simulated driving task.

Methods: Simulated driving performance was assessed in 14 infrequent cannabis users at two timepoints (30 min and 3.5 h) under three different conditions, namely controlled vaporization of 125 mg (i) THC-dominant (11% THC; <1% CBD), (ii) THC/CBD equivalent (11% THC; 11% CBD), and (iii) placebo (<1% THC & CBD) cannabis. Plasma and oral fluid samples were collected before each driving assessment. We examined whether *per se* limits of 1.4 and 7 ng/mL THC in plasma (meant to approximate 1 and 5 ng/mL whole blood) and 2 and 5 ng/mL THC in oral fluid reliably predicted impairment (defined as an increase in standard deviation of lateral position (SDLP) of >2 cm relative to placebo).

Results: For all participants, plasma and oral fluid THC concentrations were over the *per se* limits used 30 min after vaporizing THC-dominant or THC/CBD equivalent cannabis. However, 46% of participants failed to meet SDLP criteria for driving impairment. At 3.5 h post-vaporization, 57% of participants showed impairment, despite having low concentrations of THC in both blood (median = 1.0 ng/mL) and oral fluid (median = 1.0 ng/mL). We highlight two individual cases illustrating how (i) impairment can be minimal in the presence of a positive THC result, and (ii) impairment can be profound in the presence of a negative THC result.

Conclusions: There appears to be a poor and inconsistent relationship between magnitude of impairment and THC concentrations in biological samples, meaning that *per se* limits cannot reliably discriminate between impaired from unimpaired drivers. There is a pressing need to develop improved methods of detecting cannabis intoxication and impairment.

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Cannabis; THC; driving; per se limits; DUIC; policy

Introduction

Recent policy changes have greatly increased cannabis accessibility and acceptance of use for both medicinal and non-medicinal purposes, making accurate detection of driving under the influence of cannabis (DUIC) a major public safety concern. Legislative approaches toward the detection and prosecution of DUIC generally fall under three categories: effect-based, *per se* and zero-tolerance. Effect-based approaches require proof that a driver was behaviorally impaired at the time of the offense, while the latter two categories involve the collection and testing of biological specimens (typically blood and/or oral fluid) to test for Δ^9-tetrahydrocannabinol (THC). Under *per se* laws, a driver is deemed to have committed an offense if THC is detected at or above a pre-determined cutoff (analogous to blood alcohol concentration (BAC) limits for alcohol), while zero tolerance laws make it an offense for a driver to have any detectable amount of THC (or in some cases, THC metabolites) in a given biological matrix.

In the U.S., 19 states currently have *per se* or zero tolerance laws in place for cannabis (Foundation for Advancing Alcohol Responsibility 2019). For those states with *per se* laws (Illinois, Montana, Nevada, Ohio, Pennsylvania, Washington and West Virginia), cutoffs range from 1 to 5 ng/mL THC in whole blood. In three of these states (Nevada, Ohio and Pennsylvania), *per se* limits also apply to THC metabolites with cutoffs of 1-5 ng/mL for 11-hydroxy-Δ^9-tetrahydrocannabinol (11-OH-THC) and 1 ng/mL for 11-nor-9-carboxy-

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Δ^9-tetrahydrocannabinol (11-COOH-THC). Colorado has a 'reasonable inference' law which states that a driver can be presumed to have been under the influence if their blood contained >5 ng/mL THC at the time of the offense. The remaining states either have zero tolerance laws for THC only (n = 3) or for THC and/or a metabolite (n = 8).

Several international jurisdictions (e.g., Australia, Belgium, France) use oral fluid, rather than blood, to assess DUIC. In Australia, point-of-collection testing (POCT) devices are used to screen drivers' oral fluid for THC at the roadside. Positive results are verified via laboratory analysis. POCT devices are used in some Canadian jurisdictions, although an officer or drug recognition expert (DRE) must also demonstrate that the driver was behaviorally impaired at the time of the offense to prosecute a DUIC case. Screening cutoffs for THC in oral fluid vary depending on the device used: this can be as low as 5 ng/mL (e.g., Securetec DrugWipe 5 s). In jurisdictions with zero-tolerance legislation, the mere presence of THC is sufficient to indicate DUIC; therefore, the screening cutoff is the lowest THC concentration that can be reliably detected by the device, or an otherwise specified cutoff that is appropriate for the test. For roadside drug testing, the screening cutoff may be set to a higher value than the detection limit of the device to minimize the risk of false positives.

Though many jurisdictions use blood or oral fluid *per se* limits to infer DUIC, few controlled studies have explicitly evaluated the utility of extant *per se* limits for predicting driving impairment following cannabis administration. In this report, we explore the validity of a range of oral fluid THC *per se* cutoffs as well as plasma THC cutoffs, meant to approximate whole blood THC *per se* limits, in predicting impairment of simulated driving performance in a sample of infrequent cannabis users who had inhaled vaporized cannabis in a controlled, laboratory setting. Driving impairment was examined 30 min and 3.5 h after vaporization of THC-dominant, THC/CBD-equivalent and placebo cannabis. We also describe data from two participants in detail to illustrate the complexities associated with using biological concentrations of THC as a proxy for impaired driving.

Methods

The methods provide a brief overview of the study design and procedures; additional details are described in our prior report (Arkell et al. 2019) and in the Appendix.

Study methods, design and procedures

Fourteen healthy adult (aged 18-65 years) infrequent cannabis users (≤ 2 uses/week in the previous 3 months) completed this within-subjects, double-blind crossover study. Participants completed three experimental sessions at Royal Prince Alfred Hospital in Sydney, Australia, (separated by ≥7 days), in which they inhaled vaporized THC-dominant ('THC'; 11% THC, <1% CBD; 13.75 mg THC), THC/CBD-equivalent ('THC/CBD'; 11% THC, 11% CBD; 13.75 mg THC and 13.75 mg CBD) or placebo (<1% THC, <1% CBD) cannabis (Tilray, BC, Canada). All procedures were approved by the Sydney Local Health District (RPAH Zone) Human Research Ethics Committee.

Biological sample collection and analysis

Blood and oral fluid samples were collected prior to the first (30 min) and second (3.5 h) driving tasks and analyzed via LC-MS/MS.

Driving simulator and scenarios

In this report, we focus on the results of a car-following task in which participants had to follow and maintain a constant distance to a lead vehicle while driving in steady traffic along a stretch of straight highway. This was completed twice during each experimental session (30 min and 3.5 h after cannabis administration). The primary outcome measure was standard deviation of lateral position (SDLP; lane weaving); a widely-used measure of driving impairment that is highly sensitive to the effects of cannabis and alcohol (Verster and Roth 2011; Hartman et al. 2015b; Helland et al. 2015; Jongen et al. 2017).

Additional outcomes

Subjective drug effects (e.g., "Stoned", "Confident to drive") were evaluated before and after the 30 min and 3.5 h post-dosing driving timepoints using the Drug Effect Questionnaire (DEQ). Self-reported sleep quality and hours of sleep were also collected.

Data analysis

Because most *per se* laws apply to whole blood, a conversion factor of 0.71 (median ratio of whole blood to plasma THC among 32 cannabis users in a vaporized cannabis administration study (Hartman et al. 2015a) was applied to the 5 and 1 ng/mL whole blood limits to yield plasma limits of 7 and 1.4, respectively. Sensitivity, specificity, and agreement analyses determined whether driving performance results (impaired or not impaired) were correctly confirmed by these two plasma cutoffs. We also examined driving performance in relation to two oral fluid THC cutoffs: 5 ng/mL (detection limit for Securetec DrugWipe® and Dräger DrugTest® 5000 POCT devices) and 2 ng/mL (LC-MS/MS limit of detection for oral fluid THC in this study).

Determination of driving impairment in the THC-dominant and THC/CBD-equivalent conditions was based on whether participants' SDLP increased by more than 2 cm from their placebo condition at the respective timepoint (30 min or 3.5 h); this cutoff is consistent with what is considered to be the lowest criterion for clinically relevant driving impairment (Jongen et al. 2017) and is equivalent to the predicted increase in SDLP associated with a BAC of 0.05% (Irwin et al. 2017), the legal alcohol limit in many countries. Therefore, participants with a change in SDLP (from placebo) of greater than 2 cm were considered impaired, while those with a change in SDLP of 2 cm or less were considered not impaired.

Results were categorized as: true positive (driving impairment + biological concentration over *per se* limit), true negative

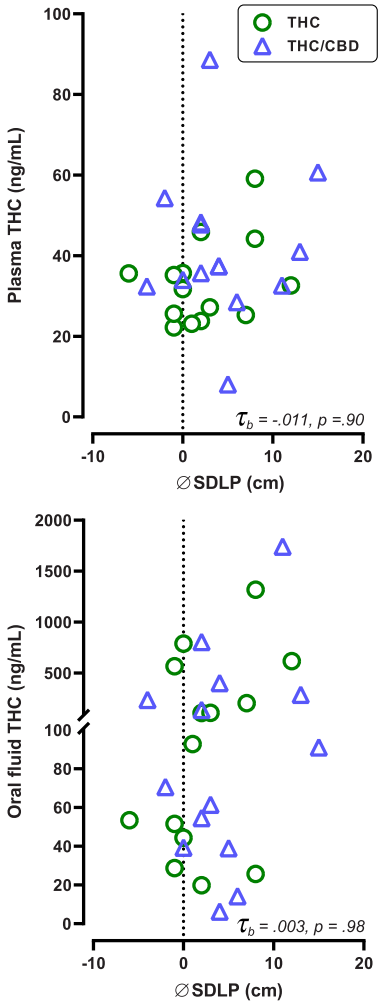

Figure 1. Left panel: Plasma THC concentrations (ng/mL), y-axis, by SDLP values, x-axis, for each individual participant in the THC and THC/CBD conditions. Right panel: Oral fluid THC concentrations (ng/mL), y-axis, by SDLP values, x-axis, for each individual participant in the THC and THC/CBD conditions. Blood and oral fluid THC concentrations were not significantly correlated with driving impairment (SDLP).

(no driving impairment + biological concentration under *per se* limit), false positive (no driving impairment + biological concentration over *per se* limit), or false negative (driving impairment + biological concentration under *per se* limit). Sensitivity, specificity and agreement were calculated as: sensitivity (100 × [TP/(TP + FN)]), specificity (100 × [TN/(TN + FP)]) and agreement (100 × [(TP + TN)/(TP + TN + FP + FN)]).

Results

eTable 1 (Appendix) shows driving and subjective effect data and plasma and oral fluid cannabinoid concentrations for each participant at both timepoints.

Driving performance

Thirty minutes after cannabis administration, 7/14 and 8/14 participants displayed impaired driving in the THC-dominant and THC + CBD conditions, respectively. At 3.5 h after cannabis administration, 6/14 and 10/14 participants displayed impaired driving in the THC-dominant and THC + CBD conditions, respectively. Self-reported sleep quality and hours of sleep prior to study sessions did not influence driving performance (see Appendix).

Table 1. Classification of driving impairment following vaporization of THC-dominant (THC) and THC/CBD-equivalent (THC/CBD) cannabis using *per se* limits of 7 ng/mL and 1.4 ng/mL blood plasma THC.

	7 ng/mL		1.4 ng/mL	
	Time 1 (30 min)	Time 2 (3.5 h)	Time 1 (30 min)	Time 2 (3.5 h)
THC				
#True Positive (%)	7 (50.0)	0 (0)	7 (50.0)	2 (14.3)
#True Negative (%)	0 (0)	8 (57.1)	0 (0)	5 (35.7)
#False Positive (%)	7 (50.0)	0 (0)	7 (50.0)	3 (21.4)
#False Negative (%)	0 (0)	6 (42.9)	0 (0)	4 (28.6)
% Sensitivity	100.0	0.0	100.0	33.3
% Specificity	0.0	100.0	0.0	62.5
% Agreement	50.0	57.1	50.0	50.0
THC/CBD				
#True Positive (%)	8 (57.1)	0 (0)	8 (57.1)	4 (28.6)
#True Negative (%)	0 (0)	4 (28.6)	0 (0)	3 (21.4)
#False Positive (%)	6 (42.9)	0 (0)	6 (42.9)	1 (7.1)
#False Negative (%)	0 (0)	10 (71.4)	0 (0)	6 (42.9)
% Sensitivity	100.0	0.0	100.0	40.0
% Specificity	0.0	100.0	0.0	75.0
% Agreement	57.1	28.6	57.1	50.0

Note: Cutoff for impaired driving = SDLP change from placebo of >2 cm. These cutoffs of 7.0 and 1.4 ng/mL are meant to approximate two common whole blood per se cutoffs (5 and 1 ng/mL) used in the U.S.

Table 2. Classification of driving impairment following vaporization of THC-dominant (THC) and THC/CBD-equivalent (THC/CBD) cannabis using *per se* limits of 5 ng/mL and 2 ng/mL oral fluid THC.

	5 ng/mL		2 ng/mL	
	Time 1 (30 min)	Time 2 (3.5 h)	Time 1 (30 min)	Time 2 (3.5 h)
THC				
#True Positive (%)	7 (50.0)	3 (21.4)	7 (50.0)	3 (21.4)
#True Negative (%)	0 (0)	7 (50.0)	0 (0)	6 (42.9)
#False Positive (%)	7 (50.0)	1 (7.1)	7 (50.0)	2 (14.3)
#False Negative (%)	0 (0)	3 (21.4)	0 (0)	3 (21.4)
% Sensitivity	100.0	50.0	100.0	50.0
% Specificity	0.0	87.5	0.0	60.0
% Agreement	50.0	71.4	50.0	64.3
THC/CBD				
#True Positive (%)	8 (57.1)	2 (14.3)	8 (57.1)	3 (21.4)
#True Negative (%)	0 (0)	4 (28.6)	0 (0)	3 (21.4)
#False Positive (%)	6 (42.9)	0 (0)	6 (42.9)	1 (7.1)
#False Negative (%)	0 (0)	8 (57.1)	0 (0)	7 (50.0)
% Sensitivity	100.0	20.0	100.0	30.0
% Specificity	0.0	100.0	0.0	75.0
% Agreement	57.1	42.9	57.1	42.9

Note: Cutoff for impaired driving = SDLP change from placebo of >2 cm.

Correlations

Neither plasma nor oral fluid THC concentration was significantly correlated with SDLP (Figure 1).

Sensitivity, specificity, and agreement analyses

Full sensitivity, specificity, and agreement results are presented in Tables 1 (plasma) and 2 (oral fluid).

Plasma THC

Median (range) plasma THC concentrations across both active cannabis conditions were 37.6 ng/mL (8.1–88.6 ng/

mL) at 30 min and 1.0 (0.0–2.5) ng/mL at 3.5 h. Both blood plasma *per se* cutoffs (7 and 1.4 ng/mL) produced high rates of false positives at the 30 min timepoint. That is, though all participants had plasma concentrations above these cutoffs immediately after vaping, only 7/14 participants in the THC-dominant condition and 8/14 participants in the CBD + THC condition displayed impaired driving. Participant F, described below, is an example of a false positive at 30 min. Conversely, at 3.5 h, 6/14 cases were false negatives in the THC condition and 10/14 in the THC/CBD condition with the 7 ng/mL cutoff (these participants displayed impaired driving, but their plasma THC levels had fallen under 7 ng/mL by this time). Participant C, described below, is an example of a false negative case at 3.5 h. At the 1.4 ng/mL cutoff 3.5 h after dosing, the incidence of true positives increased, though there were still numerous false negatives and several false positives (Table 1).

Oral fluid THC

Median (range) oral fluid THC concentrations across both active cannabis conditions were 92.0 ng/mL (6.3–1740.6 ng/mL) at 30 min and 1.0 (0–23.7) ng/mL at 3.5 h. At 30 min, both oral fluid *per se* cutoffs used (5 and 2 ng/mL) were similarly ineffective at identifying impaired driving. That is, all samples obtained were above both cutoffs used, but only half of the participants exhibited impaired driving ability. At 3.5 h, 14-21% of cases were true positives with a 5 ng/mL cutoff, and 21% with a 2 ng/mL cutoff and there were few false positives. However, at 3.5 h, 21-57% and 21-50% of cases were false negatives with cutoffs of 5 and 2 ng/mL, respectively (Table 2).

Case studies

Extended descriptions of the case studies are presented in the Appendix.

Participant C

Participant C's SDLP values at the 30 min timepoint were similar in the THC and placebo conditions (29 cm; 30 cm), but markedly increased in the THC/CBD condition (45 cm), suggesting extreme impairment. At 30 min, her rating of "Confident to drive" (5/100) in the THC/CBD condition was far lower than in the THC or placebo conditions (66/100; 46/100). Although Participant C displayed worse driving performance in the THC/CBD condition, she had similar plasma THC concentrations at 30 min in the THC and THC/CBD conditions (35.7 ng/mL vs. 34 ng/ml). Oral fluid THC concentrations were also similar in the THC and THC/CBD conditions (44.4 ng/mL vs. 39.3 ng/mL).

Participant C continued to exhibit significant driving impairment at 3.5 h in the THC/CBD condition (37 cm) relative to her performance in the THC (25 cm) and placebo (24 cm) conditions, indicating that the extreme SDLP values observed at 30 min in the THC/CBD condition were not erroneous. However, at 3.5 h, THC was not detected in plasma or oral fluid in the THC and THC/CBD conditions. Although her driving performance was still impaired at 3.5 h in the THC/CBD condition, her subjective drug effect ratings had decreased and "Confident to drive" ratings had increased markedly relative to 30 min; ratings on these measures were similar at 3.5 h to those in the THC condition where she did not display driving impairment.

Participant F

Contrary to Participant C, Participant F's SDLP values at 30 min were identical in the THC and placebo conditions (20 cm), and slightly higher in the THC/CBD condition (22 cm), just under the SDLP threshold for impairment. His rating of "Confident to drive" was 0/100 in the THC and THC/CBD conditions. His peak plasma THC concentrations were 23.1 ng/mL in the THC condition and 41.0 ng/mL in the THC/CBD condition. Oral fluid THC concentrations were 92.8 ng/mL (THC) and 286.2 ng/mL (THC/CBD). Thus, at 30 min, Participant F had THC levels well above the selected *per se* cutoffs and reported significant subjective impairment yet exhibited no driving impairment.

By 3.5 h, his plasma THC concentrations were < LLOQ in the THC condition and 1.5 ng/mL in the THC/CBD condition while oral fluid THC concentrations were < LLOQ in both conditions. At 3.5 h, SDLP values were highest in the placebo condition and lowest in the THC condition. Despite this, his rating of "Confident to drive" was lower in the THC condition (1/100) than the THC/CBD (19/100) and placebo (96/100) conditions.

Discussion

Per se limits for THC, analogous to BAC limits for alcohol, are increasingly applied as a legal definition of cannabis-impaired driving. The present study explored the validity of several plasma (7 and 1.4 ng/mL; meant to approximate 1 and 5 ng/mL whole blood) and oral fluid (5 and 2 ng/mL) cutoffs in relation to impaired driving performance. We also described two individual participants' experimental sessions in detail to highlight challenges associated with using blood and oral fluid THC concentrations to determine cannabis-related driving impairment.

The blood and oral fluid *per se* limits examined often failed to discriminate between impaired and unimpaired drivers. Moreover, blood and oral fluid THC concentrations were poorly correlated with driving impairment; other studies have likewise shown a poor relationship between blood/oral fluid THC and cognitive/psychomotor performance (Ramaekers et al. 2006; Vandrey et al. 2017). Blood and oral fluid THC concentrations for all participants exceeded extant *per se* limits shortly after vaporization (30 min), but roughly half of participants displayed little or no driving impairment at this time. Conversely, several participants continued to exhibit impaired driving 3.5 h after cannabis exposure, by which time their THC concentrations had typically fallen below the *per se* limits examined here. Thus, following cannabis inhalation, the window of detection for THC in blood and oral fluid is often much shorter than the window of impairment.

The two detailed cases highlight these and other shortcomings of *per se* limits for THC. In the first case,

Participant C exhibited profound driving impairment in one drug condition (THC/CBD) but not the other (THC), yet had similar plasma and oral fluid THC concentrations in both conditions. Participant C (in the THC/CBD condition) also highlights that some individuals may exhibit substantial driving impairment well past the point at which THC is detectable in plasma or oral fluid. This observation has important real-world implications because blood is often collected hours after a crash occurred, by which time THC concentrations may be a fraction of what they were at the time of the crash and therefore poorly representative of a driver's impairment at the time of the crash. Critically, though she was still impaired at 3.5 h, Participant C felt more confident in her ability to drive and reported less intense subjective drug effects relative to those observed 30 min after cannabis exposure. In the second case, Participant F exhibited little to no driving impairment at 30 min, despite having blood/oral fluid THC concentrations well above any existing *per se* cutoff. Despite his apparent lack of impairment at 30 min, Participant F still reported maximal subjective drug effects and very low confidence in his driving ability, suggesting subjective intoxication may be a poor proxy for actual driving ability. Given that his last reported use of cannabis was nearly 2 months prior to study entry, this lack of impairment was not likely due to tolerance. The variability in the magnitude and duration of impairment observed in this study highlights the need to better understand factors that contribute to individual differences in susceptibility to cannabis intoxication.

The present plasma and oral fluid cannabinoid data are consistent with previous studies showing that THC concentrations peak shortly after, or during, cannabis inhalation and decline rapidly thereafter (Huestis and Cone 2004; Spindle et al. 2019). Subjective ratings of intoxication and cognitive impairment, on the other hand, are typically maximal within the first hour of cannabis inhalation and begin to decline slowly thereafter. Because THC is rapidly distributed into tissue and metabolized into 11-OH-THC, which is also psychoactive, blood and oral fluid THC concentrations are typically declining while cannabis' intoxicating and impairing effects are increasing.

With other routes of administration (e.g., oral), THC displays very different pharmacokinetics. For example, following ingestion of brownies containing 10, 25, or 50 mg THC, blood THC concentrations did not exceed 3 ng/mL (10 mg), 4 ng/mL (25 mg) or 5 ng/mL (50 mg) (Vandrey et al. 2017); even though this latter dose is almost four-fold higher than that of the present study, and produced significant cognitive impairment, no participants would have been classified as impaired with a 5 ng/mL *per se* limit. This incongruity is particularly pertinent given the growing popularity of cannabis edibles. Although lower cutoffs (e.g., 1 ng/mL) would seemingly reduce false negatives, chronic cannabis users – analogous to medical cannabis patients using prescribed cannabinoid products on a daily basis - can have low levels of THC in their blood for several weeks to a month after their last use without displaying cognitive or psychomotor impairment (Bergamaschi et al. 2013). While these problems might have been non-issues when cannabis was illegal, in this current context of increasing cannabis legalization, they are very real issues that need to be addressed in current regulation.

Many jurisdictions have adopted *per se* limits for cannabis because they make prosecuting DUIC cases straightforward and mirror policies for alcohol impaired driving. However, it is critical for policy makers to understand that when it comes to easily and reliably detecting drug-induced impairment, alcohol is the exception to the rule. Though alcohol breathalyzers are commonly used to detect alcohol impairment, no analogous biological detection method currently exists for cannabis. Alcohol displays zero-order, or linear, pharmacokinetics, meaning that a constant amount of alcohol is eliminated per unit time from a person's system, independent of the amount of alcohol consumed (Wilkinson 1980). THC, on the other hand, is highly lipophilic and has a short-distribution half-life, meaning that the drug is rapidly taken up into fatty and vascularized tissues from where it is slowly released back into blood (Huestis 2007). Consequently, it is almost impossible to infer how much cannabis was consumed, or when it was consumed, based solely on a given concentration of THC in any biological matrix.

Some jurisdictions rely on standard field sobriety tests to classify DUIC because these tests are proven to be valid predictors of alcohol impairment. However, several controlled studies have found standard field sobriety tests often lack sensitivity to cannabis-induced cognitive/driving impairment (Papafotiou, Carter, and Stough 2005; Bosker et al. 2012). Additional research is needed to identify novel biomarkers of cannabis exposure and objective behavioral measures that can reliably detect cannabis intoxication. Until such novel impairment detection methods are realized, a multidimensional approach to identifying drivers who may be impaired by cannabis is advisable. In cases of suspected DUIC, officers could first look for signs of recent cannabis use (e.g., smell of cannabis, cannabis paraphernalia) and use standardized field sobriety tests (SFST) to assess behavioral impairment, focusing on the individual components of these tests that are most sensitive to cannabis intoxication. If a driver fails this initial assessment, blood and/or oral fluid testing could then follow. Jurisdictions might also consider public health campaigns aimed at decreasing DUIC. Such efforts could educate cannabis users about the unpredictable relationship between cannabis dose and impairment, the additive impairing effects of consuming cannabis with alcohol (Hartman et al. 2015b), the poor relationship between subjective feelings of intoxication and actual impairment, and the differences in onset of effects between inhaled and oral cannabis.

There were several study limitations. First, we only examined infrequent cannabis users, so these data may not be applicable to other populations (e.g., daily users) with greater THC tolerance. Second, while there are clear advantages to using a driving simulator (e.g., safety and experimental control), simulation only partly captures the complexity and experience of real-world driving, and conclusions must therefore be treated with caution. Third, blood plasma samples were collected as opposed to whole blood, but cannabis *per se* laws typically apply to whole blood. Moreover, we applied a conversion factor so that the plasma

per se limits used in this study would approximate common whole blood *per se* limits; the suitability of this approach may have differed across participants. Fourth, although SDLP is a valid and widely used driving impairment measure, we did not examine other factors related to driving impairment (e.g., braking latency). Lastly, there was a delay of 10-20 minutes between the time of blood and oral fluid sampling and the beginning of the driving task; therefore, actual THC concentrations during both drives would have likely been lower than those reported.

Overall, our findings highlight the complexities and limitations with using *per se* limits to identify cases of DUIC. These data are consistent with the conclusion of a recent AAA Foundation for Traffic Safety report that the available scientific evidence does not support the use of quantitative thresholds for THC (Logan, Kacinko, and Beirness 2016). Due to erratic and route-dependent differences in THC pharmacokinetics as well as significant inter- and intra-individual variability, blood and oral fluid THC concentrations, unlike BAC for alcohol, provide little information as to the amount of cannabis consumed or the extent to which an individual may be intoxicated. Collectively, these results suggest that the *per se* limits examined here do not reliably represent thresholds for impaired driving.

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Disclosure statement

Ryan Vandrey has received consulting fees from Zynerba Pharmaceuticals, Battelle Memorial Institute, and Canopy Health Innovations Inc and has received compensation for being on the advisory boards for Insys Therapeutics, Brain Solutions Inc., and The Realm of Caring Foundation. Iain McGregor acts as a consultant to Kinoxis Therapeutics, has received compensation for sitting on the advisory board of BOD Australia and has received speaker fees from Janssen. In addition, Iain McGregor holds patent AU2017904438 pending, and patents WO2019/227167 and WO2019071302 that are relevant to cannabinoid therapeutics.

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