

Review

Association of driving with blood delta-9-tetrahydrocannabinol: a systematic review

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Abstract

Importance: Driving under the influence of cannabis increases the risk of motor vehicle collisions. In some jurisdictions, deterrence rests on the ability to detect delta-9-tetrahydrocannabinol (THC) in blood. Recent evidence suggests that there may be a nuanced relationship of blood THC to driving.

Objective: The purpose of this systematic review was to summarize all published papers investigating the presence of a linear relationship between blood THC and driving, primarily measured by simulated driving in the lab.

Outcomes: The main outcomes assessed included “weaving”/lateral control (eg, standard deviation of lateral position), speed, car following (following distance; coherence), reaction time, and overall driving performance.

Results: Of the 4845 records from the literature search, only 12 met the inclusion criteria. Ten of these reported no significant linear correlations between blood THC and measures of driving (8 out of 9 for “weaving”/lateral control, 4 out of 5 for speed, 2 of 3 for car following tasks (coherence/headway maintenance task), 1/1 for reaction time, 3/3 for overall driving performance). The studies that did find an association between driving and blood THC employed complex driving situations.

Conclusions: This synthesis has important implications for road safety given driving situations can be complex due to challenging road situations and increases in potency of cannabis over the past years. Current methods of detection of impairment may be suited to some types of situations but more large-scale studies on the relationship of blood THC and driving are needed that systematically vary driving complexity and cannabis potency.

Keywords: standard deviation of lateral position; weaving; reaction time; speed; cannabis.

INTRODUCTION

Cannabis increases the risk of a motor vehicle collision.¹⁻⁶ Laboratory studies provide converging evidence that cannabis increases “weaving” (standard deviation of lateral position [SDLP]),⁷⁻¹⁸ slows reaction time,^{8,10,12,19} produces compensatory decreases in speed^{8,10,12,20,21} and results in headway maintenance.^{12,13,20} A number of studies have found that there are dose-dependent changes in SDLP^{9,22} and speed,^{7,10,13,23-25} suggesting that the degree of impairment may be related to the dose or potency of cannabis consumed. While most published studies used potencies of cannabis that are lower than those available on the legal retail market,²⁶ recently there has been some suggestion that there are no dose-dependent increases in changes in driving at potencies up to 13.4%.²⁷

Delta-9-tetrahydrocannabinol (THC) is the psychoactive component of cannabis responsible for its impairing and intoxicating effects. One method of deterring driving after the use of cannabis rests on the ability to detect THC in the blood of the driver. The THC concentration in the blood at which driving is believed to be impaired varies by jurisdiction but is generally in the range of 2 to 5 ng/mL.²⁸ Given that there is some evidence for a dose-response relationship of driving to potency of cannabis, it is of interest to determine whether there is a linear relationship of blood THC to driving. Demonstration of a clear relationship between changes in driving and blood THC would help to provide guidance into the detection of cannabis-impaired driving.

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The purpose of the present synthesis was to review all published reports that attempted to determine whether blood THC is related to driving. Particular attention was paid to studies that employed correlational or regression analyses to attempt to elucidate whether there is a linear relationship between blood THC and driving. A literature search was conducted on peer-reviewed papers published until 2023 that measured both driving (simulated or on-the-road) and blood THC. The relationship of driving variables to blood THC was assessed.

METHODS

This study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines.²⁹ A protocol was pre-registered on Prospero, the international prospective register of systematic reviews (registration number CRD42023493758).

Information Sources and Search Strategy

A comprehensive search strategy (see [Supplementary Material, eAppendix 1](#)) was drafted in Ovid Medline by a Medical Librarian (R.B.) and refined with input from the research team. The following terms were searched broadly (THC/cannabis) AND (blood or oral fluid or substance detection) AND driving. The Medline strategy was adapted into PsycINFO, Embase, Cochrane Central, Cochrane Database of Systematic Review via Ovid platform, Web of Science's Core Collection, Ebsco's Criminal Justice Abstracts, ProQuest's Dissertations & Theses Global, and Transport Research International Documentation (TRID Database). All strategies used database-specific syntax, and controlled vocabulary when translated. To increase the specificity of results, an animal studies filter was used³⁰; no further limits were applied. Each database was searched from inception to September 2023. Reference lists of included articles were scanned to identify further studies meeting eligibility criteria.

All database records were imported into Covidence for de-duplication and title and abstract screening. Endnote, a citation and reference management tool, was also used to manage records.

Inclusion Criteria

The primary focus of this synthesis was to evaluate studies that conducted a correlational analysis between blood THC and driving (on-the-road or simulated). However, understanding that this may not capture the breadth of knowledge and literature on the topic, similar measures of association such as linear regression or general linear model (GLM) regressions were also included. Only studies in English were included, due to the lack of personnel available to translate and complete the full-text extraction and risk of bias assessment.

Only peer-reviewed published articles were included of the following types: randomized controlled trials (RCTs), before-and-after studies, cohort, case-control, cross-sectional, and longitudinal studies. Only studies of human participants were included that focused on the acute effects of cannabis (ie, in the hours after administration). Moreover, this review only included studies of the effects of THC-dominant cannabis and not cannabidiol. Driving measures of interest included but were not limited to SDLP ("weaving"), reaction time, mean speed, maximum speed, collisions, and for car following tasks (coherence/headway maintenance task—the ability to consistently follow the lead vehicle).

Exclusion Criteria

The review excluded the following study designs: meta-analyses/reviews, case studies, and qualitative studies. Conference abstracts and posters and grey literature were also excluded.

Selection and Data Collection Process

All the articles from the literature search were transferred into Covidence. Following the removal of duplicates, title/abstract screening, full-text review, and data extraction were completed independently by 2 authors (D.B., S.Z.). Full-text review was followed by data extraction (see [eTable 1](#) and [eAppendix 2 in Supplementary Material](#)), which was completed independently on Covidence by 2 authors (D.B., S.Z.). Any disagreement or conflict was addressed through discussion, and a third reviewer (P.D.C.) was consulted on differences that could not be resolved.

Risk of Bias

Following full-text extraction, 2 authors (D.B., S.Z.) utilized the Scottish Intercollegiate Guidelines Networks (SIGN) methodology checklists to individually assess the risk of bias for the included studies.³¹ Any disagreement or conflict was addressed through discussion, and a third reviewer (P.D.C.) was consulted for a final decision on differences that could not be resolved. The SIGN methodology checklists assess the risk of bias through the following characteristics: study design, randomization, concealment, blinding, allocation, treatment vs control group differences, outcome assessment method, attrition, and confounding. It ends with an overall assessment of the study as either high quality, acceptable, low quality, or unacceptable (reject). This provides a method to rank the degree of bias present in the study, and the overall confidence in the results.

As per the protocol, correlational analysis on oral fluid THC and driving measures was also observed. However, given the limited literature available, there is not sufficient data to be presented as part of the "results" synthesis, but it is discussed in [eAppendix 3 of the Supplementary](#).

RESULTS

The selection process is visualized from the PRISMA Flow Diagram attached as [Figure 1](#). The literature search resulted in 4845 records. After the literature search, another 2 studies relevant to the review were published and were also included. Overall, a total of 1648 duplicates were removed, leaving 3199 unique articles to be screened. From these, 3102 were excluded during the title and abstract screening. Of the remaining 97 articles, 96 underwent full-text screening, as one study could not be retrieved. Of the 96 articles screened, 12 were included in the review. An overall breakdown of the reasons for study exclusion is provided in [Figure 1](#). Overall, the included studies date from 1998 to 2024.

Of the 12 papers included, 11 used inhaled (smoked/vaped) routes, and 1 used edibles ([Table 1](#)). Only 2 papers studied oral fluid ([eAppendix 2 in Supplementary Material](#)). Although the studies varied in endpoints and the number of blood collections and drives, 9 of the 12 studies' first blood collection and drive used for data were within 30 min of cannabis consumption. One study had a comparable drive time of 40 min,²² while another³⁶ had a drive time of 60 min. The only study²¹ with a significantly delayed first drive time of 120 min, was the sole edibles study in this review.

Weaving/Lateral Control

Nine articles included data on blood THC and SDLP or other measures of lateral control; 8 found no relationship and 1 found a relationship. Zhao et al.²¹ was the sole study to use edibles and participants consumed an average of 7.30 mg THC, and Pearson r correlations revealed no significant correlation between blood THC and SDLP (single task: $r = -0.202$, $P = .366$; dual task:

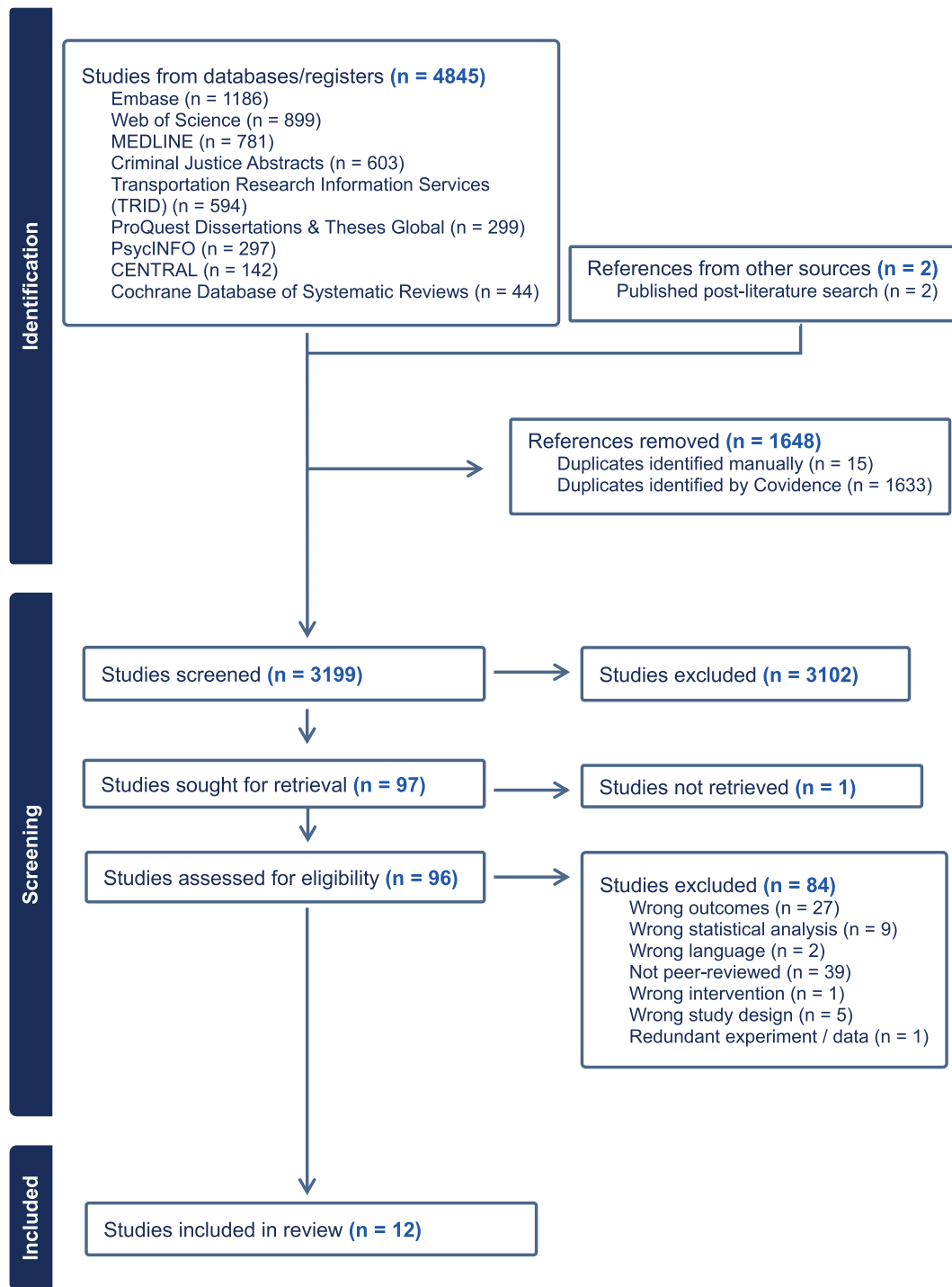


Figure 1. PRISMA flow diagram for study selection

$r = -0.096$, $P = .671$). In Arkell et al.³³ participants vaped 13.75 mg THC and upon conducting Kendall's tau-b correlation, found that blood THC was not significantly correlated ($T_b = -0.11$, $P = .90$) with SDLP. For Robbe,²² participants smoked 20.8 mg THC on average and reached the same conclusion that there was no significant correlation between blood THC and SDLP or mean lateral position. In Hartley et al.,³⁶ participants smoked doses of up to 30 mg THC and used linear regression to determine that there was no significant association between blood THC pharmacokinetic parameters (C_{max} , T_{max} , and area under the curve (AUC))

and SDLP. In Di Ciano et al.,⁷ participants smoked an average of 56.93 mg THC, and there was no significant correlation (Pearson's r) between blood THC and SDLP (single task $r = 0.147$, $P = .43$; dual task: $r = 0.027$, $P = .89$). For Brands et al.,²³ participants smoked 93.75 mg THC and using bivariate correlations discovered that there was no significant correlation (single task $r = -0.16$, $P = .21$; dual task $r = 0.16$, $P = .22$) between blood THC and change in lateral control. In Di Ciano et al.,³⁴ participants smoked 94 mg THC and upon conducting Spearman's correlations, also found that blood THC did not significantly correlate ($r = 0.201$) with SDLP.

Table 1. General characteristics of included articles.

Authors, year	Study design	Sample size (% female)	Age range/mean	Cannabis use inclusion	Cannabis administration	THC dose	Driving assessment scenario	Driving measures	Method of assessing association	Blood draw and driving times used for assessment	Significant association
Studies using inhaled routes for cannabis that found a relationship between blood THC and driving											
Hartman et al., 2015 ⁶	Randomized controlled trial (RCT)	18 (27.8%)	21–37 Mean = 26.1	Cannabis use ≥ 1×/3 months but ≤ 3 days/week over the past 3 months	-Vaped -Ad libitum	Placebo 2.9% THC (~14.5 mg THC) 6.7% THC (~33.5 mg THC)	NADS-1 Driving simulator - Urban (2-lane city roadway; 40–72 km/h with signal—controlled/uncontrolled intersections) - Interstate (4-lane expressway; 113 km/h) - Rural (2-lane undivided roads with curves, a gravel portion, and 10 min timed straightaway)	SDLP - dual task Standard deviation of steering wheel (curvy and straight routes) - dual task Lane departures/min - dual task Maximum lateral acceleration (sharp and non-sharp events) - dual task	General linear model (GLM) regression models	Blood 0.17 h, 0.42 h, 1.4 h, and 2.3 h after inhalation Drive 0.5 to 1.3 h after inhalation	Yes
Hartman et al., 2016 ⁶	RCT	18 (27.8%)	21–37 Mean = 26.1	Cannabis use ≥ 1×/3 months but ≤ 3 days/week over the past 3 months	-Vaped -Ad libitum	Placebo 2.9% THC (~14.5 mg THC) 6.7% THC (~33.5 mg THC)	NADS-1 Driving simulator - Urban (2-lane city roadways; 40–72 km/h with signal—controlled/uncontrolled intersections) - Interstate (4-lane expressway; 113 km/h) - Rural (2-lane undivided roads with curves, a gravel portion, and 10 min timed straightaway)	Mean speed - dual task Standard deviation of speed - dual task Percent speed high - dual task Percent speed low - dual task Car following (Mean following distance) - dual task Maximum longitudinal acceleration (high/low) - dual task Minimum longitudinal acceleration (low/stopping) - dual task	GLM regression models	Blood 0.17 h, 0.42 h, 1.4 h, and 2.3 h after inhalation Drive 0.5 to 1.3 h after inhalation	Yes

Table 1. Continued

Authors, year	Study design	Sample size (% female)	Age range/mean	Cannabis use inclusion	Cannabis administration	THC dose	Driving assessment scenario	Driving measures	Method of assessing association	Blood draw and driving times used for assessment	Significant association
Studies using inhaled routes for cannabis that did not find a relationship between blood THC and driving											
Tank et al., 2019 ³²	Controlled trial	15 (20%)	19–41 Mean = 25	Regularly consumed between 1 g and 7 g per week and at least twice per month within the past 6 months	-Smoked -Ad libitum	Used 22% dronabinol 300 µg of THC/kg bodyweight per cigarette (could smoke up to 3 cigarettes)	Modified VW up/ Driving simulator -City (urban)	Driving performance (accidents, roadway deviation, traffic lights) - single task	Correlation	Blood Carried out after each simulated drive Drive First [post smoke] drive is shortly after the last joint is smoked. Second drive 3 h after inhalation. Third drive 6 h after inhalation.	No
Arkell et al., 2021 ³³	RCT	14 (21%)	21–38 Mean = 27.5	Infrequent cannabis use (≤ 2 times/week in the previous 3 months and ≥ 10 lifetime exposures)	-Vaped -Fixed	Placebo THC-dominant - 13.75 mg THC THC/CBD equivalent - 13.75 mg THC	Driving simulator -5-min highway segment (2 lane; 90–110 km/h) -25 min, both highway and rural segments (single lane; 60–100 km/h)	Standard deviation of lateral position (SDLP) -Single task	Kendall's tau-b (τ_b) correlation	Blood 30 min and 3.5 h (prior to driving) after inhalation Drive 30 min and 3.5 h after inhalation	No
Robbe 1998 ²²	RCT	Study 1–24 (50%) Study 2–16 (50%) Study 3–16 (50%); 32 with alcohol group	21–40	Smoked the drug more than once a month, but not daily.	-Smoked -Fixed	THC conditions: -100 µg/kg -200 µg/kg -300 µg/kg Mean THC consumed—20.8 mg THC	On-the-road driving - Closed highway -Highway in the presence of other traffic -City driving	SDLP - single task Mean lateral position - single task Maintaining constant speed - single task Standard deviation of speed - single task Car following test - single task Overall driving proficiency test - single task	Correlation	Blood 30 min and 90 min after inhalation Drive 40 min and 100 min after inhalation	No

Table 1. Continued

Authors, year	Study design	Sample size (% female)	Age range/mean	Cannabis use inclusion	Cannabis administration	THC dose	Driving assessment scenario	Driving measures	Method of assessing association	Blood draw and driving times used for assessment	Significant association
Hartley et al., 2019 ³²	RCT	30 (0%)	20–34 Mean = 21.5	2 groups: chronic consumers smoking 1 or 2 joints/day occasional consumers smoking 1 or 2 joints/week.	-Smoked -Fixed	Placebo 10 mg THC 30 mg THC	York driving simulator -Four-lane highway	SDLP -single task Mean reciprocal reaction time (mRRT) -single task	Linear regression	Blood 5 min, 15 min, 30 min, 1h, 2 h, 4 h, 6 h, 8 h, 12 h, 24 h after inhalation Drive 1 h, 2 h, 4 h, 6 h, 8 h, 12 h, 24 h after inhalation	No
Di Ciano et al., 2024 ³⁴	Cohort	31 (32%)	65–78 Mean = 68.7	Cannabis use at least once a month, and at least once in the previous 6 months	-Smoked -Ad libitum	Mean THC consumed—56.93 mg/18.74%	Virage V5500M driving simulator - Rural highway (2 lane—80 km/h)	SDLP -single task and dual task Mean Speed -single task and dual task	Pearson r correlation	Blood 30 min and 180 min after inhalation Drive 30 min and 180 min after inhalation	No
Brands et al., 2019 ³³	RCT	91 (29%)	19–25	Regular cannabis users (1–4 days/week)	-Smoked -Ad libitum	Placebo [30] THC group - 12.5% THC (93.75 mg THC) [61]	Virage V5500M driving simulator - Rural highway (2 lane—80 km/h)	Change in mean speed -single task and dual task Lateral control (mean absolute deviation in meters from the center of the lane) -single task and dual task	Pearson r correlation	Blood 30 min after inhalation Drive 30 min after inhalation	No
Di Ciano et al., 2023 ³⁴	RCT	27 (44%)	Mean = 22.54	Use of cannabis at least once a week	-Smoked -Ad libitum	Placebo alcohol and active cannabis group ~ 94 mg THC	Virage V5500M driving simulator - Rural highway (2 lane—80 km/h)	SDLP -single task	Spearman's correlation	Blood ~20 min after inhalation Drive ~20 min after inhalation	No
Fitzgerald et al., 2023 ³⁵	RCT	191 (38%)	Mean = 29.9 years	2 groups: Frequent users: ≥ 4 times/week Occasional users: ≥ 4 times/week but less than < 4 times/week	-Smoked -Ad libitum	Placebo (0% THC) [63] 5.9% THC (~ 41 mg THC) [66] 13.4% THC (~ 94 mg THC) [62]	STISIM M300WS-console driving simulator -City (urban) -Country (rural)	SDLP -single task Car following (coherence) -single task	Spearman's correlation	Blood 13 min, 86 min, 200 min, and 262 min after inhalation Drive 26 min, 96 min, 211 min, and 273 min after inhalation	No

Table 1. Continued

Authors, year	Study design	Sample size (% female)	Age range/mean	Cannabis use inclusion	Cannabis administration	THC dose	Driving assessment scenario	Driving measures	Method of assessing association	Blood draw and driving times used for assessment	Significant association
Marcotte et al., 2022 ⁷	RCT	191 (38.2%)	Mean = 29.9 years	Using cannabis 4 or more times in the past month	-Smoked -Ad libitum	Placebo (0% THC) [63] 5.9% THC (~ 41 mg THC) [66] 13.4% THC (~ 94 mg THC) [62]	STISIM M300WS-console driving simulator -City (urban) -Country (rural)	Composite drive score -dual task	Spearman's correlation	Blood 15 min, 60 min, 90 min, 125 min, 200 min, 240 min, 260 min, and 315 min after inhalation Drive 30 min, 1.5 h, 3.5 h, and 4.5 h after inhalation	No
Zhao et al., 2023 ²¹	Cohort	22 (27%)	19–74 Mean = 47.59	Use of cannabis edibles at least once in the past 6 months	-Edibles - Ad libitum	Mean THC consumed—7.30 mg	Virage VS500M driving simulator -Rural highway (2-lane)	SDLP -single task and dual task Mean speed -single task and dual task	Pearson r correlation	Blood 120 min after inhalation Drive 120 min after inhalation	No

Study using oral/edibles routes for cannabis that did not find a relationship between blood THC and driving

Abbreviation: THC, delta-9-tetrahydrocannabinol.

In Fitzgerald et al.,³⁵ participants similarly smoked doses up to ~94 mg THC and using Spearman's correlations discovered that blood THC was not significantly correlated ($r = -0.02$, $p_{adj} = 0.89$) with SDLP.

Hartman et al.¹⁶ was the only study that found a significant relationship of blood THC to SDLP. Their participants inhaled up to ~33.5 mg THC and conducted GLM regression models, finding a significant association ($b = 0.26$, $P = .0004$) between blood THC and SDLP. The data from the model indicated that for every 1 $\mu\text{g/L}$ increase in blood THC, there was a 0.26 cm increase in SDLP. However, there was no association between blood THC and the standard deviation of the steering wheel (curvy and straight routes), lane departures/min, or maximum lateral acceleration (sharp and non-sharp events).

Speed

Five of the included studies included measures of blood THC and speed, 4 of these studies found no relationship of blood THC to speed. Zhao et al.²¹ found no significant correlation between blood THC and mean speed (single task: $r = 0.151$, $P = .503$; dual task: $r = 0.139$, $P = .536$). Robbe²² conducted a correlational analysis and found no significant correlation between blood THC and maintenance of constant speed or standard deviation of speed. Di Ciano et al.⁷ also found no significant correlation between blood THC and mean speed (single task: $r = 0.206$, $P = .27$; dual task: $r = 0.056$, $P = .76$). Brands et al.²³ conducted Pearson r correlations and found no significant correlation (single task $r = -0.18$, $P = .15$; dual task $r = -0.083$, $P = .53$) between blood THC and change in mean speed.

Hartman et al.²⁰ conducted GLM regression models and found significant associations between blood THC and mean speed relative to the speed limit ($b = 0.11$, $P < .0001$) and percent speed low [percent of time spent $> 10\%$ below the speed limit] ($b = 0.07$, $P < .0001$). Essentially, higher blood THC was associated with decreased mean speed and increased time spent at low speeds. However, they also found that blood THC was not associated with a standard deviation of speed, percent speed high, maximum longitudinal acceleration, and minimum longitudinal acceleration.

Car Following (Coherence/Headway Maintenance Task)

Three studies conducted car following tasks, with 1 finding a significant correlation. Robbe²² conducted a car following test and found no significant correlation with blood THC. Fitzgerald et al.³⁵ observed the association between coherence and blood THC, and upon using Spearman's correlations, found no significant correlation ($r = -0.102$, $P = .46$) between the 2.

Hartman et al.²⁰ conducted GLM regression models and found significant associations between blood THC and headway maintenance [mean following distance] ($b = 2.18$, $P = .0139$). Higher blood THC was associated with increased following distance.

Reaction Time

Hartley et al.³⁶ was the only study to analyze reaction time and found no significant association between blood THC pharmacokinetic parameters (C_{max} , T_{max} , and AUC) and mean reciprocal reaction time using linear regression.

Overall Driving Performance

Three studies focused on correlating blood THC with overall driving performance, and none found a significant correlation. Robbe²² conducted the Royal Dutch Tourist Association's Driving

Proficiency Test and found no significant correlation with blood THC. Tank et al.³² gave their participants 300 μg THC/kg body-weight per cigarette with a 3-cigarette allowance, resulting in blood THC concentration ranging from 2.4 to 42.9 ng/mL. They found no significant correlation between blood THC and overall driving performance (which included measures such as collisions, roadway deviation, and traffic lights). In a study conducted by Marcotte et al.,²⁷ participants smoked doses going up to ~94 mg THC; using Spearman's correlations, no significant correlation ($r = 0.025$, $P = .78$) between blood THC and the composite drive score (incorporates lane tracking and car following) was found. Hence, both articles are in agreement that there is no correlation between blood THC and composite measures of overall driving performance.

Quality of Studies

Using the SIGN methodology checklists, all 12 studies were assessed for bias. Nine of the included studies were RCT studies, all of which were assessed to be of high quality.^{16,20,22,23,27,34-36} The 2 cohort studies were assessed to be of high quality.^{7,21} The exception was Tank et al.,³² a controlled trial which was assessed using the RCT checklist and determined to be of acceptable quality. A summary of the risk of bias assessment is available in [eTable 3 in the Supplementary Material](#).

DISCUSSION

The purpose of the present synthesis was to evaluate the peer-reviewed papers published on the relationship between driving and blood THC levels. Of the 12 papers included in the present review, 10 found no correlation between blood THC and any measure of driving,^{7,21-23,27,32-34,36} including SDLP, speed, car following, reaction time, or overall driving performance. The 2 papers that did find a significant association were from the same study and found a significant relationship with blood THC and SDLP,¹⁶ speed, and following distance.²⁰

The consensus is that there is no linear relationship of blood THC to driving. This is surprising given that blood THC is used to detect cannabis-impaired driving. However, roadside detection is based on cutoffs, which vary by jurisdiction.²⁸ In this regard, one manuscript found that SDLP was significantly higher in people whose blood THC was above the legal cutoff of 5 ng/mL than those who were below.³⁴ Similarly, when a median split was conducted based on levels of blood THC data at 7.3 ng/mL, there were more changes in driving in those above the median split.²³ In these same studies,^{23,34,37} there were no correlations between blood THC and driving. Thus, there may be limits above which driving is impaired, which may explain why the one study with high doses found significant correlations between driving and blood THC.³⁸

The 2 Hartman et al.^{16,20} papers that came from the same study and found significant relationships between blood THC and driving, used complex driving situations that consisted of a combination of rural, urban, and interstate roads. By comparison, the other studies used either rural roads^{7,21-23,36,34} or urban³² situations. Only a few studies combined the use of 2 types of drives within a single scenario.^{22,27,33,35} Additionally, the Hartman et al.^{16,20} simulated drives were more complex as they included distractors such as deer emerging in rural areas, car doors opening into traffic, and kids on bicycles. They also conducted the drives under dual task conditions, which only a few of the other studies^{7,21,23,27} integrated. The dual tasks placed additional cognitive load on participants

and required divided attention as they involved watching lights in the rearview mirror and selecting a specific music CD title. Thus, the only 2 studies which combined more than 2 types of drives, had complex distractors and observed dual task conditions, found significant correlations between blood THC and driving. Thus, scenario and task complexity may be an important variable in revealing an association between blood THC and driving. Future studies will need to vary the task demands of the drive to unravel the complex relationship of blood THC to driving.

One variable which may have influenced the results is the potency of cannabis used and the method of administration. An abstract submitted³⁸ suggests dose-related effects of THC on measures of driving. In this study, the highest dose condition provided participants with 22% THC or up to 165 mg THC in a procedure that involved a fixed dose administration. Both SDLP (slope = 0.01, SE = 0.001, $P < .001$) and reaction time (slope = 0.01, SE = 0.003, $P < .001$) showed significant positive associations with blood THC. This indicates that for each 1 ng/mL increase in blood THC, SDLP increased by 1 cm, and reaction time increased by 10 milliseconds. It was noted that minimal differences were observed in the low (6.25%/up to 47 mg THC) and medium dose (12.5%/up to 94 mg THC), but consistent and significant differences were present in the high dose.³⁸ It is known that the potencies of cannabis on the legal market are increasing,²⁶ and thus it can be inferred that people are using higher doses of THC than those used in most existing studies. In addition, the fixed dose procedure used in part of this study may have influenced the results.³⁹ Ad libitum dosing studies may lead to increased variability in the data with little distinction between doses,^{27,35} as people can titrate to their desired effect. Orderly relationships between blood THC and driving may be evident only with discrete increments in dosing. Future studies will need to include more realistic higher potency cannabis, and vary the dosing method, because it is possible that blood THC may have orderly relationships to higher potency cannabis use.

Other variables that may influence the results are different driving simulators and driving tasks across studies. Many studies in this systematic review used different simulators, and the studies that did use the same simulator were likely from the same laboratory. Different models may vary in their degree of fidelity, which could influence results when making direct comparisons. Moreover, beyond scenario complexity, differences in dictated speed and scenario length, while measuring the same outcome, could impact the results of direct comparisons. Moving forward, having a greater degree of standardization may help eliminate these differences. Future studies should also look to provide additional information on the data collected, such as the resolution for measurements (ie, 10 Hz vs 60 Hz), which would assist in the interpretation and comparison of results.

Limitations

This synthesis is not without limitations. First, all but one²¹ of the included studies investigated the inhaled (smoked, vaped) route of administration. The use of edibles is on the rise⁴⁰⁻⁴² and edibles have a different pharmacokinetic relationship than the inhaled route,⁴³⁻⁴⁹ which suggests that the relationship of cannabis edibles to blood THC may be different. Additionally, the study²¹ had a noticeably low THC concentration of 2.8 ng/mL, 2 hours after oral consumption of a low average 7.3 mg THC. Given the differing pharmacokinetics of oral THC ingested through edibles, lower blood THC concentrations are expected due to variable absorption, degradation in the stomach, and first-pass metabolism.^{50,51}

Our study³⁴ with inhaled cannabis found that changes in driving are smaller below 5 ng/mL, but it is not clear at this time whether this is also true for edibles, and should be a focus for future research.

Further, only 2 studies used naturalistic designs.^{7,21} With legalization, it is now possible, in some jurisdictions, to study a user's preferred legal source of cannabis in the lab. In addition to the considerations around the potency of cannabis and method of administration, future studies should vary task complexity with a variety of routes of administration, both controlled and naturalistic.

Conclusions

The present synthesis suggests that driving after the use of cannabis may be difficult to detect through blood THC, except in situations where there is a high task complexity; there is some evidence for a relationship when the potencies of cannabis are high. Driving can involve a number of challenging situations and future studies will need to explore the relationship of THC to driving after a number of different task situations and cannabis potencies.

Supplementary material

Supplementary material are available at *International Journal of Neuropsychopharmacology* (IJNPPY) online.

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None.

Author contributions

Danial Behzad (Data curation [equal], Formal analysis [equal], Writing—original draft [equal]), Sampson Zhao (Data curation [equal], Formal analysis [equal]), Reena Besa (Data curation [equal], Formal analysis [equal]), Bruna Brands (Writing—review & editing [equal]), Christine M. Wickens (Writing—review & editing [equal]), Marilyn A. Huestis (Writing—review & editing [equal]), Bernard Le Foll (Writing—review & editing [equal]), and Patricia Di Ciano (Conceptualization [lead], Project administration [lead], Supervision [lead], Writing—original draft [equal])

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Conflicts of interest

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He has participated in a session of a National Advisory Board Meeting (Emerging Trends BUP-XR) for Indivior Canada and is part of the Steering Board for a clinical trial for Indivior. He has been a consultant for Shinogi. He got travel support to attend an event by Bioprojet. He is supported by CAMH, Waypoint Centre for Mental Health Care, a clinician-scientist award from the Department of Family and Community Medicine of the University of Toronto, and a Chair in Addiction Psychiatry from the Department of Psychiatry of the University of Toronto.

Data availability

Data will be made available upon approval, by request to the corresponding author

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