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Recreational Marijuana and Traffic Fatalities: Sensationalism or New Safety Concern

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RECREATIONAL MARIJUANA AND TRAFFIC FATALITIES: SENSATIONALISM

OR NEW SAFETY CONCERN?

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Abstract

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Recreational marijuana continues to gain support in the United States. As of early 2018, nine states and the District of Columbia have made recreational marijuana use legal, despite the federal stance that marijuana is a dangerous and highly abused substance. Although marijuana impairs a driver's ability to operate a vehicle, previous research has shown that medical marijuana laws decreased fatality rates, likely due to substitution away from alcohol. In contrast to the literature on medical marijuana, this study finds that recreational marijuana legalization is associated with a 7-17 percent increase in traffic fatalities; part of this increase in traffic fatalities is lagged, and may be attributable to changing attitudes towards marijuana use and commercial availability of the drug. There is a lack of evidence to suggest that recreational marijuana legalization is associated with a decrease in drunk driving prevalence.

I. Introduction

Since the end of 2012, there has been unprecedented nationwide movement towards legalization of marijuana for recreational use in the United States. Beyond decriminalization of marijuana possession, referendums passed in Washington and Colorado in 2012 allowed for retail stores to sell recreational marijuana after obtaining permits, just as liquor stores sell alcohol through liquor licenses. As of January 2018, Alaska, Oregon, Maine, Massachusetts, Nevada, California, Vermont, and the District of Columbia have joined Colorado and Washington in legalizing recreational marijuana.[1] Over 20% of the U.S. population now lives in states with legal recreational marijuana, and the industry is expected to grow to almost $22 billion by 2020 (Huddleson 2016). States may be enticed to legalize marijuana to create jobs and generate additional tax revenue.

Gallup polling has shown consistent increases in the acceptance of marijuana legalization since the late 1990s (Figure 1). With such a substantial portion of Americans approving recreational use of marijuana, it's important to understand the problems potentially surrounding marijuana legalization. Opponents commonly cite marijuana's addictive properties, harm to youth, and effect on road safety (Drug Rehab 2015, Strouse 2016, New Health Advisor 2018). This paper investigates the third of these concerns.

Utilizing data from the Fatality Analysis Reporting System (FARS) from 2009-2016 and controlling for spatial and temporal trends, this paper shows how traffic fatalities have changed in association with state adoption of recreational marijuana laws. Although previous research has shown a negative or null effect of marijuana liberalization on traffic fatalities, I present evidence that Washington and Colorado have seen significant increases in their traffic fatality

[1] Vermont and Washington D. C. have not legalized the sale of marijuana for recreational use. It is legal to possess marijuana but you cannot buy or sell it.

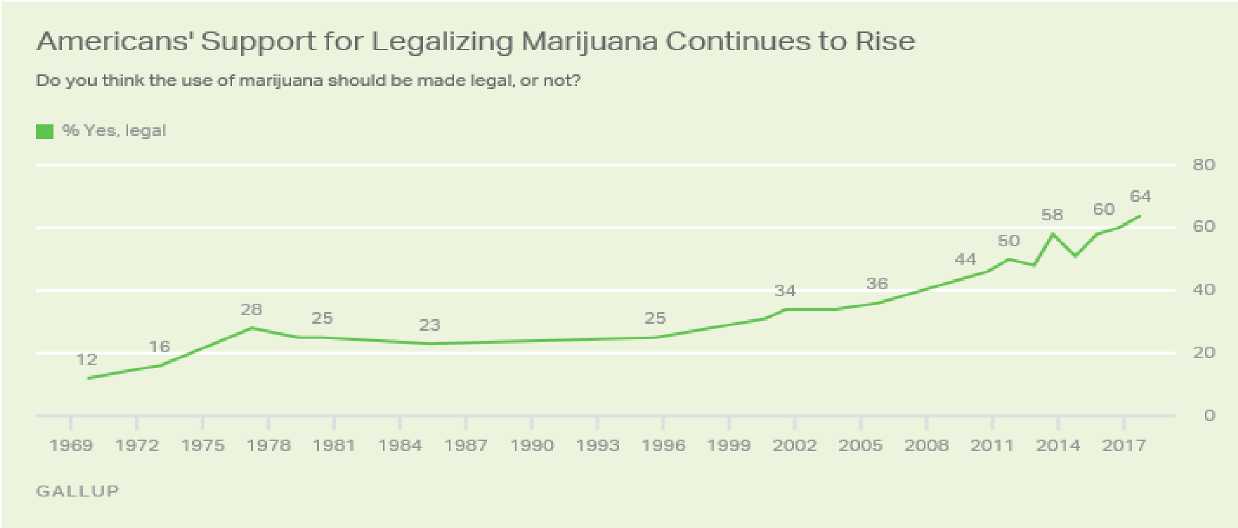

Figure 1 (95% confidence interval has margin of error ± 4%)
http://news.gallup.com/poll/221018/record-high-support-legalizing-marijuana.aspx

rates after legalizing marijuana. I investigate effects on drunk driving fatalities by estimating changes in night time and weekend fatalities where alcohol related crashes are overrepresented. There is weak evidence that Washington and Colorado have had fewer alcohol related crashes due to recreational marijuana legalization.

I expand the sample to include Oregon and Alaska (both of which legalized recreational marijuana in early 2015) to check consistency of results. Estimates from this regression are larger in magnitude and likely due in part to the shorter post-treatment sample period. Effects of recreational marijuana legalization on traffic fatality rates are nonetheless precisely estimated and significant. Alcohol related traffic fatalities have risen in Oregon and Alaska since marijuana legalization.

The rest of the paper proceeds as follows. Section II delves into the history of marijuana laws in the United States, including the stance of the federal government to individual state marijuana legalization. Section III reviews literature related to marijuana's effect on driving. Section IV presents the data and methodology. Section V begins with results from the restricted sample looking at traffic fatality rates in Washington and Colorado, before expanding the scope to include all 50 states. Section VI checks for methodological problems, and Section VII concludes.

II. Background

The legal status of marijuana use has been a subject of American debate since at least the early 20th century. Previous to this time period, cannabis (another name for marijuana) was recognized in the *United States Pharmacopoeia* and was used in many medications (Bilz 1992), mostly in extract form. Recreational marijuana was popularized in the late 1800s by Mexican immigrants, and racism likely played a strong role in shaping future policy (Bilz 1992). In the early 1900s marijuana was classified as a narcotic causing insanity and death, even at a time when people were unaware that marijuana was the same as cannabis (Gieringer 1999). Riding the back of the Progressive Era moral reform, California became the first state to make cannabis use illegal in 1913, and the first state arrest for illegal use was made in 1919 (Gieringer 1999). From 1913 onward, other states joined California in making marijuana illegal, and in 1937 the Marihuana Tax Act was passed, de facto ending marijuana's use as a prescription drug due to the associated costs invoked by the Act (Bilz 1999).

In 1970 marijuana's national identity was solidified by the Controlled Substances Act, which placed marijuana into the Schedule I category. To qualify as a Schedule I drug, the drug must have "high potential for abuse" and "no currently accepted medicinal use in treatment" (Bilz 1999, p. 123). In 1971 President Nixon declared that "America's public enemy number one in the United States is drug abuse" and began the War on Drugs, of which marijuana remains a major part.

The political landscape of marijuana changed in 1996 when California became the first state to legalize medical marijuana; through 2008, 12 more states legalized medicinal marijuana use despite the federal government's stance that marijuana has no medicinal value. Individuals in full compliance with state law still ran the risk of federal prosecution for possession of a controlled substance, and indeed the Drug Enforcement Agency made numerous raids throughout this time period on state dispensaries of medical marijuana (Eddy 2010). These raids continued until October 2009 when David Ogden, then Deputy Attorney General, wrote a memorandum for United States Attorneys stating:

> "The prosecution of significant traffickers of illegal drugs, including marijuana, and the disruption of illegal drug manufacturing and trafficking networks continues to be a core priority… As a general matter pursuit of these priorities should not focus federal resources in your States on individuals whose actions are in clear and unambiguous compliance with existing state laws for providing for the medical use of marijuana." (Ogden 2009, p. 1-2).

This memo assured medical marijuana providers and patients that federal agents would no longer intervene into their affairs. As of 2017, 29 states and the District of Columbia have legalized marijuana for medical purposes.[2]

In November 2012, just three years after the Ogden memo, Washington and Colorado passed referendums legalizing recreational marijuana. The Obama administration assuaged fears of federal backlash against these newly enacted laws with the release of the Cole memo in August of 2013, which extended the language of the Ogden memo to include recreational legalization, noting:

> "The Department's guidance in this memorandum rests on its expectation that states and local governments… will implement strong and effective regulatory and enforcements

[2] Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Delaware, Florida, Hawaii, Illinois, Maine, Maryland, Massachusetts, Michigan, Minnesota, Montana, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Dakota, Ohio, Oregon, Pennsylvania, Rhode Island, Vermont, Washington, and West Virginia.

systems that address the threat those state laws could pose to public safety, public health, and other law enforcement interests." (Cole 2013, p. 2)

This memo was taken as federal confirmation that as long as states create and police their marijuana policy in good faith, (e.g. not selling to minors) the federal government will stay out of the way. January 1, 2014 saw the first legal sale of recreational marijuana in Colorado, and Washington followed shortly behind with their first sale on July 8, 2014.

On January 4, 2018 now Attorney General Jeff Sessions rescinded the Cole memo (and the Ogden memo by extension) as guidance for district attorneys, stating special treatment should not be given to marijuana (Sessions 2018). While the memo did not instruct federal prosecutors to target legal marijuana, it revoked the wording of the Cole memo that specifically told federal prosecutors not to prosecute legal marijuana businesses and users in compliance with state law. In spite of this update to the national stance on state's rights to legalize marijuana, business has continued as usual in all states that have legalized, and there have not been federal raids of marijuana operations acting within state law. Readers can find a 2018 map of marijuana legality by state in Appendix D.

III. Related Literature

There are several ways past studies have tackled the question of how dangerous the psychoactive ingredient of marijuana, tetrahydrocannabinol (THC), is for driving. Driving studies, epidemiologic studies, marijuana prevalence in accident rates, and difference in difference trend analysis are all methods that have been employed by researchers to improve understanding of the issue.

THC impairs most cognitive abilities required for driving, including visual coordination and complex multi-tasking that requires split attention (Sewell et al. 2009). Despite this, driving studies have not shown marijuana to be extraordinarily dangerous. There is evidence that marijuana subjects tend to engage in compensating behavior such as driving at slower speeds or avoiding risky maneuvers while driving under the influence, a sharp contrast to alcohol impaired drivers, who tended to engage in more risky behavior (Sewell et al. 2009, Kelly et al. 2004). A major hypothesis for this difference in performance comes from research showing drivers under the influence of THC are more likely to overestimate their level of impairment, while drivers given alcohol tended to underestimate their level of impairment (Sewell et al. 2009). THC impaired drivers are dangerous and more likely to crash relative to sober drivers, but perform substantially better than alcohol impaired drivers. The main drawbacks to these studies are they don't predict whether people will choose to drive under the influence or not and there may be differences in behavior due to a laboratory effect on subjects.

Epidemiologic studies utilize real crash data in order to produce an odds-ratio (OR) that represents the relative risk of driving under the influence of drugs versus being sober. These studies can be conducted one of two ways: culpability studies consider the population of drivers involved in crashes and then compares the proportion of drug use among culpable drivers (those responsible for the crash occurring) versus non-culpable drivers. Case-control studies consider the population of drivers as two groups: those that crashed and those that did not. Comparing drug use across these two groups shows how much more likely a person is to be in a crash if they are using a substance. Case-control studies produce their comparison group through roadside sampling, and run the risk of acceptance and convenient sampling biases.

There is quite a large range of OR estimates produced from this literature. Studies have produced OR estimates as small as 0.7 (Terhune et al. 1992), which implies that marijuana users are less likely to cause a crash than unimpaired drivers, and as large as 6.6 (Drummer et al. 2004), implying that marijuana makes drivers almost 7 times as likely to cause a crash. A meta-analysis by Asbridge et al. (2012) found that marijuana impaired drivers are roughly twice as likely to cause a fatal crash as non-impaired drivers. However, this meta-analysis focused on studies that failed to control for confounding risk categories like age and sex (Neavyn et al. 2014). Young men are overrepresented in both traffic fatalities and proportion of marijuana users so results may be driven by age-related risky behavior rather than marijuana use. Rogeberg & Elvik (2016) completed a follow-up analysis of the studies used by Asbridge et al. (2012); after adjusting for methodological failings noted previously, an odds ratio of 1.36 was produced.

In general, epidemiologic studies suffer from two main biases both related to testing for the presence of THC. Since the mind altering effect of THC is quickly metabolized, any delay in blood sampling may incorrectly label drivers who were high at the time of crash as sober (Sewell et al. 2009). On the other hand, research involving the use of urine tests will incorrectly label sober drivers as intoxicated. Urine samples test for the metabolite carboxy-THC, a non-psychoactive chemical which can remain in the body for weeks after marijuana use. The use of urine tests is the likely reason that Terhune et al. (1992) found that marijuana impaired drivers were less likely than sober drivers to be in a crash. Detection of marijuana intoxication levels is a serious problem for law enforcement, and a lack of reliable testing kit like a breathalyzer makes proving drivers' intoxication difficult, both for prosecution of offenders and research studies. Epidemiologic studies performed since 2012 have yielded odds ratios that have been greater than 1, but never larger than 2 (Li et al. 2013, Dubois et al. 2015, Romano et al. 2017). It is relatively safe to say that epidemiologic studies have shown that driving while high on marijuana makes you somewhere between slightly more likely, to twice as likely to be involved in an accident as compared to a sober driver.

On the other hand, epidemiologic studies have shown drivers under the influence of alcohol to be significantly more dangerous. Odds ratios for alcohol impaired drivers range from between 5.0 (Williams et al. 1985) and 17.8 (Martin et al. 2017), and these studies have fewer of the methodological problems that plague marijuana comparisons. When combined, alcohol and marijuana have an additive if not multiplicative effect, a result corroborated by every major study listed above. This means small amounts of both drugs can cause significant impairment.

An important portion of the causal effect of marijuana legalization on traffic fatalities rests upon the relationship between marijuana and alcohol consumption. If increased access to marijuana also increases alcohol use, then marijuana and alcohol are complements. If increased access to marijuana reduces the amount of alcohol people consume, then they are substitutes. Research is far from definitely answering the nature of this relationship. Meta-analysis by Guttmannova et al. (2016) reveals support for both complementary and substitutive relationships between the drugs, contradictory results that nonetheless persist over many different specifications and law change analyses. Martin et al. (2017) looked at accidents in metropolitan areas of France and found that half of the drivers testing positive for marijuana also tested positive for alcohol. Dubois et al. (2015) looked at FARS data from 1991-2008 and found that in all years the proportion of drivers testing positive for both THC and alcohol was larger than the proportion testing positive for THC alone. These results seem to suggest that alcohol and marijuana are complements in consumption, but both Anderson et al. (2013) and Santaella-Tenorio et al. (2017) argue that marijuana and alcohol are substitutes.

In the specific case of traffic fatalities, substitution between alcohol and marijuana could make road travel safer – driving while high on marijuana seems relatively safe compared to driving under the influence of alcohol as evidenced by epidemiologic studies (Sewell et al. 2009). If alcohol and marijuana are complements, traffic fatalities would be expected to spike sharply after marijuana legalization. Finally, if alcohol and marijuana use are independent, then we would still expect traffic fatalities to increase, but at a lesser amount than the case of a complement.

Studies have shown that an increasing number of drivers are using marijuana in Colorado (Salomonsen-Sautel et al. 2014, Maxwell & Mendelson 2016, Rocky Mountain High Intensity Drug Trafficking Area (RMHIDTA) 2017) and Washington (Couper & Peterson 2014, Tefft et al. 2016). The proportion of drivers involved in fatal accidents in Washington that tested positive for THC more than doubled between 2013 and 2014 (the year of commercialization) from 8.3% to 17% (Tefft et al. 2016) using blood tests only. In Colorado, the proportion went from 11.4% in 2013 to 15.4% in 2014, and by 2016 is at 20.6% (RMHIDTA 2017) although these numbers were obtained from a mixture of blood and urine tests. These studies support the hypothesis that commercialization of marijuana leads to an increase in marijuana use, but do not necessarily imply that traffic fatalities have increased as a result. Detecting THC, even in blood, is not nearly as reliable an indicator of impairment as blood alcohol content due to non-linear absorption rates (Sewell et al. 2009). Although blood THC levels are more accurate at measuring recent consumption than urine levels, these studies looked for any presence of THC, not specifically at a concentration that is considered drug impaired by state law (5 ng/mL). Fundamentally, these studies lack the explanatory power to conclude that increasing rates of fatally injured drivers testing positive for THC is causing an increased in overall traffic fatality rates, although they are suggestive of a trend of increased marijuana use by the general population of Washington and Colorado after recreational marijuana legalization.

Similar to the question of how recreational marijuana legalization has impacted traffic fatality rates, a few studies have researched how medical marijuana laws (MMLs) have affected traffic fatality rates. Studies done by Anderson et al. (2013) and Santaella-Tenorio et al. (2017) both found that states passing MMLs saw resulting decreases in fatality rates of about 10%. Both papers hypothesize these results are driven by substitution away from alcohol. Anderson et al. (2013) found larger and more robust reductions in traffic fatalities during the weekend and at night, both periods of time where alcohol related fatalities are overrepresented. The largest reductions in crash fatalities after medical marijuana passage came from the 25-44 year olds, the age range overrepresented in alcohol related traffic fatalities (Santaella-Tenorio et al. 2017). Regressing alcohol related fatalities against medical marijuana enactment runs a similar confounding risk as epidemiologic studies: not all crashes have drug tests – there may be systematic differences in testing policies of certain areas over time such that drunk driving is methodically under/over reported relative to the comparison group. Nonetheless, Anderson et al. (2013) find a statistically significant reduction in traffic fatalities involving alcohol in states that passed a MML.

As of early 2018, a couple of studies have looked at recreational marijuana and traffic fatalities. Aydelotte et al. (2017) find an imprecisely estimated increase in traffic fatalities, which they interpreted as a lack of evidence to suggest a causal link between marijuana legalization and decreased road safety. In contrast, Vogler (2017) finds that recreational marijuana has caused a statistically significant increase in traffic fatalities of 7.8% using the same time frame for estimation: 2009-2015. Differences in results likely stem from counterfactual construction and covariate choice differences between the two studies, as well as Vogler's (2017) inclusion of Alaska and Oregon in his treatment estimation, despite these states having less than a full year of legalization in the dataset. Aydellote et al. (2017) compares differences in the traffic fatality rates of Washington and Colorado with only eight other states, which were selected to be ex ante similar, although the authors are not explicit about their matching criteria. Vogler (2017) compares treatment effects in Washington, Colorado, Alaska, and Oregon to the other 46 states. Finally, Aydellote et al. (2017) include alcohol consumption as a covariate, which over-controls the effect of marijuana on traffic fatalities given the results of previous research. If part of the way through which marijuana legalization affects traffic fatalities is a change in alcohol consumption, not allowing alcohol consumption to vary in the model will not produce representative estimates.

Driving simulations and epidemiologic studies suggest that marijuana consumption increases the risk of traffic fatalities, and studies have found that an increasing number of drivers are testing positive for marijuana after recreational legalization. Despite this, medical marijuana legalization studies have shown that traffic fatalities actually fell on average by approximately 10% in states where MMLs were passed. The question of whether these results can be extended to recreational marijuana laws is unanswered; while one study finds no significant change in traffic fatalities after legalization, another has attributed an almost 8% rise in traffic fatalities to recreational marijuana.

IV. Data & Methodology

The primary dataset comes from the Fatality Analysis Reporting System (FARS) which is a census of all crashes occurring on a publicly accessible roadway in the United States where a motorist or non-motorist died within 30 days of the crash. Time and day of crash are recorded nearly 100% of the time, allowing for analysis of smaller samples, such fatal crashes occurring on weekends. While it is likely that marijuana legalization has differing effects on non-fatal crash rates, fatal crash rates are the statistic of interest because of data availability (there is no comparable census of non-fatal crashes available like FARS) and because they are especially violent and costly in terms of human life lost.

Publically available data from FARS comes in several different units of analysis files (e.g. accident level, person level, vehicle level). I utilized the accident file, which contains a data entry for every accident resulting in at least one fatality. Entries contain associated information on total number of fatalities, time of crash, whether any drivers tested positive for alcohol, and additional indicators like road type and weather condition. The data is collapsed into unique state years after aggregating relevant crash statistics.

In concordance with past research on traffic fatalities I exclude Alaska and Hawaii based on their unique topography and physical and cultural isolation from the contiguous United States. The District of Columbia is excluded as an influential outlier due to its uniqueness in terms of size and lack of rural roads. In addition, I exclude Oregon because they legalized in July of 2015 and commercialized in October 2015. The short time frame of legalized recreational marijuana could have undue influence on results in the case of an outlier year compared to the more reliable variance of 4 years of traffic fatality data from Washington and Colorado. Another reason to exclude Oregon is the geographic proximity to Washington. Attitudes towards marijuana were positive in Oregon in 2014 and it would have been easy for Oregon residents to cross the state line into Washington to legally purchase marijuana.[3]

Figure 2 shows fatalities per 100,000 people in Washington, Colorado, and the average of the other 45 states not listed above. Both Washington and Colorado have lower than average fatality rates; for Colorado this difference is diminishing since 2013, when decriminalization occurred. Washington saw declining fatality rates until 2014 and 2015, although 2016 saw a reduction in

[3] The Oregon recreational marijuana legalization referendum passed in November 2014 with 56% yea with strong influence from the coastal counties and especially the Portland area, which is less than an hour drive to the Washington border.

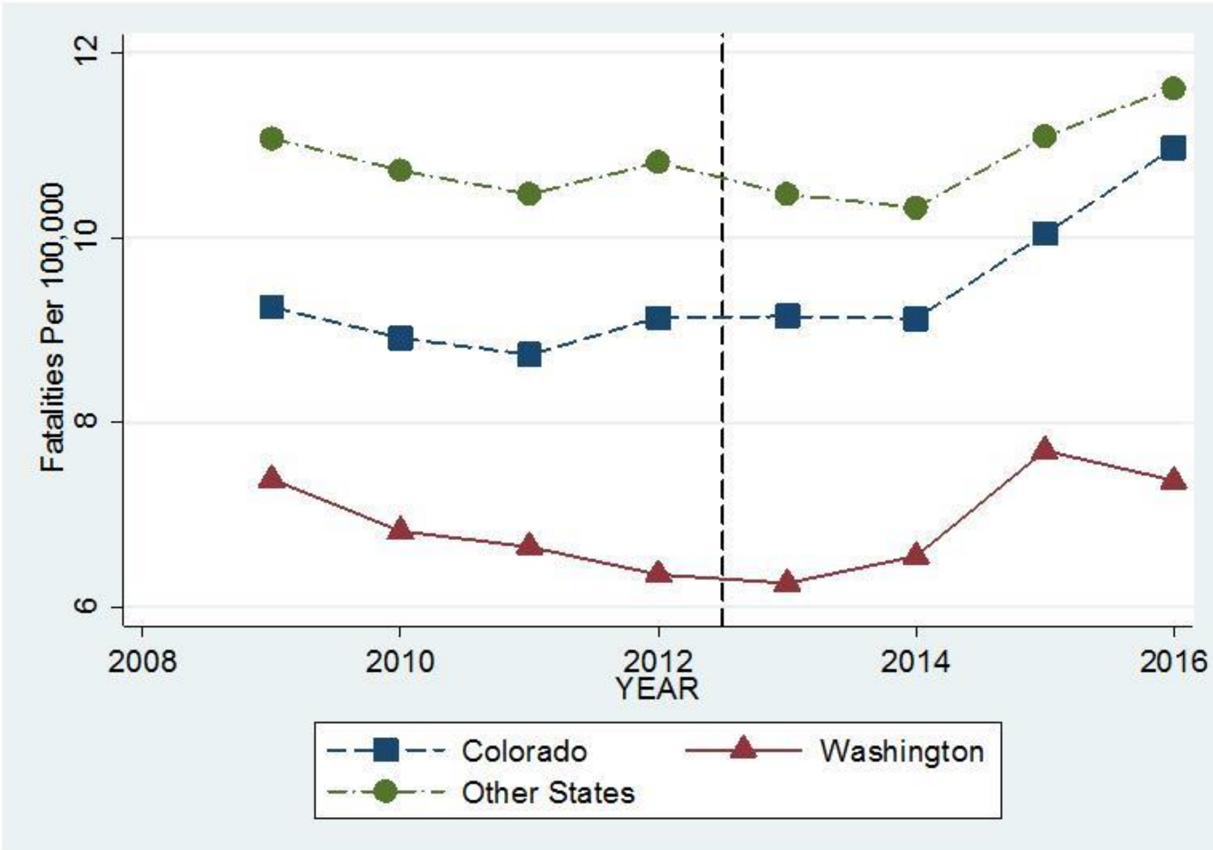

Figure 2 - Traffic fatality rates per 100,000 population (Other states excludes WA, CO, OR, HI, AK, & D.C.)

traffic fatalities back to roughly 2009 levels, a statistic not matched by the national average. The nationwide uptick in traffic fatalities after 2014 is likely attributable to increased vehicle miles travelled along with a healthier economy and lower unemployment rate (National Safety Council, 2016).

The analysis selected utilizes difference in differences estimation. This empirical technique is often used to analyze effects of a policy change. Difference in differences imposes a parallel trend assumption on the treatment and control groups, which is to say the treatment group is expected to follow the same trajectory as the control group. This assumption creates a “counterfactual” endpoint where we would expect the treatment group to arrive at the end of the time period. The difference in the expectation of the treatment group and its observed outcome is

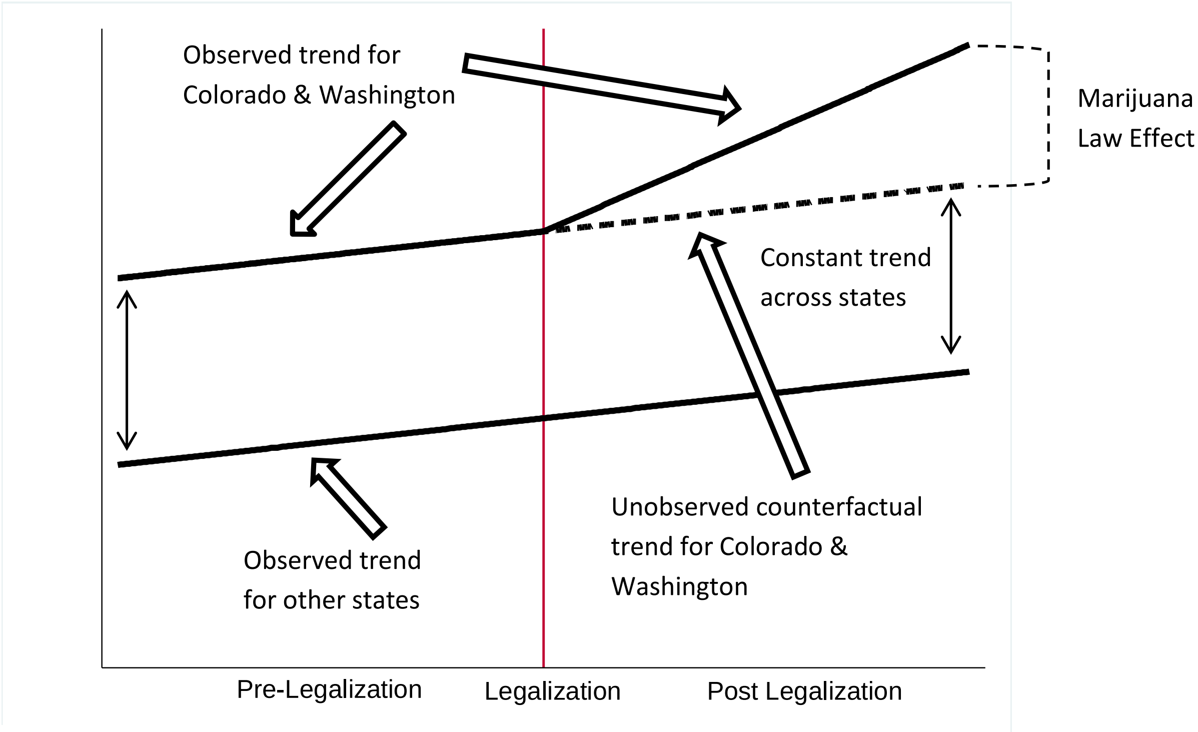

Figure 3 – Example of difference in differences estimator.

the intervention effect, our parameter of interest. Figure 3 provides a graphical illustration of these concepts. With a properly specified model, the difference in trend for policy enacting states versus a control group can be interpreted as evidence for a policy effect.

The following model is used to examine the relationship between marijuana commercialization and traffic fatalities:

$$Y_{st} = \beta_0 + \beta_1 I_{st} + \boldsymbol{X_{st}\beta_2} + a_s + v_t + \epsilon_{st}$$

Y_{st} represents the natural log of traffic fatalities per 100,000 population in state *s* during year *t*. I_{st} is the indicator for whether a state was commercially selling marijuana in year t, making β_1 the coefficient of interest. a_s and v_t are state and time fixed effects respectively. $\boldsymbol{X_{st}}$ is the row vector of time varying state covariates which contains: unemployment rate, percent of vehicle miles travelled on rural roadways, vehicle miles travelled per licensed driver, and various statewide policies that research has shown to have appreciable effects: whether a state had a speed limit above 70 miles per hour, mandatory seatbelt laws, texting bans, marijuana decriminalization, a drugged driving per se law, and a zero tolerance per se law. Policy variables are indicators that take fractional values when implemented partway through the year. Standard errors are clustered by state to correct for the correlation of residuals within state observations. Unemployment rate is a standard predictor variable in traffic fatality difference in difference estimation since work by Partyka (1984) and Evans & Graham (1988) showed that macroeconomic conditions had significant effects on traffic fatalities. Accidents on rural roadways have increased likelihood of fatality because they tend to be at higher speeds and will be further from Emergency Services. As total vehicle miles travelled per driver increase over time in a state, more accidents are expected due to increased travel distance and time.

Crashes that happen at higher speeds tend to be more severe and more likely to cause death (Aarts & van Schagen 2006). When speed limits are increased, average driver speed increases and traffic fatalities rise (Farmer et al. 1999, Ossiander & Cummings 2002, Ashenfelter & Greenstone 2004, Freidman et al. 2007). An indicator variable is utilized to control for if a state has a speed limit greater than 70 miles per hour. Seatbelt use plays an important role in fatality risk given a crash occurring. Although a seminal paper in the field found that seatbelt use was causing compensating behavior that actually caused increased risk to non-occupants of vehicles (Peltzman 1975), modern research agrees that seatbelts are effective at reducing fatality risk from crashes (Cohen & Einav 2003, Houston & Richardson 2007, Carpenter & Stehr 2008, Lee et al. 2015). In particular, seatbelt laws which consider infractions a primary offense (i.e. law enforcement can pull a vehicle over and issue a ticket for this infraction alone) are more effective in reducing traffic fatalities than secondary laws (Cohen & Einav 2003, Houston & Richardson

Table 1: Summary Statistics for Selected States (Alaska, Hawaii, Oregon omitted) 2009-2016

	Mean	Standard Deviation	Minimum	Maximum
Vehicle Fatalities per 100,000 Population	12.38	4.64	4.3	27.5
Vehicle Miles Travelled per Driver (1,000)	14.79	2.49	10.3	23.3
Unemployment Rate	6.85	2.20	2.7	13.7
Rural Percentage of Total Vehicle Miles	40.37	18.51	4.5	75.7
Primary Seatbelt Law	0.62	0.48	0.0	1.0
Handheld Device Ban	0.16	0.36	0.0	1.0
Texting Ban	0.62	0.47	0.0	1.0
Marijuana Decriminalized	0.24	0.42	0.0	1.0
Per Se Drugged Driving Law	0.12	0.32	0.0	1.0
Zero Tolerance Drugged Driving Law	0.31	0.46	0.0	1.0
Graduated Driver's License Program	0.99	0.10	0.0	1.0
Medical Marijuana Law	0.32	0.46	0.0	1.0
Speed Limit 70+ MPH	0.72	0.45	0.0	1.0
Observations	376			

Note: Policy variables take a decimal value if the effective date of enforcement happened part way through the year.
Sources for data available in Appendix B

2007, Carpenter & Stehr 2008, Lee et al. 2015) and therefore the indicator utilized is a primary seatbelt law. A three step graduated driver license (GDL) program grants an intermediate license to young drivers, usually aged 15-16, with limitations like reduced number of passengers, curfew, or special phone use requirements. GDLs have been shown to effectively reduce fatality rates among teens (Dee et al. 2005, Shope 2007). While states have implemented different restrictions and research has shown that the strength of GDL laws is proportional to their fatality reduction effect (Dee et al. 2005, Shope 2007), the indicator variable I use is the baseline GDL law.

The other included policy controls have more nebulous effects. Texting and handheld device bans have questionable effectiveness in reducing traffic fatalities (McCartt et al. 2014); some studies have found insignificant effects (Burger et al. 2014, Ehsani et al. 2014) or effects that dissipated quickly (Abouk & Adams 2013). On the other hand, some studies have shown statistically significant decreases in traffic fatalities after these bans (Nikolaev et al. 2010, Rocco & Sampaio 2016). Given the ambiguity of the research in the area and the popularity of these policies in the years 2009-2016 (40 states implemented a primary texting ban and 9 states implemented a handheld device ban during this time period) indicator variables for both primary texting and handheld bans are included.

Per se drugged driving laws, like per se alcohol laws, allow the judicial system a clearer path to prosecute drivers under the influence of drugs (DuPont et al. 2012). A per se limit means that any driver over that limit is considered impaired by law, regardless of actual behavioral impairment. Zero tolerance laws are equivalent to a per se law that sets the legal limit of a substance at zero; any amount of drug detected incriminates a driver of being too intoxicated to drive. While alcohol per se laws have been effective in reducing traffic fatalities (Dee 2001, Freeman 2007) there is currently no evidence that drugged driving per se laws, zero-tolerance or otherwise, have any effect on traffic fatalities (Anderson & Rees 2015). Although a pattern of effectiveness has not yet been established, per se laws represent recognition by elected officials that drugged driving is a problem. I include an indicator variable for a zero tolerance law, and a separate indicator variable for a per se law limit greater than zero.

Finally, I include indicators for whether a state enacted a medical marijuana law and whether marijuana has been decriminalized. While states that have decriminalized marijuana still find possession illegal, getting caught with small quantities has no arrest, prison time, or criminal record associated with it. Most states that have decriminalized consider this small level of possession akin to a minor traffic infraction. Given the findings of Anderson et al. (2013) and

Santaella-Tenorio et al. (2017) we expect that traffic fatalities should fall after medical marijuana law enactment, and perhaps similarly that decriminalization also leads to declining traffic fatalities.

V. Results

Table 2 presents results from the simple regression outlined above. Legalizing marijuana in Washington and Colorado was associated with a statistically significant increase in traffic fatality rates of 7.14%[4] (99% confidence interval [1.21%, 13.4%]). By this estimate, making marijuana recreationally usable was associated with approximately 140 additional deaths from vehicular accidents in Washington in the four years of traffic data since 2013. In Colorado, approximately 152 additional deaths happened in the same time span. These life losses are equivalent in magnitude to what we would expect if there was a 16% increase in vehicle miles travelled in these states, or about half of the increase in fatality rate attributed to the repeal of the US National Speed Limit in 1995 (Farmer et al. 1999, Ashenfelter & Greenstone 2004). With respect to the estimates of this model, there is moderate evidence suggesting that primary seatbelt laws were associated with a 10.7% decrease in traffic fatality rates[5], yet only 34 states have primary seatbelt enforcement. Considering that over a dozen states have yet to enact these life-saving laws, the traffic fatality rate increases associated with marijuana legalization may not be large enough or salient enough to stall further legislation.

Column 2 presents results from lags in the indicator for recreational marijuana laws to investigate differences in effect on traffic fatalities over time. The lags are jointly significant, although the year of law passage loses its explanatory power, with the strongest effects two years

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[4] For some indicator variable coefficient $\hat{\beta}_1$, the exact percentage change of a logged dependent variable Y caused by the indicator variable is given by the equation $\%\Delta Y = 100 \cdot [\exp(\hat{\beta}_1) - 1]$ (Wooldridge 2013). A useful approximation is simply $\%\Delta Y = 100 \cdot \hat{\beta}$ when the percentage change is small.

[5] See Appendix A for a full table of covariate estimates

Table 2 - Recreational Marijuana Laws (RML) and Traffic Fatalities, 2009-2016

	(1)	(2)	(3)	(4)	(5)
3 Years before RML			-0.015		-0.015
			(0.029)		(0.029)
2 Years before RML			0.019		0.019
			(0.018)		(0.018)
1 Year before RML			-0.035		-0.035
			(0.045)		(0.045)
RML	0.069***	0.023	0.043*	0.022	0.043*
	(0.021)	(0.044)	(0.022)	(0.042)	(0.022)
Retail Marijuana				0.089**	0.030***
				(0.041)	(0.008)
1 Year after RML		0.044	0.044		0.021
		(0.034)	(0.034)		(0.039)
2 Years after RML		0.059*	0.059*		0.051*
		(0.033)	(0.033)		(0.028)
3 Years after RML		-0.013	-0.013		-0.013
		(0.047)	(0.047)		(0.047)
R^2	0.310	0.314	0.314	0.313	0.314
N	376	376	376	376	376

The dependent variable is the natural log of fatalities per 100,000 people. All regressions have state and year fixed effects and covariates from Table 1. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses. RML: Recreational Marijuana Law
Significance Levels: * p < 0.10 ** p < 0.05 *** p < 0.01

after passing. This is the first full year that residents in both Colorado and Washington had access to commercial stores selling marijuana. Column 4 estimates the unlagged model by including an indicator variable for whether commercial purchase of marijuana was possible. Similar to the lagged model, the coefficient on recreational marijuana laws remains insignificant; now the explanatory power lies in commercial sales. Having dispensaries for recreational marijuana is associated with a 9.2% increase in traffic fatality rates over this time period in Washington and Colorado.

To test for potentially spurious results, I include three years of leads in the recreational marijuana law indicator to the model previously estimated. Column 3 presents results; these coefficients on the leads are individually and jointly insignificant, implying an absence of confounding pre-trend or some unexpected change prior to recreational marijuana laws passing. Finally, column 5 presents estimates from a model fully specified with lags and leads, along with an indicator for commercial marijuana. Consistent with previously estimated models, leads are jointly insignificant and lags are jointly significant. Commercial marijuana explains a significant part of the increase in traffic fatalities, but this is based solely on one observation difference from the first year lag of the recreational marijuana law, interpretation should be done cautiously. There remains evidence of an increase in traffic fatalities two years after the referendum passed. This effect may be explained by growing popularity of marijuana use over time as the drug becomes more acceptable in mainstream culture. Beyond a simple increase in marijuana use, perhaps as time goes on people newer to the drug may become desensitized to the risks of driving while high and their willingness to drive under the influence increases.

Relevant Marijuana Policies

Table 3 displays selected marijuana policy covariate regression results from the simple equation estimate of column 1 in Table 2. Medical marijuana laws passed from 2009 to 2016 did not see a decrease in traffic fatality rate like those states that adopted laws from 1990-2010. There is moderate evidence that marijuana decriminalization, on the other hand, is associated with a reduction in traffic fatality rates by 10.8%. This estimate is very near to the reduction in traffic fatalities estimated by medical marijuana laws by Anderson et al. (2013).This estimate stands at odds with results from estimates about recreational marijuana legalization. We would expect that a recreational marijuana law would have a stronger effect (in the same direction) than marijuana

Table 3 - Selected Covariates

	(1)
Marijuana Decriminalized	-0.114*
	(0.057)
Medical Marijuana Law	0.039
	(0.029)
R^2	0.310
N	376

The dependent variable is the natural log of fatalities per 100,000 people. The regression includes state and year fixed effects. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses.
Significance Levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$

decriminalization on traffic fatality rates. Note that Colorado decriminalized marijuana in 1975, and Washington did not decriminalize prior to passing their recreational marijuana referendum. Since difference in difference estimation measures variation across time within states, and the decriminalization status of these states did not change from 2009 to 2016, the effect of decriminalization of marijuana on traffic fatality rates is not influenced by these two states. The difference in outcome between decriminalization and recreational legalization may be attributable to differences in intent with respect to the laws and the public perception thereof. Decriminalization, where laws are relaxed to treat marijuana possession as a minor offense similar to a traffic violation, still considers marijuana illegal and not acceptable by society. If marijuana use must be kept secret, there is less incentive to drive. While Washington and Colorado forbid public consumption, there is no need to hide possession of the substance, which may lead users in these states to be more likely to drive high. There may be a difference in public perception about the dangers of driving between decriminalized states and recreationally legal states. The traffic fatality rate increase after two years may reflect part of this change in perception on using marijuana and driving while high.

Table 4 - Alcohol, Nighttime, and Weekend Nighttime Crashes, 2009-2016

	(1) Drunk Driving	(2) Nights (12am - 4:59am)	(3) Weekend Nights (12am - 4:59am)
Recreational Marijuana Law	-0.019	-0.088*	-0.297***
	(0.090)	(0.052)	(0.080)
Marijuana Decriminalized	-0.213***	-0.275***	-0.073
	(0.067)	(0.093)	(0.058)
Medical Marijuana Law	0.045	0.058	-0.057
	(0.048)	(0.049)	(0.057)
R^2	0.252	0.224	0.155
N	376	376	376

The dependent variable is the natural log of fatalities per 100,000 people, with the sample restriction specified by the model title. All regressions have state and year fixed effects and covariates from Table 1. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses.
Significance Levels: * p < 0.10 ** p < 0.05 *** p < 0.01

Marijuana Policy on Alcohol Related Traffic Fatalities

While FARS reports whether one or more drivers was under the influence of alcohol, responding officers are not required to administer a breathalyzer. There is significant potential for sampling bias due to systematic differences in collection rates across states and years. Nevertheless, column 1 of Table 4 presents estimates from the effect of marijuana policies on traffic fatality rates after restricting our sample to fatalities occurring from one or more drivers testing positive for some amount of alcohol (i.e. BAC >= .01). While recreational marijuana laws have no appreciable effect, a 19% decrease in the traffic fatality rate across these states is associated with the decriminalization of marijuana, evidence in favor of marijuana and alcohol being substitutes in consumption.

In an attempt to nullify the potential bias in drunk driving reporting, I restrict the sample to crashes that occurred between 12 am and 4:59 am. This creates a useful proxy for drunk driving because compared to the rest of the day, a significantly larger portion of drivers are under the influence of alcohol during this time (Rhum 1996, Dee 1999, Portman et al. 2013), while percentage of drivers under the influence of marijuana tends to be relatively constant from day to night (Berning et al. 2015). When we restrict our sample to these hours, decriminalizing marijuana once again has a strong association with fatality rate, this time a 24% decrease. There is also some evidence of a moderate negative association between traffic fatalities and recreational marijuana as well, once again suggesting that areas with more liberal marijuana laws see fewer alcohol related crashes.

The final column further restricts the sample to weekend nights. This is the most likely time for drivers to be drunk (Dee 1999, Portman et al. 2013) but also imposes a massive restriction on sample size. The sample of weekend night fatal crashes is less than 10% of overall fatal crashes during this time period, so estimates may not be fully representative. Marijuana decriminalization retains its negative sign, although its effect drops to 7.1% and cannot be considered significant at conventional levels. On the other hand recreational marijuana laws are associated with an almost 26% decrease in the weekend nighttime fatality rate in Washington and Colorado. Medical marijuana laws passed between 2009 and 2016 were not associated with any significant difference in traffic fatality rates.

Taken together, these results suggest that liberalizing marijuana policies may reduce alcohol related traffic fatality rates. This implies that alcohol and marijuana are substitutes in consumption. While this was a potential outcome in theory, it begs the question of why recreational marijuana in Colorado and Washington has yielded higher traffic fatality rates despite the apparent substitution away from alcohol and into marijuana. The answer could be that there are an increased number of non-sober drivers on the roads after recreational marijuana laws. Drivers who would not be willing to drive while drunk are willing to drive while high on marijuana. Whitehill et al. (2014) found that young college students were significantly more likely to drive after marijuana use than drinking alcohol. Alcohol related traffic fatalities accounted for a massive proportion of total traffic fatalities decades ago, being a factor for 60% of fatal crashes in the mid-1970s (NIAAA 2013). A massive public information campaign along with effective laws for prosecuting drunk driving has resulted in only 1 out of every 3 fatal crashes involving alcohol in 2016. There have not been public awareness programs of comparable size highlighting the dangers of driving on marijuana.

Davis et al. (2016) found that willingness to drive while high was responsive to knowledge of the dangers of driving while high, but not responsive to knowledge of driving under the influence laws, suggesting that internalization of risk is more valuable to prevention of drugged driving than punitive laws. States looking to legalize marijuana should consider upfront investment in educational campaigns focused at raising public awareness of the risks of drugged driving in order to mitigate associated increases in traffic fatality rates.

Results from all 50 States

To test for external validity, I extend the sample to all 50 states, still excluding District of Columbia. Alaska's recreational marijuana policy took effect February 24th, 2015 and Oregon's on July 1, 2015. While there is less time for trend analysis and the potential for a single year to heavily influence estimates, it is still informative to see if results from earlier agree after the inclusion of the states that legalized recreational marijuana in 2014. Figure 3 plots traffic fatality rates against year for these two states and the national average. Oregon has a severe upswing in traffic fatality rates in 2015 and 2016, right when recreational marijuana was legalized. The fatality rate of Alaska is highly variable; with such a small population, small variation in total fatalities has large effects on the fatality rate. Nonetheless, average traffic fatality rates for 2015/2016 are noticeably higher than the average of the 2009-2014 time period.

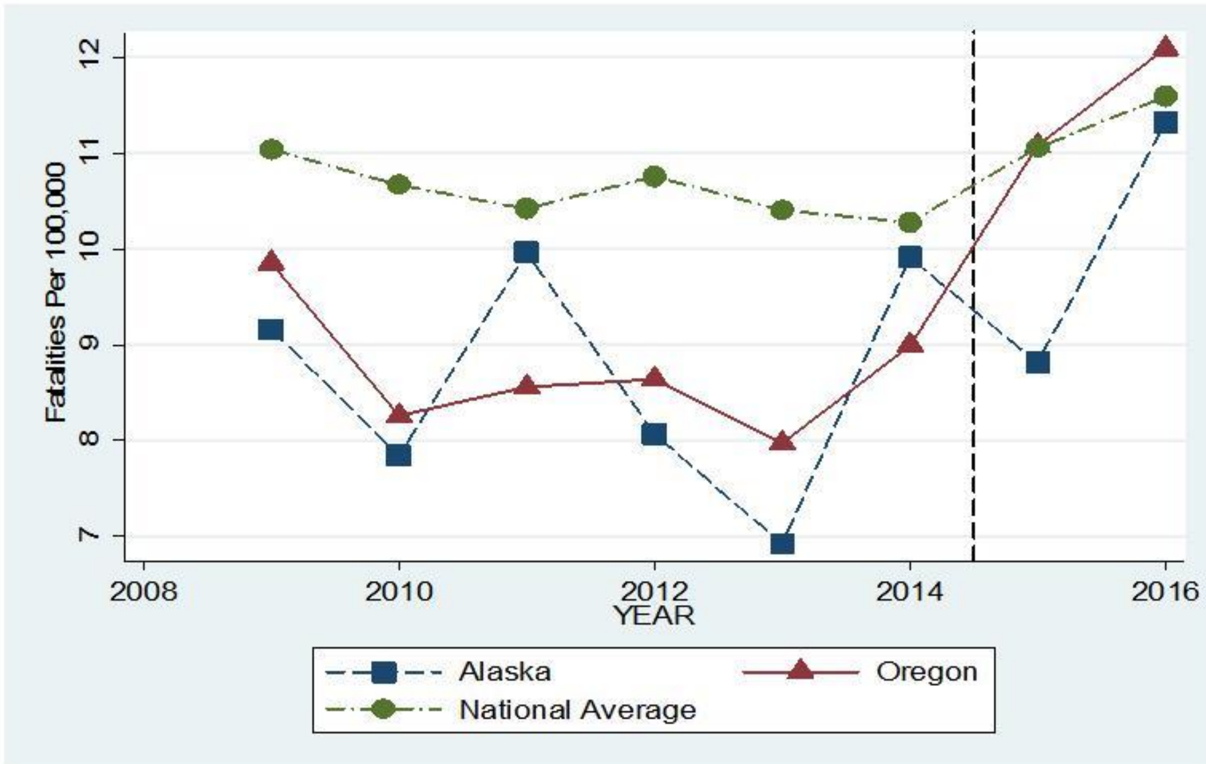

Figure 4 - Traffic fatality rates per 100,000 population (National Average includes Oregon and Alaska)

Table 5 presents results from equivalent regressions as Table 2 but with all 50 states. Column 1 represents the simple regression of recreational marijuana legalization on traffic fatalities, including state and year fixed effects and state level covariates. Recreational marijuana legalization is associated with a statistically significant increase in traffic fatality rates of 17.2%. While I am cautious of assigning causality to this number given the reasons laid out above, it further suggests a pattern that legalizing marijuana for recreational use has decreased road safety. Column 2 introduces lags to the indicator for the recreational marijuana law; the lags are jointly insignificant, perhaps unsurprising given that Alaska and Oregon are considered untreated by the second and third year lag. Adding a full series of leads to the model does not reveal any statistically significant pretreatment differences, although the coefficient estimate on the year before legalization is large in magnitude. This is potentially attributable to Oregon's proximity to

Table 5 - Recreational Marijuana Laws (RML) and Traffic Fatalities - All 50 States, 2009-2016

	(1)	(2)	(3)	(4)	(5)
3 Years before RML			-0.043		-0.045
			(0.030)		(0.030)
2 Years before RML			0.007		0.008
			(0.031)		(0.030)
1 Year before RML			0.118		0.113
			(0.121)		(0.115)
RML	0.159***	0.120**	0.024	0.122***	0.035
	(0.033)	(0.046)	(0.091)	(0.036)	(0.057)
Retail Marijuana				0.077**	0.080**
				(0.032)	(0.032)
1 Year after RML		0.071	0.084		
		(0.045)	(0.054)		
2 Years after RML		0.023	0.019		
		(0.044)	(0.049)		
3 Years after RML		-0.019	-0.020		
		(0.047)	(0.047)		
R^2	0.316	0.319	0.328	0.319	0.327
N	400	400	400	400	400

The dependent variable is the natural log of fatalities per 100,000 people. All regressions have state and year fixed effects and covariates from Table 1. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses. RML: Recreational Marijuana Law

Significance Levels: * p < 0.10 ** p < 0.05 *** p < 0.01

Washington; in 2014 (the one year lead) Oregon residents could easily cross the Washington border to purchase marijuana and bring it back to their homes. Column 4 estimates effects of commercialization in tandem with the recreational marijuana law, and column 5 presents a fully specified model with leads in the recreational marijuana law indicator and an indicator for the presence of retail commercialization of marijuana. All estimates retain expected sign from the 47 state analysis, and magnitude increases.

Table 6 recreates the analysis of Table 4 with 50 states, presenting results for selected marijuana liberalization policies and their effect on approximations of driving fatalities involving alcohol.

Table 6 - Alcohol, Nighttime, and Weekend Nighttime Crashes - All 50 States, 2009-2016

	(1) Drunk Driving	(2) Nights (12am - 4:59am)	(3) Weekend Nights (12am - 4:59am)
Recreational Marijuana Law	0.270**	0.314**	0.275
	(0.111)	(0.154)	(0.209)
Marijuana Decriminalized	-0.213***	-0.280***	-0.078
	(0.064)	(0.092)	(0.052)
Medical Marijuana Law	0.044	0.048	-0.068
	(0.047)	(0.050)	(0.057)
R^2	0.243	0.214	0.147
N	400	400	400

The dependent variable is the natural log of fatalities per 100,000 people, with the sample restriction specified by the model title. All regressions have state and year fixed effects and covariates from Table 1. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses.
Significance Levels: * p < 0.10   ** p < 0.05   *** p < 0.01

Unsurprisingly, the coefficients on marijuana decriminalization and medical marijuana laws are stable with the inclusion of Alaska, Hawaii, and Oregon. The recreational marijuana law estimates, on the other hand, have changed massively in sign and magnitude. Alaska and Oregon saw severe increases to traffic fatalities attributable to drunk driving and late night fatal crashes. Crashes between 12 am and 4:59 am in 2015 and 2016 stand in stark contrast to years prior to legalization. Similarly, alcohol related fatalities increase during this same time period, almost 50% higher after recreational marijuana without corresponding population or vehicle miles travelled increases. The large increases of Alaska and Oregon override the moderate or insignificant changes in these selected fatality rates of Washington and Colorado. Table 6 suggests that recreational marijuana is complementary to alcohol in a way that decriminalized marijuana is not. The results are sensitive to the one and a half year of post-treatment time period in Alaska and Oregon; these states may have experienced extreme years and effects may normalize over time. Despite this, Washington and Colorado did not see immediate or delayed

Table 7 - Per Se Drugged Driving Laws and Traffic Fatalities - All 50 States, 2009-2016

	(1) Simple Regression	(2) Fully Specified	(3) Drunk Driving	(4) Nights	(5) Weekend Nights
Per Se Drugged Driving Law	-0.072* (0.037)	-0.081* (0.045)	-0.136 (0.132)	-0.261 (0.176)	-0.334 (0.237)
Zero Tolerance Drugged Driving Law	-0.019 (0.031)	-0.019 (0.031)	-0.003 (0.044)	0.082 (0.078)	0.116 (0.071)
R^2	0.316	0.327	0.243	0.214	0.147
N	400	400	400	400	400

The dependent variable is the natural log of fatalities per 100,000 people. Columns 1 & 2 represent a full sample of fatal crashes in the 50 states. Column 2 represents the fully specified model with leads and an indicator for commercial availability of marijuana. Column 3 restricts the sample to accidents where at least one driver had a positive BAC test. Column 4 restricts the sample to crashes between 12am and 4:59am. Column 5 further restricts this to accidents happening on Saturday and Sunday between 12am and 4:59am. All regressions include state and year fixed effects and the full set of covariates. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses.
Significance Levels: * p < 0.10 ** p < 0.05 *** p < 0.01

increases in their associated fatality rates, which points to heterogeneous effects of recreational marijuana laws on propensity to drive after consuming alcohol.

Per Se Drugged Driving Laws

Washington and Colorado both passed per se THC driving limits after legalizing recreational marijuana; Oregon and Alaska did not. Table 7 displays coefficients for different regression specifications and samples and displays the effects of both per se drugged driving laws and zero tolerance laws. Zero tolerance laws had no appreciable effect in reducing traffic fatality rates. For this time period, per se laws were passed in Montana, Colorado, and Washington. In the latter two states, the effect of per se laws is difficult to disentangle from the effect of recreational marijuana itself, especially in the model with only 47 states. When we include all 50 states, there is enough variation between the two treatment indicators to show some evidence of a respectable decrease in overall traffic fatalities. The estimates of effects on drunk driving are negative and large, but imprecisely estimated. Per se laws may partially explain why Oregon and Alaska seem to have had more extreme increases in traffic fatality rates than Washington and Colorado, despite previous research finding these laws ineffective (Anderson & Rees 2015).

Per se drugged driving laws do have significant flaws. Police officers must recognize impairment, and then draw blood in order to provide chemical evidence. Any delay in this sampling allows THC to metabolize, which could result in an impaired driver being incorrectly identified as sober. Currently, no orally administered test has shown appropriate sensitivity and specificity to be considered reliable (Hedlund 2017). Differences in individual tolerance and metabolism means large ranges of drug concentration have yielded similar behavioral impairment indicators in subjects, making a concrete limit of THC impairment less defined than BAC limits (Sewell et al. 2009, Berning et al. 2015). Labs testing blood may face backlogs, meaning blood results will be unavailable by the time the case goes to trial (Hedlund 2017). While states with drugged driving laws are making the right effort and improvements continue to be made, enforcement lags behind intent; possibly the major reason that these laws have not shown similar decreases in traffic fatalities as alcohol per se laws. Once testing technology improves and understanding THC's intoxication effect becomes more robust, it will be imperative for states to adopt per se THC limits to curb drugged driving.

Other Notable Covariates

Estimates of recreational marijuana's effect on traffic fatalities are robust to covariate choice. While many of the listed covariates were significant predictors of traffic fatality differences over time, none of these covariates was especially correlated with the effect of recreational marijuana legalization on traffic fatalities.[6] Appendix A has covariate point estimates for all previously discussed regressions. In general, coefficient estimates are of appropriate sign and magnitude:

[6] Dropping all covariates from the model changes the coefficient on recreational marijuana legalization in Washington and Colorado from .069 to .078. For the all 50 state model the coefficient changes from .159 to .130.

texting and handheld phone bans did not result in significant changes to traffic fatalities, a result likely attributable to the difficulty of enforcement. The unusual estimates were speed limit changes, graduated licenses, and rural percentage of total vehicle miles, which were not significant predictors of changes in traffic fatality rates. The 70+ speed limit indicator, although a staple of estimation in the late 1990s and early 2000s, may be too blunt to properly capture speed limit differences in states for the time period of 2009-2016. The lack of significance in the estimate of the effect of the graduated license program is explained by the effect of the law: the intermediate stage between a learner's permit and a full license does not allow the license holder to drive at night (9 pm to 5 am in both Kansas and North Dakota, the only states that did not have a three stage GDL program prior to 2009). Once the sample is restricted to night-time driving, GDL laws had large and significant reductions in traffic fatalities; however, these effects were too small to translate into significant overall traffic fatality rate reductions. The rural percentage of vehicle miles has the expected positive and rather large coefficient but a very imprecise standard error, which implies a lack of sufficient variation to draw conclusions, a common result in fixed effects models.

VI. Robustness

A major weakness of difference in difference estimation lies in the intrinsic nature of the treatment indicator variable. The indicator can only take a value of 0 or 1, which can exacerbate problems with serial correlation in the dependent variable, resulting in underestimated standard errors which cannot be fully corrected by clustering standard errors (Bertrand et al. 2004). To test if this model is affected by this estimation concern, I implement a series of permutation tests for the sample of 47 states and the full 50 states sample. In the 47 states test, I randomly assign two states a "placebo" recreational marijuana indicator for 2013 onward using a uniform

Table 8 - Placebo Regressions

	47 States (Alaska, Hawaii, Oregon Omitted)	All 50 States
Iterations	9974	9924
Positive Coefficient	5045	5024
Significant Result Given Positive Coefficient	1500	838
Significant Coefficient as Large in Magnitude as Actual Treatment	698	0
Percentage Significance	15.04%	8.44%
Percentage Significance & Magnitude	7.00%	0.00%

The dependent variable is the natural log of fatalities per 100,000 people. All regressions had state and year fixed effects, along with covariates listed in Appendix A. Standard errors, used for significance testing, were corrected for clustering at the state level. A coefficient is considered "significant" if the p-value is less than an α level of .05 after the check for if the coefficient is positive. If the coefficient is positive and significant, its magnitude is compared to the real data coefficient estimate on recreational marijuana's effect on traffic fatalities.

sampling distribution. For the 50 states test, two states receive the recreational marijuana indicator for 2013 onward, one state receives the indicator in March 2015, corresponding to Alaska's legalization, and one state receives the indicator in July 2015, corresponding to Oregon's legalization. Regressions are run on these placebo treatments and results are presented in Table 8. When comparing the significance of results to an alpha level of .05, we expect roughly 5% of placebo tests to also return significant results.

Table 8 reveals that despite clustering standard errors, this model disproportionately assigns significance to results due to underestimated standard errors. The 47 states model finds that in 15% of cases, assigning two random states a recreational marijuana treatment for 2013-2016 yields a result significant at the 5% level. Of those cases, close to half yield coefficient estimates on the effect of recreational marijuana on traffic fatality rates that is as large as or larger than the 7.14% increase estimated for Washington and Colorado. The 50 states model does fare significantly better – the difference in recreational marijuana adoption time means variation in treatment effect over time, implying lower odds for results to be spuriously driven. Indeed, only 8.4% of permutation tests yielded a result significant at the 5% level. Of these positive results, not a single random treatment assignment yielded a coefficient of equal or higher magnitude than what was found by the regression on the true data.

While the analysis focusing on Washington and Colorado has more years of post-recreational marijuana legalization and is the preferred model as a result, it is more prone to producing spurious results. The permutation regressions suggest that the estimates produced from the restricted model offer only weak to moderate evidence that recreational marijuana is truly associated with more traffic fatalities. However, including Oregon, Hawaii, and Alaska to the analysis alleviates a significant portion of this problem of underestimated standard errors. This is most likely due to the staggered implementation of legalization, which reduces the chance for a spurious time trend to emerge. In the unrestricted sample, the coefficient on recreational marijuana legalization is so large mainly due to the increase in traffic fatalities seen in Oregon in 2015 and 2016, along with an increase in Alaska in 2016, a fact that means no combination of placebo states in nearly 10,000 iterations produced as large an effect. The concern with the 50 states model is that traffic fatality rates from these states are less stable with less than two full years of post-legalization. Although both models have drawbacks, significant and positive changes in traffic fatality rates are found in both.

VII. Discussion and Conclusion

While the susceptibility of the models to spurious results are certainly problematic, conclusions of individual models are robust to covariate choice, display no sign of confounding pre-trends, and consistently show increases in traffic fatality rates after legalizing recreational marijuana. Although previous research has shown a decrease in traffic fatality rates after legalizing medical marijuana, recreational marijuana has shown the opposite effect. The trend of increased percentage of fatally injured drivers testing positive for marijuana in Washington and Colorado, combined with results from this analysis, suggests an increase in drugged drivers on roads. There is not significant evidence that recreational marijuana legalization is associated with fewer drunk driving fatalities. When Alaska and Oregon are included in model estimation, it appears that willingness to drive while drunk may have even increased with recreational marijuana legalization. Commercial sales of marijuana appear to have a separate and significant effect on traffic fatalities.

States looking to legalize marijuana need to seriously consider the additional traffic fatalities they are likely to incur as a result. While commercial marijuana removes black market operations and puts money into state coffers through taxes, there is evidence suggesting that a significant proportion of the increase in traffic fatalities is coming from the commercial availability of the drug. Drugged driving per se laws remain law enforcement's best way to combat driving under the influence of marijuana, but proving intoxication remains difficult without the THC equivalent of a breathalyzer test. Recognition of drivers that may be under the influence of marijuana requires special police officer training that is costly, time consuming, and less objective than a number on a machine. Blood tests for THC levels are the best means of proving and prosecuting impairment, but blood extraction is invasive and time sensitive. Once blood is sampled, it still needs to be tested in a lab, creating delay in feedback to both driver and police officer. Since drugged driving laws are currently difficult to enforce, it may be prudent for states to invest in education campaigns. The transition of marijuana from illegality to cultural acceptance has sent mixed signals about the dangers of the drug. Generating awareness around the honest dangers of driving while high may help curtail the increased traffic fatality rates associated with recreational marijuana.

The results of this paper stand in opposition to the lack of evidence for a change in fatality rates found by Aydellote et al. (2017). This difference is largely attributable to the inclusion of the 2016 data year. Despite differences in covariate choice and counterfactual construction, model estimation after removing observations from 2016 yields similar results to Aydellote et al. (2017). Interestingly, the model estimation with leads and lags shows moderate evidence of a delayed increase in traffic fatalities two years after legalization, something that Aydellote et al. (2017) did not test for. The interested reader can find regression results with the removal of the 2016 year in Appendix C.

The 2017 data year will provide a significant boost to analysis looking at effects of marijuana legalization. California, Nevada, Massachusetts, and Maine all began allowing recreational marijuana consumption in early 2017. Beyond the extra years of post-treatment variation for the states used in this study, the results of these additional states offer an external legitimacy test of results. This analysis will continue to be a priority as more states consider legalizing recreational marijuana, and especially if the idea is taken seriously at the national level.

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Appendix A

Table A1 - Determinants of Traffic Fatalities - (Alaska, Hawaii, Oregon omitted), 2009-2016

	(1) Simple Regression	(2) Fully Specified	(3) Drunk Driving	(4) Nights	(5) Weekend Nights
Recreational Marijuana	0.069***	0.043*	-0.019	-0.088*	-0.297***
	(0.021)	(0.022)	(0.090)	(0.052)	(0.080)
Unemployment Rate	-0.025***	-0.024***	-0.016	-0.063***	-0.051***
	(0.008)	(0.008)	(0.014)	(0.013)	(0.013)
Primary Seatbelt Law	-0.112*	-0.112*	-0.167*	-0.014	-0.004
	(0.058)	(0.059)	(0.090)	(0.065)	(0.102)
Vehicle Miles Travelled per Driver (1,000)	0.030**	0.030**	0.020	0.031*	0.024
	(0.013)	(0.013)	(0.021)	(0.017)	(0.029)
Rural Percentage of Total Vehicle Miles	0.334	0.315	0.507	0.118	-0.067
	(0.337)	(0.338)	(0.598)	(0.478)	(0.813)
Handheld Device Ban	0.019	0.018	0.072	-0.036	-0.179
	(0.023)	(0.024)	(0.045)	(0.048)	(0.118)
Texting Ban	0.002	0.003	0.006	0.082**	0.094*
	(0.016)	(0.017)	(0.036)	(0.037)	(0.054)
Marijuana Decriminalized	-0.114*	-0.114*	-0.213***	-0.275***	-0.073
	(0.057)	(0.057)	(0.067)	(0.093)	(0.058)
Per Se Drugged Driving Law	-0.008	-0.020	0.066	0.029	0.064
	(0.019)	(0.023)	(0.041)	(0.036)	(0.054)
Zero Tolerance Drugged Driving Law	-0.022	-0.023	-0.015	0.088	0.109
	(0.032)	(0.032)	(0.045)	(0.083)	(0.071)
Graduated Driver's License Program	0.017	0.016	0.120**	-0.207***	-0.290***
	(0.060)	(0.061)	(0.053)	(0.051)	(0.043)
Medical Marijuana Law	0.039	0.040	0.045	0.058	-0.057
	(0.029)	(0.029)	(0.048)	(0.049)	(0.057)
Speed Limit 70+ MPH	0.007	0.007	-0.003	0.076	0.051
	(0.025)	(0.025)	(0.072)	(0.076)	(0.066)
Retail Marijuana		0.030***			
		(0.008)			
N	376	376	376	376	376

The dependent variable is the natural log of fatalities per 100,000 people. Columns 1 & 2 represent a full sample of fatal crashes in the 50 states. Column 2 represents the fully specified model with lags and leads and an indicator for commercial availability of marijuana. Column 3 restricts the sample to accidents where at least one driver had a positive BAC test. Column 4 restricts the sample to crashes between 12am and 4:59am. Column 5 further restricts this to accidents happening on Saturday and Sunday between 12am and 4:59am. All regressions include state and year fixed effects. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses.
Significance Levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$

Table A2 - Determinants of Traffic Fatalities - All 50 States, 2009-2016

	(1) Simple Regression	(2) Fully Specified	(3) Drunk Driving	(4) Nights	(5) Weekend Nights
Recreational Marijuana	0.159***	0.035	0.270**	0.314**	0.275
	(0.033)	(0.057)	(0.111)	(0.154)	(0.209)
Unemployment Rate	-0.022***	-0.021**	-0.007	-0.052***	-0.041***
	(0.008)	(0.008)	(0.014)	(0.014)	(0.015)
Primary Seatbelt Law	-0.109*	-0.108*	-0.157*	-0.018	-0.008
	(0.056)	(0.057)	(0.086)	(0.061)	(0.094)
Vehicle Miles Travelled	0.031**	0.031**	0.024	0.033*	0.032
per Driver (1,000)	(0.013)	(0.013)	(0.022)	(0.018)	(0.030)
Rural Percentage of	0.203	0.236	0.354	-0.117	-0.406
Total Vehicle Miles	(0.359)	(0.344)	(0.737)	(0.467)	(0.863)
Handheld Device Ban	0.011	0.012	0.065	-0.045	-0.168
	(0.025)	(0.025)	(0.048)	(0.052)	(0.113)
Texting Ban	-0.013	-0.012	-0.037	0.045	0.049
	(0.017)	(0.018)	(0.043)	(0.042)	(0.058)
Marijuana	-0.114**	-0.114**	-0.213***	-0.280***	-0.078
Decriminalized	(0.055)	(0.056)	(0.064)	(0.092)	(0.052)
Per Se Drugged Driving	-0.072*	-0.081*	-0.136	-0.261	-0.334
Law	(0.037)	(0.045)	(0.132)	(0.176)	(0.237)
Zero Tolerance Drugged	-0.019	-0.019	-0.003	0.082	0.116
Driving Law	(0.031)	(0.031)	(0.044)	(0.078)	(0.071)
Graduated Driver's	0.022	0.021	0.131**	-0.206***	-0.283***
License Program	(0.060)	(0.061)	(0.054)	(0.053)	(0.043)
Medical Marijuana Law	0.039	0.040	0.044	0.048	-0.068
	(0.029)	(0.029)	(0.047)	(0.050)	(0.057)
Speed Limit 70+ MPH	0.010	0.011	0.005	0.076	0.056
	(0.025)	(0.025)	(0.075)	(0.079)	(0.069)
Retail Marijuana		0.080**			
		(0.032)			
N	400	400	400	400	400

The dependent variable is the natural log of fatalities per 100,000 people. Columns 1 & 2 represent a full sample of fatal crashes in the 50 states. Column 2 represents the fully specified model with leads and an indicator for commercial availability of marijuana. Column 3 restricts the sample to accidents where at least one driver had a positive BAC test. Column 4 restricts the sample to crashes between 12am and 4:59am. Column 5 further restricts this to accidents happening on Saturday and Sunday between 12am and 4:59am. All regressions include state and year fixed effects. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses. Significance Levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$

Appendix B

Data Appendix

Traffic Fatalities	Fatality Analysis Reporting System (2017)
Population	United States Census Bureau (2018)
Vehicle Miles Travelled	United States Department of Transportation Federal Highway Administration (2018)
Unemployment Rate	Bureau of Labor Statistics (2017)
Medical Marijuana Laws	Marijuana Policy Project (2017)
Marijuana Decriminalization Laws	National Organization for the Reform of Marijuana Laws (2018)
	National Conference of State Legislators (2018)
Per Se & Zero Tolerance Laws	Hedlund, James (2017)
	Goverors Highway Safety Association (2018)
Speed Limit Laws	Farmer (2017)
	Governors Highway Safety Association (2018)
Seatbelt Laws	Insurance Institute for Highway Safety (2018)
Graduated Driver's License Laws	Dee et al. (2005)
	American Automobile Association Public Affairs (2018)
Handheld Phone & Texting Laws	Rudisill et al. (In Press)
	McCartt et al. (2014)
	Insurance Institute for Highway Safety (2018)

Note: In general if enactment dates were listed instead of effective dates, local news sources were consulted to determine when laws went into effect.

Appendix C

Table C1 - Recreational Marijuana Laws and Traffic Fatalities, 2009-2015

	(1)	(2)	(3)	(4)	(5)
3 Years before RML			-0.024		-0.024
			(0.028)		(0.028)
2 Years before RML			0.019		0.019
			(0.017)		(0.017)
1 Year before RML			-0.035		-0.035
			(0.043)		(0.043)
RML	0.017	-0.016	0.006	-0.019	0.007
	(0.021)	(0.050)	(0.025)	(0.050)	(0.026)
Retail Marijuana				0.082	0.046***
				(0.062)	(0.007)
1 Year after RML		0.036	0.036		0.002
		(0.038)	(0.038)		(0.045)
2 Years after RML		0.060*	0.060*		0.048*
		(0.031)	(0.031)		(0.024)
N	329	329	329	329	329

The dependent variable is the natural log of fatalities per 100,000 people. All regressions have state and year fixed effects and covariates from Table 1. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses. RML: Recreational Marijuana Law

Significance Levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$

Table C2 - Recreational Marijuana Laws and Traffic Fatalities - All 50 States, 2009-2015

	(1)	(2)	(3)	(4)	(5)
3 Years before RML			-0.046		-0.046
			(0.029)		(0.028)
2 Years before RML			0.007		0.008
			(0.031)		(0.031)
1 Year before RML			0.125		0.124
			(0.123)		(0.123)
RML	0.071	0.062	-0.044	0.046	-0.056
	(0.043)	(0.054)	(0.086)	(0.048)	(0.086)
Retail Marijuana				0.081	0.081
				(0.057)	(0.057)
1 Year after RML		0.002	0.010		
		(0.041)	(0.033)		
2 Years after RML		0.065**	0.063**		
		(0.031)	(0.031)		
N	350	350	350	350	350

The dependent variable is the natural log of fatalities per 100,000 people. All regressions have state and year fixed effects and covariates from Table 1. Robust standard errors, corrected for clustering at the state level, are displayed in parentheses. RML: Recreational Marijuana Law
Significance Levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$

Appendix D

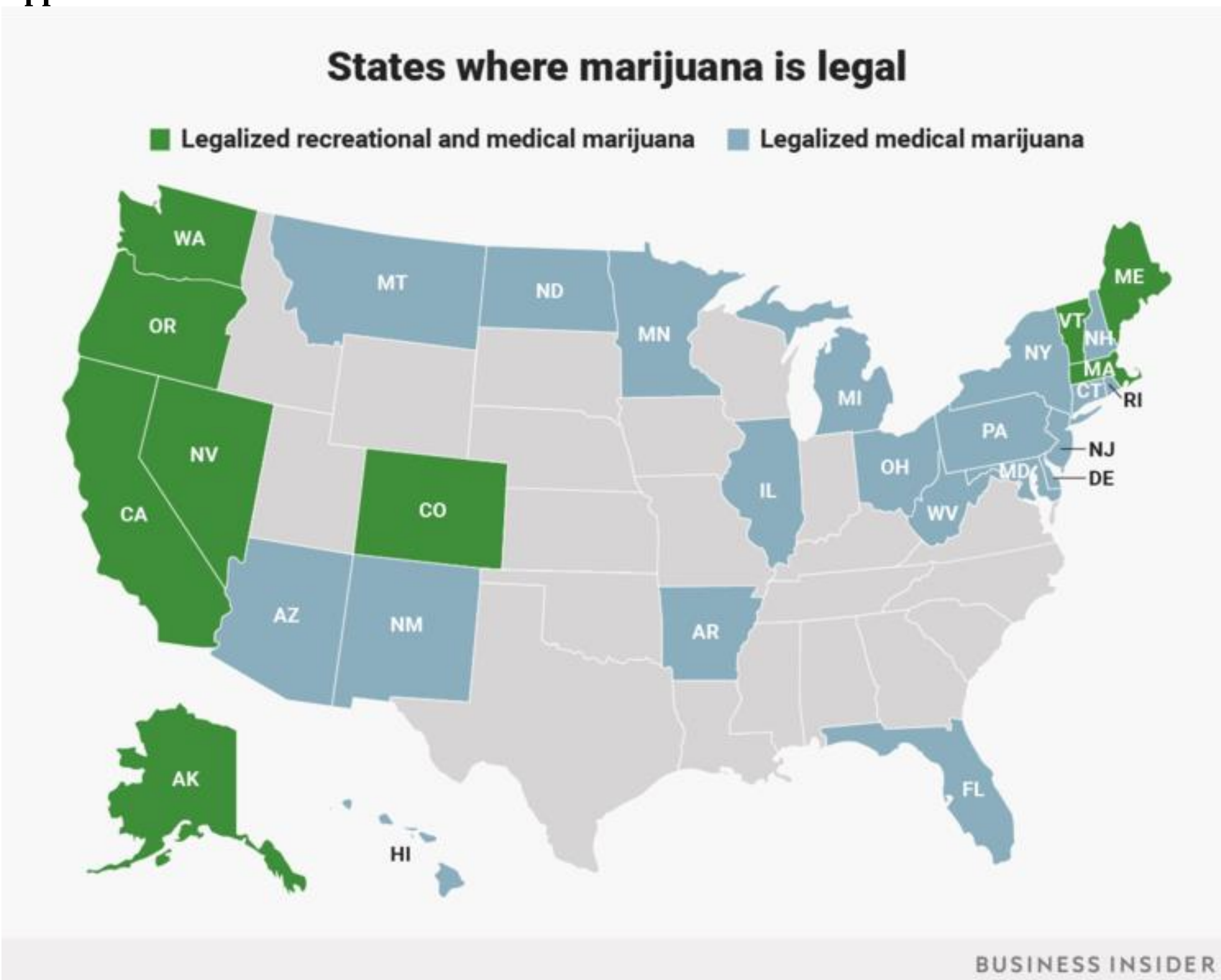

Figure D1 – Marijuana Legality in United States, 2018
http://www.businessinsider.com/legal-marijuana-states-2018-1