Early Evidence on Recreational Marijuana Legalization and Traffic Fatalities

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Abstract

Over the last several years, marijuana has become legally available for recreational use to roughly a quarter of Americans. The substantial external costs of alcohol have long worried policy makers and similar costs could come with the liberalization of marijuana policy. The fraction of fatal accidents in which at least one driver tested positive for THC has increased nationwide by an average of 10 percent from 2013 to 2016. In contrast, for Colorado and Washington, both of which legalized in 2014, these increases were 92 percent and 28 percent, respectively. However, identifying a causal effect is difficult due to the presence of significant confounds. We test for a causal effect of marijuana legalization on traffic fatalities in Colorado and Washington with a synthetic control approach using Fatal Analysis and Reporting System data from 2000-2016. We find the synthetic control groups saw similar increases in marijuana-related fatality rates despite not legalizing recreational marijuana.

JEL Codes: K42, I12, I18.

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1 Introduction

The landscape of marijuana regulation is changing rapidly. Marijuana is or will soon be legal for recreational use for a quarter of the United States population, and several countries worldwide have legalized marijuana in some form. Though legalization has reached record levels of popular support, significant opposition remains. The potential for an increase in traffic fatalities caused by impaired drivers remains at the forefront of the debate among policy makers and in the media (Aaronson, 2017; Guion and Higgs, 2018; Leblanc, 2018; Elliot, 2018). Indeed, initial reports have claimed to identify significant increases in collision frequencies in Colorado, Washington, and Oregon after marijuana markets opened in those states (Highway Loss Data Institute, 2017), as well as increases in the nominal number of drivers involved in fatal crashes who test positive for marijuana—so-called marijuana-related fatalities (Migoya, 2017).[1]

Researchers across disciplines have responded to this public interest. Several authors have examined trends in traffic fatalities in individual states following various liberalizations in marijuana policy and have generally found increases in the rates of THC-positive drivers (Salomonsen-Sautel et al., 2014; Pollini et al., 2015; Aydelotte et al., 2017). However, throughout this literature, researchers have faced a consistent set of methodological challenges. Contemporaneous trends in the state-level price of, and demand for, intoxicating substances make it difficult to find a clean event study. Achieving identification with a differences-in-differences approach is hampered by state-level variation in reporting prac-

[1]Note that, unlike alcohol, the link between particular levels of THC in the bloodstream and increases in the risk of fatal traffic accidents has not yet been precisely determined. We follow the existing literature and media coverage by using the term "marijuana-related fatalities" while pointing out that "marijuana-related" does not mean "marijuana-caused."

tices, regional-level variation in preferences for substance consumption, and spillover effects of legalization efforts (Hansen et al., 2017a) – all of which make choosing an appropriate control group *a priori* difficult (Romano et al., 2017).

We resolve these challenges by using a synthetic control approach. We create a control group by choosing weights for states which have not legalized marijuana to match moments of key variables in the pre-legalization period including testing rates for drugs and alcohol, trends in vehicle miles traveled (VMT), urbanicity, macroeconomic conditions, and pre-treatment trends of our outcome variables. We analyze our treated states and their synthetic controls in a traditional differences-in-differences framework to estimate the causal impact of legalizing marijuana for recreational use on traffic fatalities.

We find that states that legalized marijuana have not experienced significantly different rates of marijuana- or alcohol-related traffic fatalities relative to their synthetic controls. To ensure our results are not driven by an idiosyncratic selection of control weights, we show that we obtain the same result across reasonable variations in the specifications of our synthetic control. In addition to examining fatalities identified by states as drug- or alcohol-related, we also look for changes in the overall fatality rate to avoid state-level differences in classification (as opposed to state-level differences in testing) and find a similar null result.

We proceed in Section 2 with a brief summary of the history of marijuana policy in the United States and the existing research on the risks of impaired driving. In Section 3, we discuss the Fatal Analysis and Reporting System data and our synthetic control approach. We present our results in Section 4. We conclude in Section 5 with a discussion of the policy implications of our findings.

2 Background

2.1 The legal status of marijuana

Marijuana was legal in the United States until the passage of the Marijuana Taxation Act of 1938 – though many states had banned the substance earlier (Sanna, 2014, p. 88). The Controlled Substances Act of 1970 significantly strengthened the prohibition of marijuana: the substance was classified as a Schedule I drug with a 'high potential for abuse and little known medical benefit.'[2]

Public attitudes about marijuana consumption have become more favorable over the past century, particularly shifting towards support for medical uses of the substance. In 1973, Oregon became the first state to decriminalize marijuana possession, though cultivation and distribution of the drug remained felony offenses. A number of ballot initiatives and legislative efforts across states culminated with California voting to legalize marijuana for medical use (so-called "medical marijuana") in 1996. The other west coast states, Oregon and Washington, followed suit in 1998. Today, 27 states and regions permit broad forms of medical marijuana, despite the continued nominal prohibition at the federal level. Indeed, in 2009, the Department of Justice responded to changes in state laws and public opinion by declaring that "federal resources in States [with medical marijuana laws]" should not be focused "on individuals whose actions are in clear and unambiguous compliance with [those laws]" (Ogden, 2009, p.2).

The liberalization of marijuana policy reached another milestone in 2012, when voters in Washington and Colorado approved ballot initiatives which explicitly legalized the produc-

[2]Other Schedule I substances include heroin and methamphetamine.

tion and consumption of marijuana for recreational use (recreational marijuana). Alaska and Oregon followed suit with similar ballot measures in 2014, and California, Nevada, Maine, and Massachusetts legalized marijuana with ballot measures in 2016. In 2018, Vermont became the first state to legalize the recreational use of marijuana via legislative action. Figure 1 illustrates the current legal status of marijuana by state.

In 2013, during the implementation of Colorado and Washington's legalization initiatives, the Department of Justice responded to the Washington and Colorado efforts by providing enforcement guidance to U.S. Attorneys in the form of specific priorities (Cole, 2013). One major priority was "preventing drugged driving and the exacerbation of other adverse public health consequences associated with marijuana use."[3] States have responded by bolstering efforts to monitor and prevent marijuana-impaired driving (Rocky Mountain High Intensity Drug Trafficking Area, 2017; Hillstrom, 2018).

2.2 Research on impaired driving

Given that traffic accidents are a leading cause of death in the United States, there has been considerable interest in understanding the relationship between various intoxicants, including marijuana, alcohol, and other drugs, and driving performance, accidents, and fatalities. A number of interdisciplinary efforts have studied the risks of intoxicated driving using a variety of approaches, which we outline in this section.

One approach examines impaired driving in a laboratory setting by putting intoxicated subjects into driving simulators and comparing their performance to the performance of

[3] Another key priority was "preventing the diversion of marijuana from states where it is legal under state law in some form to other states." Hansen et al. (2017a) study this question by examining the change in sales along the Washington-Oregon border when Oregon's market opened, and conclude that roughly 7% of marijuana grown in Washington was trafficked out-of-state before Oregon's retailers opened.

sober subjects under a variety of traffic and road conditions (Smiley et al., 1981; Liguori et al., 1998). Due to the Schedule I status of marijuana in the U.S., this approach has been used most often in Europe (Veldstra et al., 2015). Bondallaz et al. (2017) review this literature and find that marijuana use impairs driving primarily by increasing lane weaving and decreasing the mean distance between vehicles. However, they also find significant discrepancies between studies and note that the "the neurobiological mechanisms underlying the effects... remain poorly understood, as does the correlation between body fluids concentrations and psychoactive effects of THC." Hostiuc et al. (2018) performed a meta-analysis of epidemiological studies of marijuana consumption and driving performance and found a statistically insignificant effect size and substantial publication bias.

Another series of studies uses roadside surveys to estimate the proportion of drivers who are intoxicated with various substances. These efforts are often sponsored by law enforcement agencies or other government bodies due to the expense involved. For example, the National Highway Traffic Safety Administration (NHTSA) in the United States has conducted several national surveys of weekend nighttime drivers, with the most recent survey conducted from 2013-2014 (Burning et al., 2015). The results show that the percentage of drivers with non-zero blood-alcohol levels has decreased, while the percentage of drivers with THC in their blood has increased. NHTSA also conducted a "crash risk" study in which data was collected from 3,000 crash-involved drivers and 6,000 control drivers selected by location, time of day, and direction of travel (Compton et al., 2015). They conclude that the presence of any THC in the bloodstream leads to a 25% increase in the probability of a crash of any severity. Taken together, these results suggest that concerns about increases in fatalities as a consequence of marijuana liberalization are well-founded, but cannot demonstrate a causal effect themselves.

A third line of research uses the well-known differences-in-differences approach to study the impact of particular laws on fatalities by analyzing crash data collected by the federal and state governments. In addition to those efforts mentioned previously, Anderson et al. (2013) studied the impact of medical marijuana laws and found that such laws led to decreases in traffic fatalities. Their results were replicated with additional years of data in 2017 (Santaella-Tenorio et al., 2017). Hansen (2015) provides evidence with a regression discontinuity design (derived from BAC legal limits) that harsher punishments are effective in reducing drunk driving, though Anderson and Rees (2015) studied *per se* drugged driving laws and found that such laws do not lead to decreases in fatalities.

A final approach, introduced by Levitt and Porter (2001), takes advantage of the fact that fatal crashes typically involve multiple vehicles. By examining the relative frequency of accidents involving drivers of different types (i.e. intoxicated and sober), one can separately identify the fraction of drivers who are of different types and the relative risks of causing a fatal accident. Levitt and Porter focused on alcohol intoxication and found that drivers with a blood-alcohol concentration of 0.10 or higher are 13 times more likely to be the cause of fatal accidents. However, this approach has been difficult to adapt to the question of marijuana-related accidents due to the variation in testing standards across states and the poorly understood relationship between THC blood test results and driving behaviors.

3 Data and Methodology

To study the relation between recreational marijuana and traffic fatalities, we obtain data from the Fatal Analysis and Reporting System (FARS), which is a system maintained by the federal government that records every fatal car accident in the United States. For each accident reported, the system records information on the circumstances, total injuries and fatalities, and demographics of the drivers. Each entry in the system also includes additional reports on the results from tests for illegal drugs and alcohol, if such tests occurred.

We obtain FARS data from 2000-2016 and construct a state level panel of several key variables to measure the impacts of recreational marijuana legalization on traffic fatalities. We focus on six outcomes. The first is the fraction of fatal accidents that involve at least one driver with a positive drug test for marijuana, which we refer to as marijuana-related fatalities. We also examine the fraction of fatal accidents that involve at least one driver with a positive alcohol test, which we refer to as alcohol-related fatalities. As accidents are related to the overall amount of traffic in a region, we construct the total marijuana-related fatalities per billion VMT and the total alcohol-related fatalities per billion VMT to test whether legalizing recreational marijuana creates spillover effects for drunk driving. Lastly, in part because test rates vary from 40-60 percent for drugs and alcohol in most states, we also estimate the impact of recreational marijuana laws on the total number of fatalities per billion VMT and the fraction of deaths that are "sober" (i.e. those in which none of the drivers test positive for marijuana or alcohol).

Four states—Colorado, Washington, Oregon and Alaska—legalized recreational marijuana before 2016, which is the last year currently covered by FARS. As discussed in Section 2, Washington and Colorado voted to legalize in 2012 and recreational marijuana retailers in those states began operation in 2014. Alaska and Oregon voted to legalize in 2014 and retail operations in those states began in 2015. Because FARS only provides a year of post-legalization data for Alaska and Oregon, we focus on Colorado and Washington as our treated states.[4]

Figures 2, 3, and 4 plot the trend of each of our outcomes separately for Washington, Colorado, and all other states (excluding Oregon and Alaska). The data that drive the results of previous research efforts immediately jump out: marijuana-related deaths go up significantly in both Washington and Colorado after marijuana is legalized in 2012 and these deaths are going up much faster than in the rest of the United States. However, finding appropriate control groups for states such as Washington and Colorado is difficult. Figures 2, 3, and 4 highlight that using the rest of the United States as a comparison group is highly suspect as the outcomes for Washington and Colorado do not move closely with the rest of the United States, nor do they even move closely with each other (i.e. parallel trends do not hold). Moreover, if we were to narrow the comparison group down, many of Colorado's neighbors have different levels and trends of drunk and high driving. And, while Oregon might seem like a natural counterfactual for Washington, Oregon legalized shortly after Washington. Furthermore, recent evidence from Hansen et al. (2017a) suggests inter-state spill-overs would prevent nearby states from serving as reasonable control groups.

To address this concern, we turn to a synthetic control approach inspired by Abadie et al. (2010). The approach uses state-level data to create a counter-factual group that can

[4]Furthermore, Oregon passed legislation in 2015 which substantially increased speed limits on many of its freeways. Higher speeds are associated with increased traffic fatalities, which would bias any estimates examining the effect of recreational marijuana legalization in Oregon upwards (Ashenfelter and Greenstone, 2004; van Benthem, 2015; DeAngelo and Hansen, 2014).

resemble both the averages and trajectories of treated units experiencing a change a discrete change in policy. This approach has been used to study a wide variety of policy changes including the decriminalization of prostitution (Cunningham and Shah, ming), highway police budget cuts (DeAngelo and Hansen, 2014), minimum wage increases (Jardim et al., 2017), and economic liberalization (Billmeier and Nannicini, 2013).

Consider a setting with Y_{it} where i represents a unit, such as a state, and t represents a time period, such as a year. The estimator estimates the impact of a treatment for unit i in time period t by estimating $Y_{it} - \sum_{j \neq i}^{S} Y_{jt} W_j$, where W_j is a weight for unit j. While any potential weighted average of control units is a synthetic control, the standard approach is to choose weights based on minimizing the distance of selected variables between the treated unit and the potential synthetic control units. For each of our exercise, we create a synthetic control with the lagged values of the dependent variable from 2000-2013 (in two year bins), local economic conditions as measured by the unemployment rate, alcohol and marijuana testing rates, VMT[5], and the fraction of VMT driven on urban as opposed to rural roads.

To conduct hypothesis tests, we use the placebo based inference approach suggested by Abadie et al. (2010). We estimate the same synthetic control design model for every placebo state. We then compare the ratio of the mean squared error ($\frac{PostMSPE}{PreMSPE}$) of the actual values less the synthetic control predictions for the actual treated units (Colorado and Washington) to the distribution of the placebo units. The ranking of the treated units relative to the placebo units for those ratios provides an empirical p-value as a permutation based test.

[5]Given that the onset of the great recession was accompanied by a simultaneous drop in VMT, we match on VMT flexibly. We include an average over the years 2000-2007 (pre-recession), 2008-2010 (the recession), and 2011-2013(post recession).

4 Results

4.1 Marijuana-related fatalities

Figure 5 illustrates the prevalence of marijuana-related fatalities in Colorado and its synthetic counterpart from 2000-2016. Panel (a) of the figure illustrates the fraction of accidents that are marijuana-related while Panel (b) illustrates the number of marijuana-related traffic fatalities per billion VMT. Over the 14 year window from 2000-2013 (prior to Colorado's legalization), the trends and levels of synthetic group closely mirrors Colorado's. In the period following legalization, the synthetic region still tracks Colorado's. This suggests that the upward trend in marijuana-related fatalities in Colorado would have taken place whether or not recreational marijuana was legalized. The point estimates corresponding with the Figure are in Table 6, with permutation based p-values in the brackets. The permutation tests suggest that the small deviations we observe in the data are likely due to noise, and there is little evidence supporting a causal interpretation. Panels (c) and (d) of Figure 5 visually illustrate the statistical precision of the synthetic control estimates. The solid black lines represent the difference between Colorado and its synthetic counterpart. The black line hovers around zero both before and after legalization. Moreover, the slight increase apparent for high fatalities per billion VMT is well within the deviations we see in the post period for placebo states.

We repeat the analysis for Washington in Figure 6. Panel (a) illustrates a consistent upward trend in the fraction of fatal accidents involving marijuana, although Washington displays more volatility than Colorado. The synthetic control for Washington shows a similar trend prior to legalization and, although it dips relative to Washington in 2014, similar levels in 2015 and 2016. In Panel (b), the synthetic counterpart struggles to match the overall levels and trends of Washington during the pre-treatment period. While the trend of the synthetic control is similar to Washington's overall trend upward and then back down before legalization, Washington's data are volatile and the overall fit is relatively poor compared to Colorado's. For this reason, despite a somewhat sizable percentage increase in high traffic fatalities per VMT, the placebo-based p-value seen in Table 6 is still 0.404, and indeed as shown in Panel (d), many placebo units had more volatility in the post period than Washington. Furthermore, most of Washington's estimated average increase in the fraction of fatalities that are marijuana-related is driven by a large increase in 2014. Notably, in this year marijuana sales were only 3,991 pounds in Washington, while they increased to 66,390 pounds in 2015 and 179,301 pounds in 2016. So while recreational sales were increasing over those years, the synthetic unit caught up with and more closely tracked Washington's marijuana-related traffic fatalities during the same period.

Our synthetic control estimates suggest that marijuana-related fatalities increased in states without recreational legalization. So while marijuana-related fatalities per billion VMT went up by more than 60 percent in the years after legalization, our point estimates suggest that only 45 to 60 percent of this increase is caused by the legalization of marijuana—though the effect is not statistically distinguishable from zero. While these synthetic control analyses do not provide compelling evidence that marijuana-related fatalities rose, it could be that other types of fatal accidents shifted.

4.2 Alcohol-related fatalities

Researchers have long debated the potential substitutability or complementarity between alcohol and marijuana (Miller and Seo, 2018). Indeed a naive examination of drunk related deaths in Colorado and Washington would lead to the conclusion that fraction of deaths that involve alcohol fell by roughly 10 percentage points in Colorado and Washington after legalization. With that in mind, we turn to examining alcohol-related fatalities in Washington and Colorado.

Figure 7 plots alcohol-related traffic fatality data for Colorado and its synthetic counterpart from 2000-2016. Panel (a) of the figure illustrates the fraction of all fatalities that are alcohol-related while Panel (b) depicts alcohol related traffic fatalities per billion VMT. The trends and levels of synthetic group closely follows Colorado's for the years leading into marijuana legalization. While the fraction of accidents that are alcohol related drops after Colorado's legalization, a similar drop is predicted for Colorado's synthetic counterpart. Table 2 contains the point estimates and the permutation-based p-values in the brackets. The permutation tests also suggests that the small deviations we estimate are more likely due to noise, and there is little evidence supporting an actual causal deviation. Panels (c) and (d) of Figure 7 illustrate the precision of the synthetic control estimates. Similar to the figures for high driving, the solid black lines represent the difference between Colorado and its synthetic counterpart. The black line hovers around zero both before and after legalization. Moreover, the deviations for either measure of alcohol related fatalities is well within the deviations we see in the post period for placebo states.

The analogous analysis for Washington is shown in Figure 8. The synthetic control approach performs admirably in matching the trends and levels of the fraction of accidents that are alcohol related in Panel (a). In Panel (b), the synthetic control for Washington matches both the levels and the time trends. While there is a gap between Washington and its synthetic control during the post period, the gap develops a few years earlier. If we were to take it at face value, it has almost equal magnitude (with opposite sign) to the increase in high related traffic fatalities based on the point estimates in Tables 6 and 2 (0.389 and -.0479 traffic fatalities per billion VMT). The p-values for both the fraction of fatalities that are alcohol-related and alcohol-related fatalities per VMT indicate that we cannot reject the null hypothesis that legalization caused no changes. As with the Colorado exercise, the plots in Panels (c) and (d) suggest that model fit for the treated states did not deviate sharply after treatment began.

4.3 Overall Fatalities

Our analyses of marijuana- and alcohol-related fatalities provide little evidence to support the hypothesis that recreational marijuana laws increase traffic fatalities. However, several confounding factors remain. Despite our efforts to adjust for differences in testing rates, it could be the case that fatality measures could shift in response to changes in testing regimes purely as a reporting effect. If this were the case, we would expect as testing for marijuana-related fatalities rises, sober fatalities fall. Whatever the testing regime, many individuals in traffic accidents are never tested for drugs or alcohol, so it could be the case that individuals involved in a fatal crash are impaired by substances but our prior measures would fail to capture that impairment.

At the same time, many individuals who test positive for marijuana may not be impaired at the time of driving even if they test positive for THC or cannabinoids as those chemicals persist in the bloodstream for days after use (Odell et al., 2015).[6] For this reason, we might expect to see marijuana-related fatalities increasing due to an increasing prevalence of use—use which may or may not be associated with risky driving behaviors. Indeed, in Figure 9, we compare fatal accident rates at different times of day across marijuana-related, alcohol-related, and substance-free accidents. Alcohol-related fatalities follow a distinct temporal pattern with most accidents occurring in the evening. Accidents without marijuana or alcohol show a time of day pattern consistent with commuting times, with increase in the morning and in the late afternoon and early evening. Marijuana related fatalities show a time of day pattern that more closely resembles sober driving. While there are more early morning fatal accidents, this hourly distribution is actually what one might expect if marijuana-related fatalities are driven by a latent mixture of drivers who are truly impaired by marijuana (who have a similar time-of-day pattern to drunk drivers), and drivers who test positive for marijuana but who are actually sober at the time of the accident (who have similar a time-of-day pattern to sober drivers).

As a consequence, we now focus on the overall traffic fatality rate and the rate of sober fatalities (those not involving the presence of either alcohol or marijuana). Indeed, despite our high p-values, given that we tested multiple hypotheses in the previous section, one natural solution to multiple hypothesis testing is aggregation. Lastly, analyzing the total number of fatalities informs us about the net impact of legalization including any substitution

[6]Though FARS reports blood-alcohol levels precisely, the concentrations of THC and other cannabinoids are not reported.

or complementary effects that may exist.

Figure 10 contains plots for overall traffic fatalities and sober driving in Colorado and its synthetic counterpart from 2000-2016. Panel (a) of the figure focuses on the fraction of "sober" accidents – those that do not involve alcohol or marijuana – and Panel (b) illustrates total traffic fatalities per million VMT. Over the window from 2000-2013, prior to legalization in Colorado, the trends and levels of the synthetic group closely mirrors Colorado's, particularly for overall traffic fatalities. The same is true for the fraction of fatal accidents that are sober. In the period following legalization, the synthetic region shows a slight up-tick, as does Colorado. This suggests that the overall slight upward trend in traffic fatalities per VMT would have been expected in the absence of legalization. The point estimates corresponding with Figure 10 are in Table 3, with permutation based p-values in the brackets. The permutation tests also suggests that the small deviations we estimate are more likely due to noise, and there is little evidence supporting an actual causal deviation. Panels (c) and (d) of the figure illustrate the relative statistical precision of the synthetic control estimates. The solid black lines represent the difference between Colorado and its synthetic counterpart, while the light grey lines are difference between the placebo states and their synthetic counterparts The black line hovers around zero both before and after legalization. Moreover, the slight increase apparent for high fatalities per billion VMT is well within the deviations we see in the post period for placebo states. Indeed even if we were to take the point estimate at face value, it would suggest traffic fatalities per billion VMT in Colorado have increased by a little over 3 percent. However the placebo derived p-value would suggest the we fail to reject the null hypothesis that this effect is zero.

The analogous plots for Washington are depicted in Figure 11. As shown in Panel (a), the trend of fraction of fatalities that are sober is relative stable leading in to marijuana legalization. While it increases by roughly 10 percentage points in 2014, the synthetic control shows a similar jump. The total fatalities per VMT shown in Panel (b) fall fairly sharply from 2000 to 2010, and then level out for the remain years leading into legalization. Washington's synthetic control unit shows a very similar pattern and trend. After legalization, Washington's fatalities rise, and the synthetic counterpart also shows a notable increase. The point estimate in Table 3 suggest that on average traffic fatalities per billion VMT in WA rose by 8.4 percent. However the p-value of .340 suggests we again fail to reject the null hypothesis that there was no effect of legalization. Likewise the model fits in Panels (c) and (d) suggest that difference between Washington and its synthetic control group was typically nearly the center of distribution provided by the placebo models. Furthermore, the average 8.4 percent increase is largely driven by 2015 alone. This might be more likely due to noise, when we consider the growth of the recreational marijuana market. Indeed, total sales of marijuana more than doubled in 2016, and yet the synthetic control group and Washington converged rather than diverging as the recreational market grew.

In summary, the similar trajectory of traffic fatalities in Washington and Colorado relative to their synthetic control counterparts yield little evidence that the total rate of traffic fatalities has increased significantly as a consequence of recreational marijuana legalization.

4.4 Robustness

Our estimates yield little evidence to support the notion that the legalization of recreational marijuana caused traffic fatalities to double, as has been suggested in the media (Migoya, 2017). However, we made several model choices which could have influenced the results. In this section, we measure the sensitivity of our estimates to these choices by replicating Tables 1, 2, and 3 under a different set of choices we could have reasonably made.

In the earlier analyses we assumed treatment began in 2014, which is when retail stores began selling recreational marijuana in both Colorado and Washington. However, the ballot measures in both states passed in 2012 and immediately legalized possession and consumption of small amounts of the substance, which may have lead individuals to increase their consumption of black market or medical marijuana at that time. In other words, a case could be made that treatment truly began in 2012 rather than later in 2014. As shown in the first panel of Table 4, the estimated impact on the fraction of fatal accidents involving marijuana remains relatively unchanged in both Colorado and Washington, with p-values that remain insignificant. Likewise the marijuana-related fatalities per VMT remain effectively constant in Colorado, and fall to -0.086, or roughly a 10 percent decrease (as opposed to the original 25 percent increase). However this estimate remains insignificant, and should be viewed as additional evidence that the earlier estimates may indeed be more consistent with a null effect. In the first panel of Tables 5 and 6 we report estimates for alcohol-related and overall traffic fatalities, respectively. Broadly, we find similar estimates with large p-values, suggesting that even if we consider treatment as beginning in 2012, recreational marijuana has had a limited impact on drunk driving and overall traffic fatalities in both states.

Our primary specifications allow all states other than Washington and Colorado to enter the synthetic control.[7] However, legalization in one state may lead to substantial spill-over effects in bordering states due to the opportunity for trafficking Hansen et al. (2017a). In

[7]Oregon and Alaska were also excluded as they legalized marijuana in 2015.

the second panel of Tables 4, 5, and 6 we replicate the analyses of Tables 1, 2, and 3 while excluding any states that share a border with any state that legalized recreational marijuana prior to the end of the post period. This includes California, Idaho, Nebraska, Nevada, New Mexico, Oklahoma, Texas, Utah, and Wyoming. This does have potential to affect our estimates as some of these states received positive weight as seen in Appendix Tables 1-4. However, we find similar point estimates and p-values for marijuana-related fatalities, as shown in Table 4. Likewise, the point estimates with this restricted synthetic control set are similar for both alcohol-related and overall traffic fatalities.

Another potential concern could be how sensitive the synthetic control models are to the inclusion of predetermined factors such as economic conditions, VMT, and the marijuana and alcohol testing rates. Including these may seem reasonable, but at the same time, these variables do not share the same importance as predetermined lagged values of the dependent variable in predicting the outcome variables. In the third panel of Tables 4,5, and 6, the point estimates reported reflect models where only predetermined variables were used to select the synthetic control group. For most outcomes, the p-values grew marginally larger. Moreover in some instances the estimated average impact shrunk while in other cases in grew. The estimates were of similar magnitude in most cases, and in all case the p-values remained statistically insignificant.

Lastly, another concern could be the suitability of states adopting medical marijuana as control groups for Colorado and Washington. On one hand, because Colorado and Washington had medical marijuana to begin with, they might be the most natural comparison group. On the other hand, perhaps states that adopted medical marijuana close to the time Colorado and Washington legalized could see their own surge in marijuana use. With this in mind, in the final panel of Tables 4, 5, and 6, we exclude any states that adopt a medical marijuana policy between 2012 and 2016. Generally the estimates are similar qualitatively, as some get a bit larger while others are smaller. Moreover, the p-values are consistently insignificant, suggesting again that the relative changes Colorado and Washington experience are within the expectations for any state which did not change marijuana policy.

5 Policy Implications and Conclusions

The broad trend towards the legalization of marijuana has led to a high degree of interest in social, economic, and public health consequences, both positive and negative. Faced with a steep increase in the fraction of traffic fatalities in which at least one driver tested positive for marijuana, the media and researchers alike have been eager to sound the alarm about this potentially dangerous side effect of the policy (Chen, 2016; Banta-Green et al., 2016; Migoya, 2017; Krieger, 2017). However, these early reports of steep increases are confounded by a number of factors. We contribute to this discussion by using a synthetic control method to compare the outcomes in Washington and Colorado to other states with similar pre-legalization economic and traffic trends. We find the synthetic control groups saw similar increases despite not legalizing marijuana. Moreover, the p-values suggest that the deviations Colorado and Washington did show from their synthetic counterparts are well with the range of deviations seen due to year to year variation.

Several mechanisms may be driving these results. The amount of marijuana sold in recreational stores has grown dramatically, increasing from 3,991 pounds in Washington in 2014 to 179,301 pounds in 2017, while in Colorado it grew from 36,031 pounds in 2014 to 102,871 pounds in 2016. However, it is difficult to discern how much of this growth in legal recreational weed came at the expense of sales in black market or medical marijuana. Indeed recreational marijuana can be viewed as a close substitute to black market or medical marijuana, with differences in price, quality, and ease of access. The relatively small effects we estimate are consistent with crowding-out, and could explain why we don't observe spill-over effects on alcohol-related traffic accidents as other studies have found (Anderson et al., 2013). Furthermore, Colorado has recently allowed consumption of marijuana in public spaces. This might increase the potential for negative externalities of recreational marijuana relative to medical marijuana. Despite that concern, we find limited overall evidence the fatalities are significantly increasing in Colorado and Washington following the legalization of recreational marijuana.

These results also inform optimal tax policy due to the potential externalities associated with marijuana (Hansen et al., 2017b). We show that it may be reasonable to question if recreational marijuana was responsible for the recent increase in traffic fatalities in Colorado and Washington. However, future research might consider other potential externalities such as effects on hospital admissions, crime, and drug overdoses. Accounting for the universe of externalities would help guide tax rates set to internalize externalities, although most states are likely setting tax rates with revenue in mind rather than optimal Pigovian goals.

While our results suggest that the marijuana legalization in Colorado and Washington did not lead to discernible increases in traffic fatalities, estimating the externalities of marijuana abuse and high driving is still crucial in determining future policy. Indeed, while Colorado and Washington have set the legal limit for high driving at 5 nanograms of THC per milliliter of blood, we don't yet know if the sanctions for high driving will be effective in discouraging high driving given the local population of drivers affected by that threshold (Hansen, 2015). Furthermore, there is still ample debate about what the right legal threshold would be, and if the threshold should even be based on THC. While the use of BAC is common today for measuring impairment in drunk driving, it took nearly decades of research and innovation from the passage of the first drunk driving laws to the creation of the first breathalyzers (Novak, 2013). Science and policy alike are playing catch up in both measuring the relative risks of high driving, and high driving itself.

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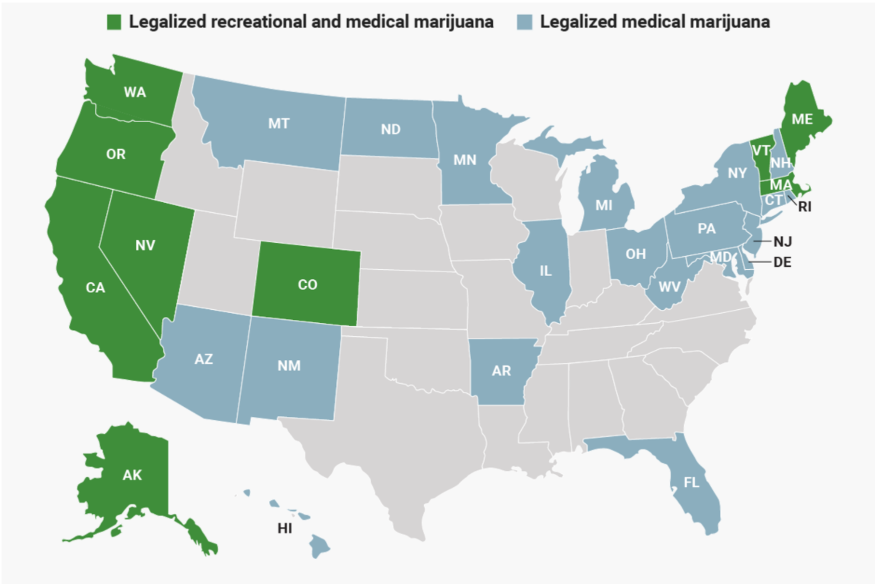
6 Figures and Tables

Figure 1: Marijuana laws by state



Source: Skye Gould/Business Insider

Figure 2: Marijuana-related traffic fatalities in Colorado, Washington and other states

(a) Fraction of Fatalities Marijuana-Related (b) Marijuana-Related Fatalities per billion VMT

Figure 3: Alcohol-related traffic fatalities in Colorado, Washington and other states

(a) Fraction of Fatalities Alcohol Related (b) Alcohol-Related Fatalities per billion VMT

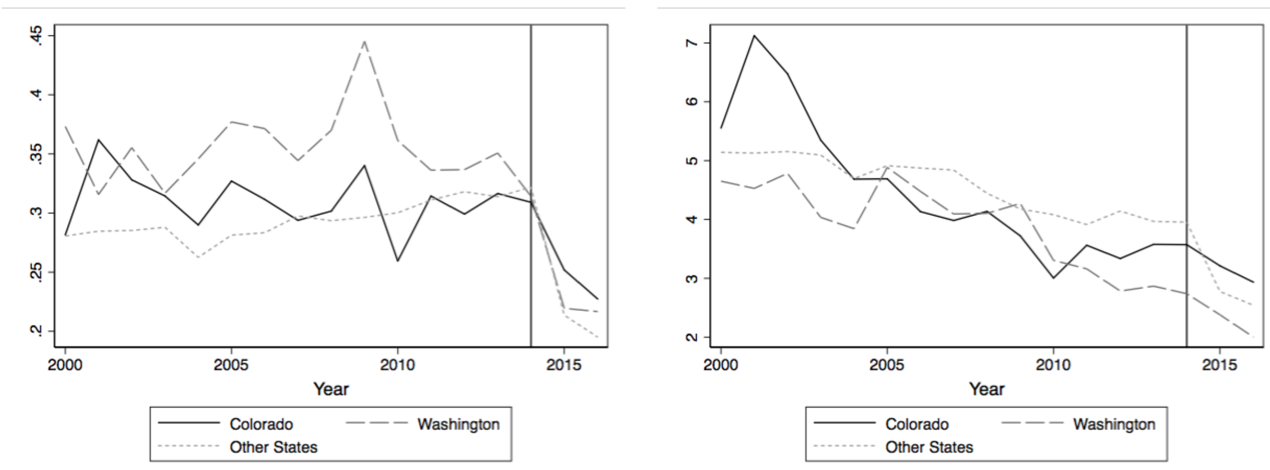
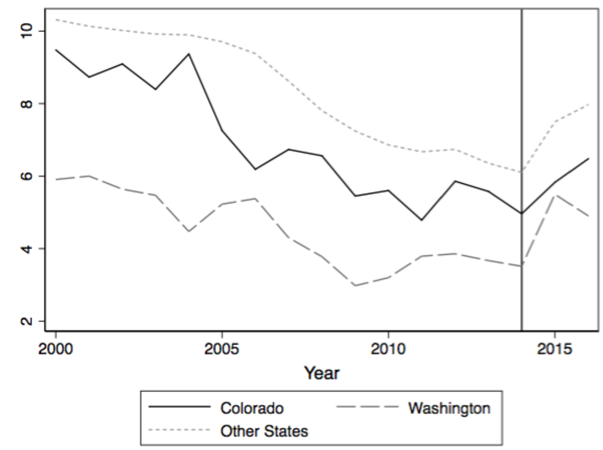


Figure 4: Fatal accident trends in Colorado, Washington and other states

(a) Sober Fatalities per billion VMT



(b) Total Fatalities per billion VMT

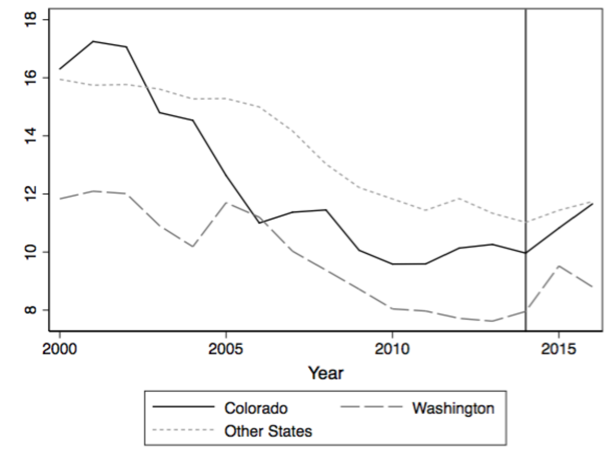
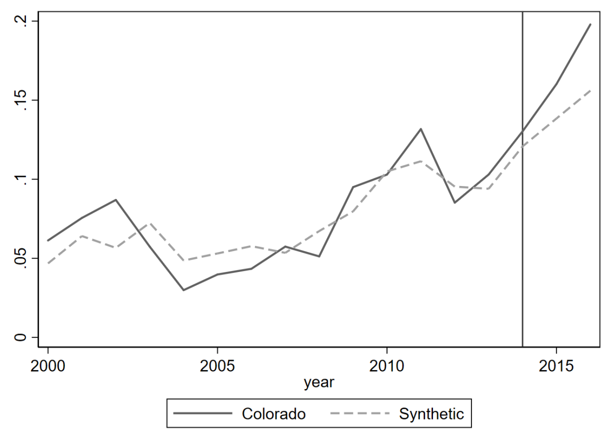
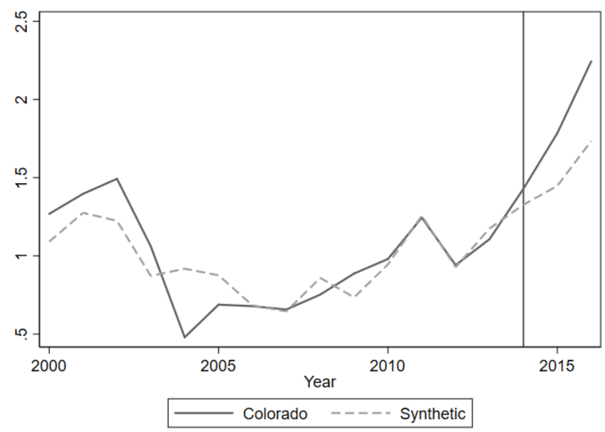


Figure 5: Marijuana-related traffic fatalities in Colorado

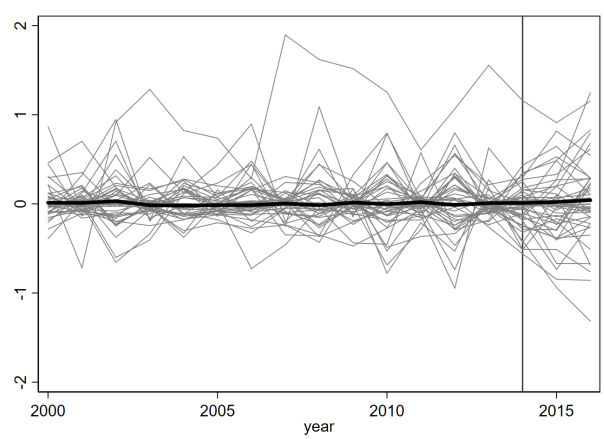
(a) Fraction of Fatalities Marijuana-Related



(b) Marijuana-Related Fatalities per billion VMT



(c) Actual Data-Synthetic Model for Colorado vs. Placebo States



(d) Actual Data-Synthetic Model for Colorado vs. Placebo States

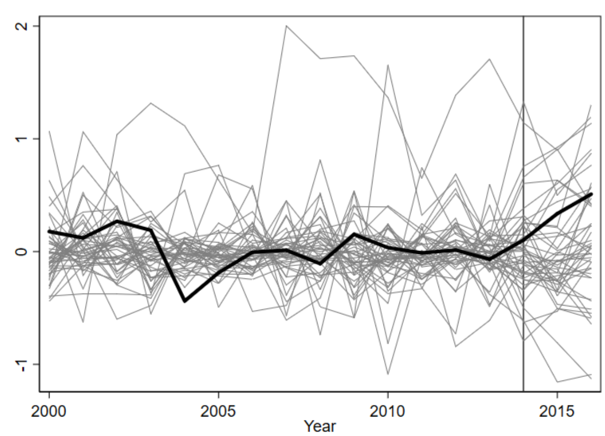
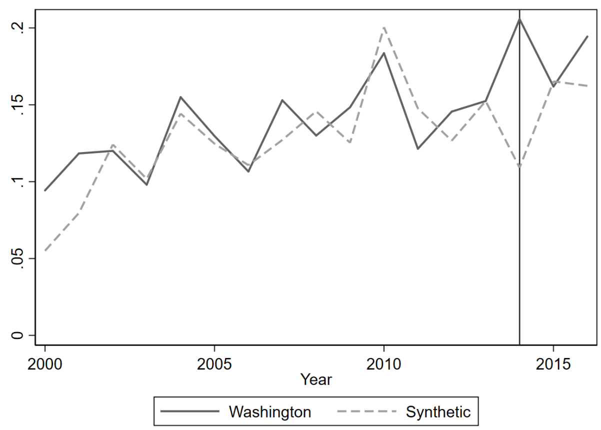
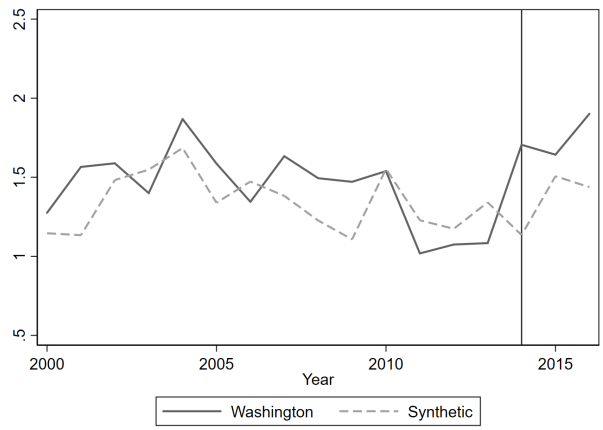


Figure 6: Marijuana-related traffic fatalities in Washington

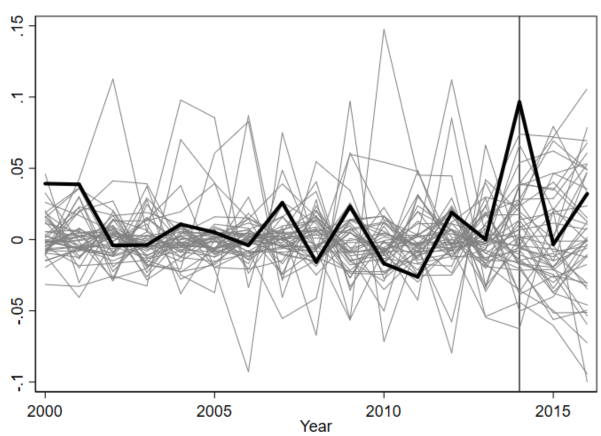
(a) Fraction of Fatalities Marijuana Related



(b) Marijuana Related Fatalities per billion VMT



(c) Actual Data-Synthetic Model for Washington vs. Placebo States



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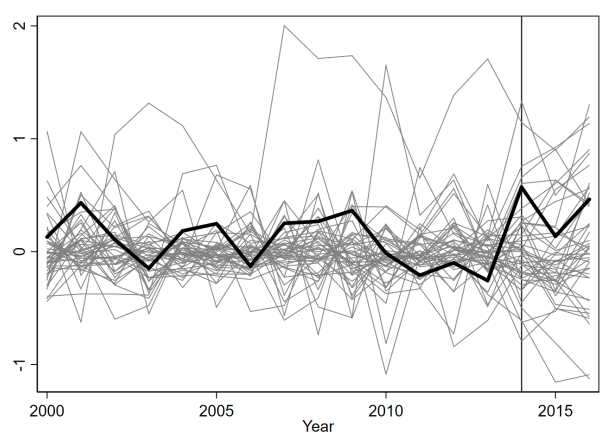
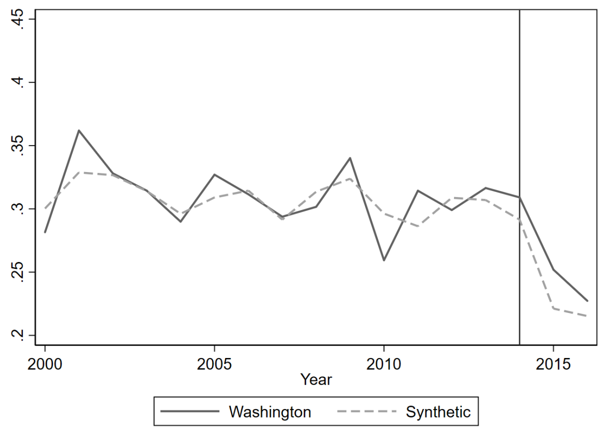
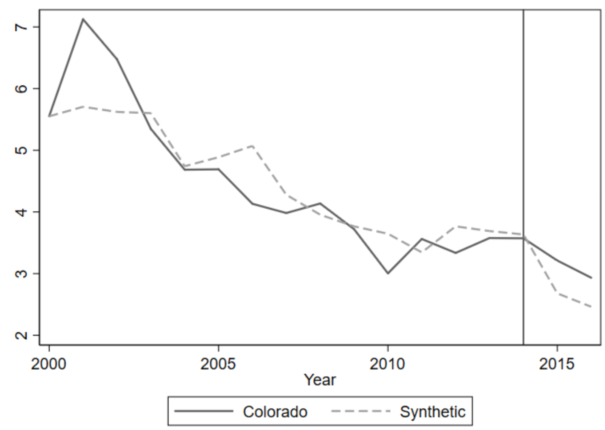


Figure 7: Alcohol-related traffic fatalities in Colorado

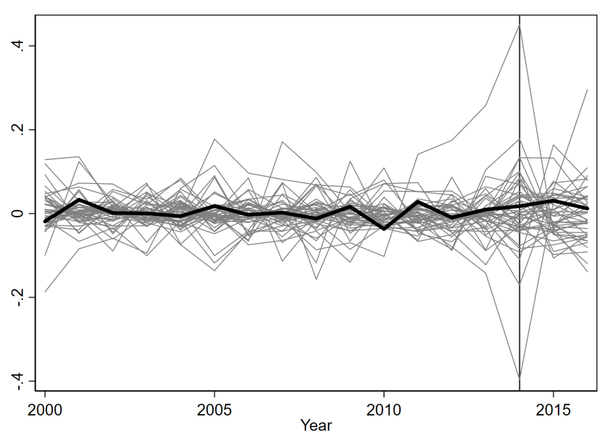
(a) Fraction of Fatalities Alcohol Related



(b) Alcohol-Related Fatalities per billion VMT



(c) Actual Data-Synthetic Model for Colorado vs. Placebo States



(d) Actual Data-Synthetic Model for Colorado vs. Placebo States

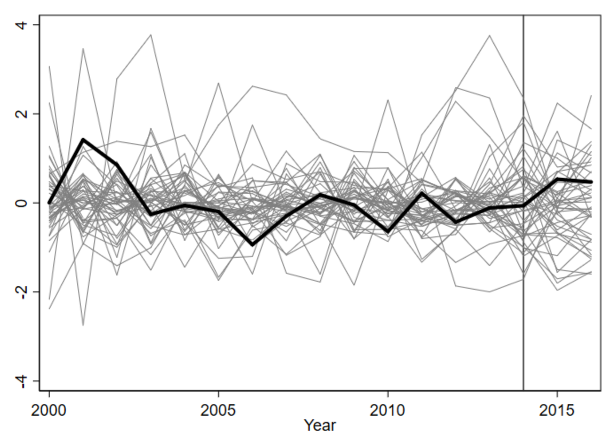
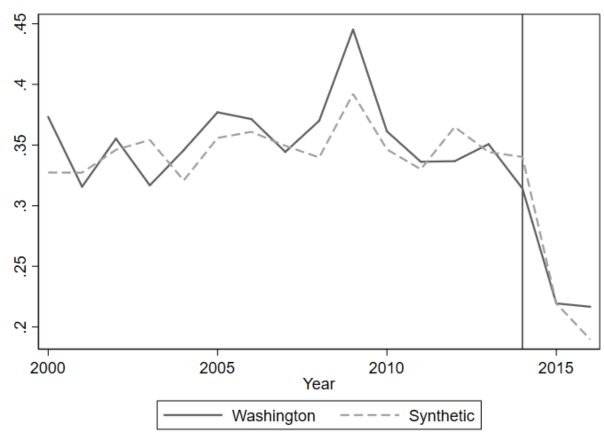
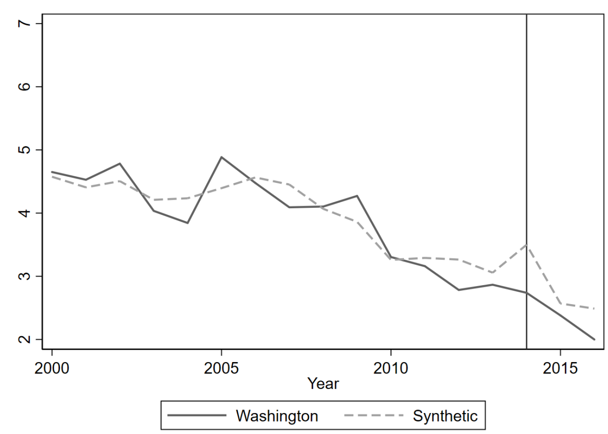


Figure 8: Alcohol-related traffic fatalities in Washington

(a) Fraction of Fatalities Alcohol Related



(b) Alcohol-Related Fatalities per billion VMT



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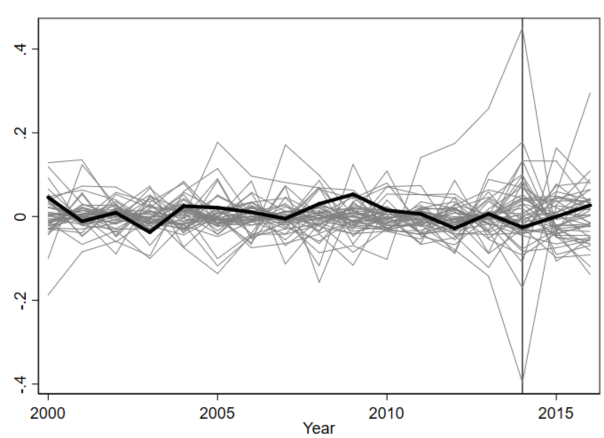


(d) Actual Data-Synthetic Model for Washington vs. Placebo States

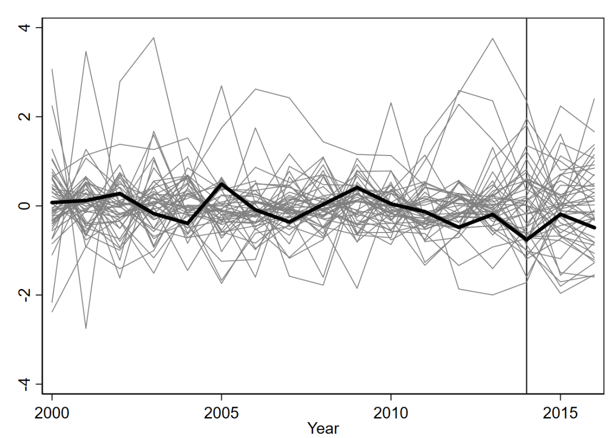
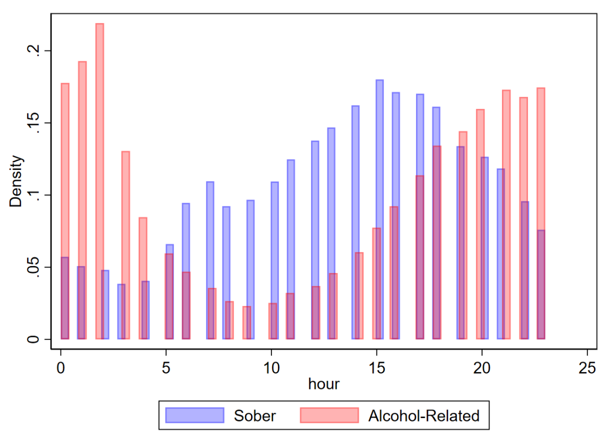


Figure 9: Time of Day for Sober, Alcohol, and Marijuana Related Fatalities

(a) Alcohol-Related Vs. Sober Fatalities



(b) Marijuana-Related vs. Sober Fatalities

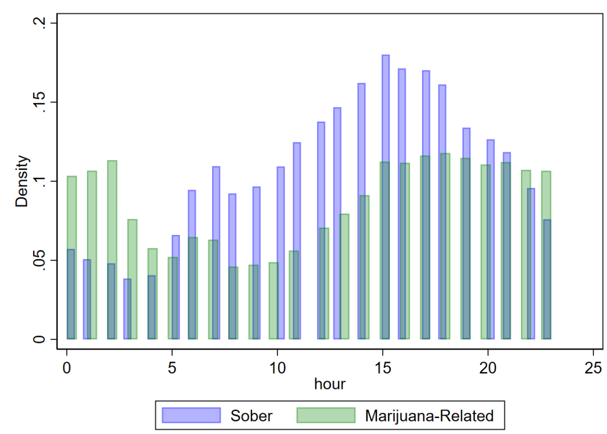
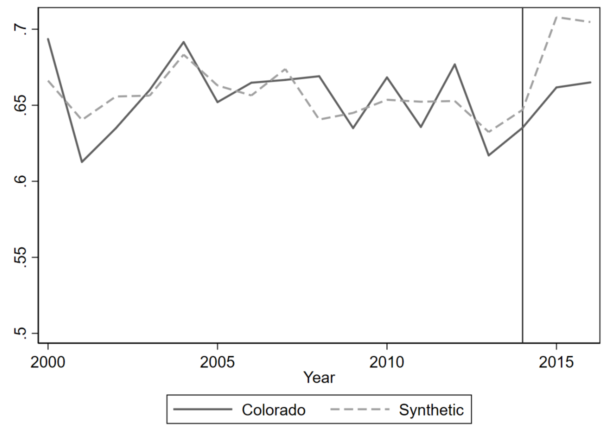
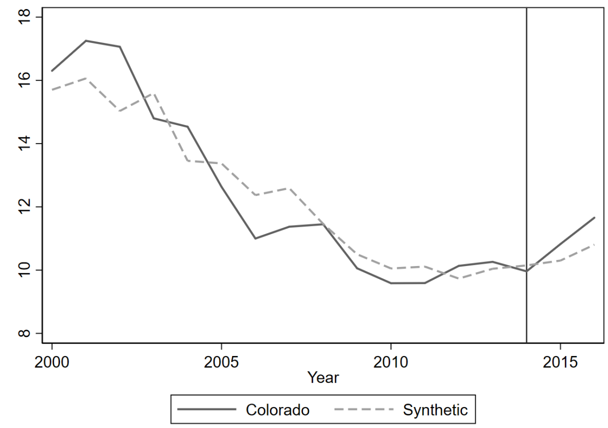


Figure 10: Overall fatalities in Colorado

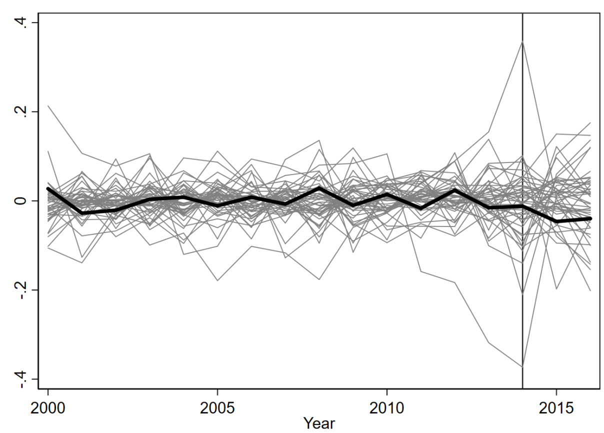
(a) Fraction of Fatalities Sober



(b) Total Fatalities per billion VMT



(c) Actual Data-Synthetic Model for Colorado vs. Placebo States



(d) Actual Data-Synthetic Model for Colorado vs. Placebo States

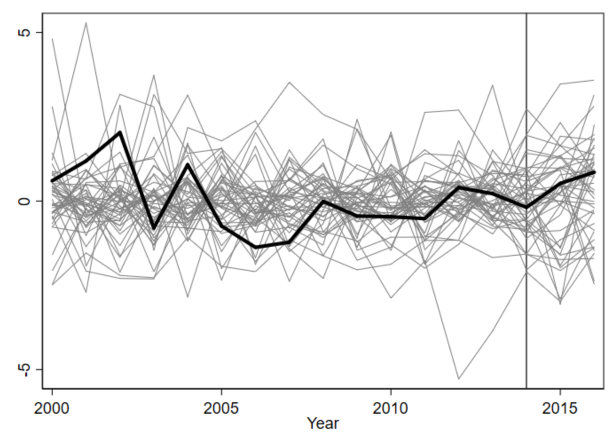


Figure 11: Overall fatalities in Washington

(a) Fraction of Fatalities Sober

(b) Total Fatalities per billion VMT

(c) Actual Data-Synthetic Model for Washington vs. Placebo States

(d) Actual Data-Synthetic Model for Washington vs. Placebo States

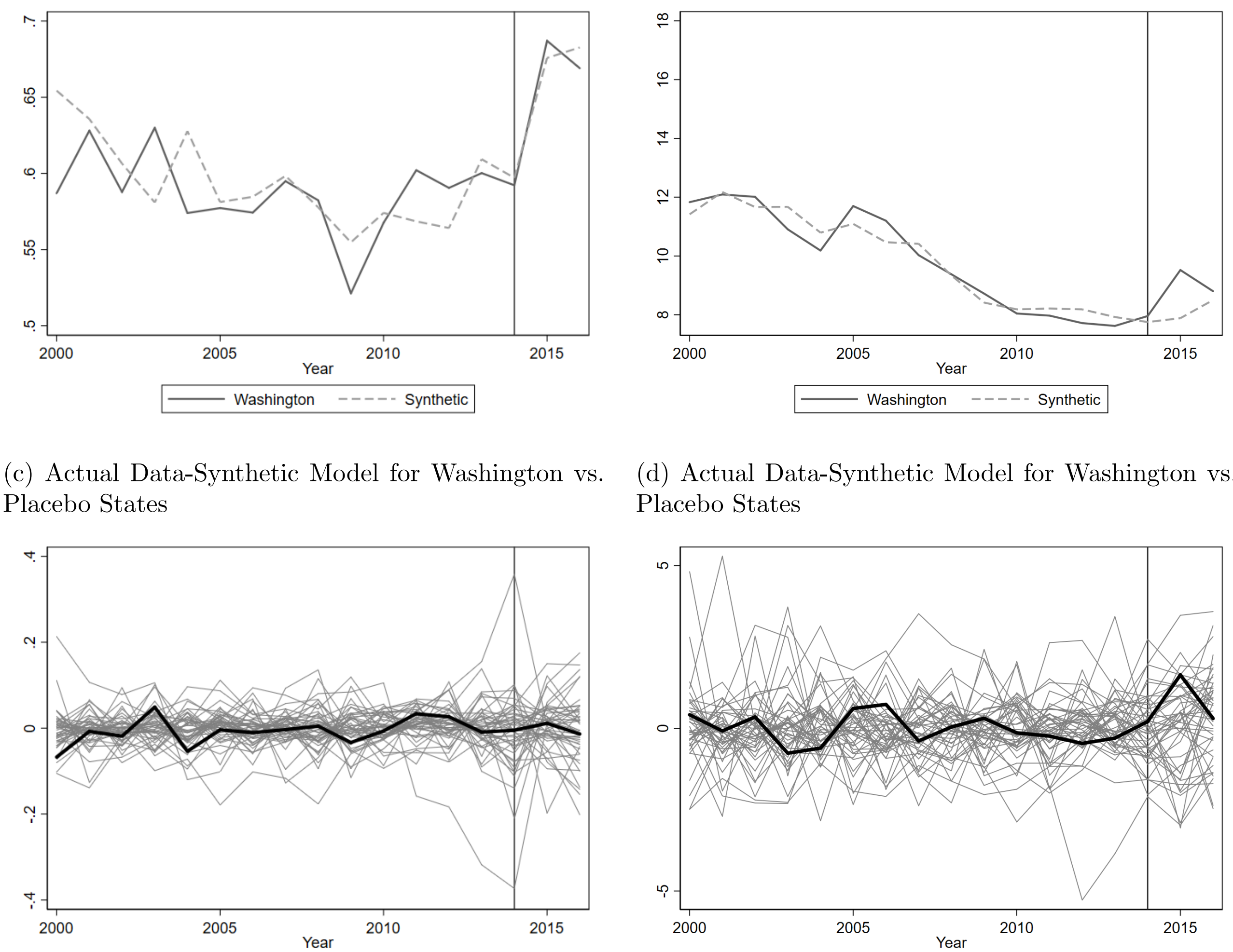


Table 1: Recreational Marijuana Law's Impact on Marijuana-Related Traffic Fatalities

	Colorado		Washington	
	Fraction Marijuana Related	Marijuana-related Fatalities per billion VMT	Fraction Marijuana Related	Marijuana-related Fatalities per billion VMT
RML	0.017	0.316	0.041	0.389
P-Value	[0.553]	[0.361]	[0.212]	[0.404]

This table includes synthetic control estimates p-values based on permutation testing of the ratio of mean squared error ratios for the post and pre-intervention periods. For matching predetermined predictors, each model includes the marijuana testing rate, the alcohol testing rate, the fraction of VMT that are urban, the unemployment rate, average VMT for 2000-2007, 2008-2009, 2010-2011, and 2012 and 2013, lagged values of the outcome for two years bins from 2000 through 2014.

Table 2: Recreational Marijuana Law's Impact on Alcohol-Related Traffic Fatalities

	Colorado		Washington	
	Fraction Alcohol Related	Alcohol-related Fatalities per billion VMT	Fraction Alcohol Related	Alcohol Fatalities per billion VMT
RML	0.020	0.313	0.0002	−0.479
P-Value	[0.702]	[0.765]	[0.872]	[0.277]

This table includes synthetic control estimates p-values based on permutation testing of the ratio of mean squared error ratios for the post and pre-intervention periods. For matching predetermined predictors, each model includes the marijuana testing rate, the alcohol testing rate, the fraction of VMT that are urban, the unemployment rate, average VMT for 2000-2007, 2008-2009, 2010-2011, and 2012 and 2013, lagged values of the outcome for two years bins from 2000 through 2014.

Table 3: Recreational Marijuana Law's Impact Overall Fatalities

	Colorado		Washington	
	Fraction Sober	Total Fatalities per billion VMT	Fraction Sober	Total Fatalities per billion VMT
RML	−0.032	0.396	−0.002	0.714
P-Value	[0.319]	[0.872]	[0.957]	[0.213]

This table includes synthetic control estimates p-values based on permutation testing of the ratio of mean squared error ratios for the post and pre-intervention periods. For matching predetermined predictors, each model includes the marijuana testing rate, the alcohol testing rate, the fraction of VMT that are urban, the unemployment rate, average VMT for 2000-2007, 2008-2009, 2010-2011, and 2012 and 2013, lagged values of the outcome for two years bins from 2000 through 2014.

Table 4: Robustness of Estimates of Recreational Marijuana Law's Impact on Marijuana-Related Traffic Fatalities

	Colorado		Washington	
	Fraction Marijuana Related	Marijuana-related Fatalities per billion VMT	Fraction Marijuana Related	Marijuana-related Fatalities per billion VMT
Treatment Begins in 2012				
RML	0.013	0.157	0.042	−0.086
P-Value	[0.489]	[0.319]	[0.170]	[0.893]
Border States Excluded				
RML	0.021	0.244	0.037	0.618
P-Value	[0.489]	[0.297]	[0.234]	[0.255]
Including only Lagged Outcomes as Matching Predictors				
RML	0.016	0.232	0.035	0.432
P-Value	[0.489]	[0.511]	[0.340]	[0.511]
Excluding States that Legalized Medical Marijuana from 2012-2016				
RML	0.043	0.451	0.038	0.445
P-Value	[0.255]	[0.234]	[0.276]	[0.297]

This table includes synthetic control estimates p-values based on permutation testing of the ratio of mean squared error ratios for the post and pre-intervention periods. For matching predetermined predictors, each model includes the marijuana testing rate, the alcohol testing rate, the fraction of VMT that are urban, the unemployment rate, average VMT for 2000-2007, 2008-2009, 2010-2011, and 2012 and 2013, lagged values of the outcome for two years bins from 2000 through 2014.

Table 5: Robustness of Estimates of Recreational Marijuana Law's Impact on Alcohol-Related Traffic Fatalities

	Colorado		Washington	
	Fraction Alcohol Related	Alcohol-related Fatalities per billion VMT	Fraction Alcohol Related	Alcohol-related Fatalities Per billion VMT
Treatment Begins in 2012				
RML	0.002	−0.384	−0.008	−0.577
P-Value	[0.914]	[0.744]	[0.723]	[0.382]
Border States Excluded				
RML	0.017	0.178	0.005	−0.140
P-Value	[0.680]	[0.893]	[0.702]	[0.680]
Including only Lagged Outcomes as Matching Predictors				
RML	0.019	0.128	−0.023	−0.626
P-Value	[0.851]	[0.872]	[0.617]	[0.234]
Excluding States that Legalized Medical Marijuana from 2012-2016				
RML	0.007	0.211	−0.028	−0.556
P-Value	[0.872]	[0.892]	[0.532]	[0.297]

This table includes synthetic control estimates p-values based on permutation testing of the ratio of mean squared error ratios for the post and pre-intervention periods. For matching predetermined predictors, each model includes the marijuana testing rate, the alcohol testing rate, the fraction of VMT that are urban, the unemployment rate, average VMT for 2000-2007, 2008-2009, 2010-2011, and 2012 and 2013, lagged values of the outcome for two years bins from 2000 through 2014.

Table 6: Robustness of Estimates of Recreational Marijuana Law's Impact on Overall Fatalities

	Colorado		Washington	
	Fraction Sober Related	Total Fatalities per billion VMT	Fraction Sober Related	Total Fatalities Per billion VMT
Treatment Begins in 2012				
RML	−0.006	0.918	−0.003	−0.016
P-Value	[0.702]	[0.723]	[0.978]	[0.340]
Border States Excluded				
RML	−0.024	0.526	−0.012	0.880
P-Value	[0.489]	[0.893]	[0.914]	[0.170]
Including only Lagged Outcomes as Matching Predictors				
RML	−0.017	0.283	0.011	0.975
P-Value	[0.829]	[0.957]	[0.872]	[0.191]
Excluding States that Legalized Medical Marijuana from 2012-2016				
RML	−0.043	0.250	0.019	0.721
P-Value	[0.277]	[0.872]	[0.851]	[0.234]

This table includes synthetic control estimates p-values based on permutation testing of the ratio of mean squared error ratios for the post and pre-intervention periods. For matching predetermined predictors, each model includes the marijuana testing rate, the alcohol testing rate, the fraction of VMT that are urban, the unemployment rate, average VMT for 2000-2007, 2008-2009, 2010-2011, and 2012 and 2013, lagged values of the outcome for two years bins from 2000 through 2014.

Appendices

A Appendix Tables

Table A.1: Synthetic Control Covariates

Panel A: Colorado

	Potential Comp. States	Colorado	Fraction Mar. Related	Mar.-related Fatalities per billion VMT	Fraction Alc. Related	Alc.-related Fatalities per billion VMT	Fraction Sober	Total Fatalities per billion VMT
Fraction Urban	0.592	0.681	0.674	0.619	0.593	0.662	0.620	0.727
Drug Test Rate	0.450	0.438	0.428	0.432	0.438	0.451	0.437	0.466
Alcohol Test Rate	0.629	0.563	0.563	0.612	0.671	0.638	0.648	0.575
VMT per Pop (2000-2007)	0.013	0.013	0.013	0.013	0.013	0.013	0.012	0.012
VMT per Pop (2008-2009)	0.013	0.012	0.012	0.012	0.012	0.012	0.012	0.012
VMT per Pop (2010-2011)	0.013	0.012	0.012	0.012	0.012	0.012	0.012	0.011
VMT per Pop (2012-2013)	0.013	0.011	0.012	0.012	0.011	0.012	0.011	0.011
Unemployment Rate	0.063	0.061	0.061	0.062	0.061	0.061	0.059	0.075

Panel B: Washington

	Potential Comp. States	Washington	Fraction Mar. Related	Mar.-related Fatalities per billion VMT	Fraction Alc. Related	Alc.-related Fatalities per billion VMT	Fraction Sober	Total Fatalities per billion VMT
Fraction Urban	0.592	0.707	0.686	0.763	0.695	0.779	0.656	0.835
Drug Test Rate	0.450	0.452	0.490	0.486	0.439	0.472	0.464	0.452
Alcohol Test Rate	0.629	0.596	0.724	0.645	0.627	0.588	0.680	0.591
VMT per Pop (2000-2007)	0.013	0.011	0.011	0.011	0.011	0.012	0.011	0.011
VMT per Pop (2008-2009)	0.013	0.011	0.010	0.010	0.011	0.011	0.011	0.011
VMT per Pop (2010-2011)	0.013	0.010	0.010	0.010	0.010	0.011	0.010	0.010
VMT per Pop (2012-2013)	0.013	0.010	0.010	0.010	0.010	0.011	0.010	0.010
Unemployment Rate	0.063	0.075	0.054	0.066	0.066	0.074	0.057	0.073

This table provides the average covariate values for all potential comparison states (all states except Washington, Colorado, Oregon, and Alaska), the treated states (Washington and Colorado), and the synthetic control for each outcome in Tables 1, 2, and 3. Lagged outcome values are also included as covariates in the models estimates in Tables 1, 2, and 3, but are not listed here. The column titles abbreviate marijuana as mar. and alcohol as alc.

Table A.2: Synthetic Control Weights Assigned to Each State for Marijuana-Related Fatality Outcomes

	Colorado		Washington	
	Fraction Marijuana Related	Marijuana-related Fatalities per billion VMT	Fraction Marijuana Related	Marijuana-related Fatalities per billion VMT
Arkansas	0.083	0.000	0.000	0.000
Connecticut	0.000	0.180	0.000	0.000
Delaware	0.429	0.165	0.000	0.000
District Of Columbia	0.000	0.000	0.166	0.123
Georgia	0.060	0.058	0.000	0.184
Hawaii	0.103	0.120	0.450	0.365
Indiana	0.000	0.000	0.047	0.000
Montana	0.000	0.000	0.054	0.000
Nevada	0.070	0.020	0.000	0.293
New Hampshire	0.051	0.000	0.193	0.000
Rhode Island	0.114	0.022	0.000	0.000
Vermont	0.000	0.000	0.091	0.035
West Virginia	0.090	0.434	0.000	0.000

This table provides the weights assigned to states for the synthetic controls used in Table 1. All states except Washington, Colorado, Oregon and Alaska were states that could have potentially received positive weight for any given synthetic control. All states that received zero weight across all four columns are excluded from this list for the sake of brevity.

Table A.3: Synthetic Control Weights Assigned to Each State for Drunk-Related Traffic Fatalities Outcomes

	Colorado		Washington	
	Fraction Alcohol Related	Alcohol-related Fatalities per billion VMT	Fraction Alcohol Related	Alcohol Fatalities per billion VMT
Arizona	0.000	0.308	0.000	0.000
California	0.000	0.000	0.000	0.354
Delaware	0.351	0.000	0.067	0.000
District Of Columbia	0.000	0.000	0.000	0.067
Florida	0.000	0.107	0.000	0.000
Georgia	0.106	0.000	0.000	0.000
Hawaii	0.089	0.000	0.189	0.000
Illinois	0.000	0.000	0.632	0.000
Louisiana	0.000	0.000	0.000	0.150
Minnesota	0.000	0.147	0.000	0.000
Nevada	0.000	0.000	0.000	0.144
New Hampshire	0.091	0.134	0.000	0.000
Rhode Island	0.190	0.178	0.000	0.114
South Dakota	0.000	0.127	0.112	0.000
Utah	0.000	0.000	0.000	0.172
West Virginia	0.174	0.000	0.000	0.000

This table provides the weights assigned to states for the synthetic controls used in Table 2. All states except Washington, Colorado, Oregon and Alaska were states that could have potentially received positive weight for any given synthetic control. All states that received zero weight across all four columns are excluded from this list for the sake of brevity.

Table A.4: Synthetic Control Weights Assigned to Each State for Overall Traffic Fatality Outcomes

	Colorado		Washington	
	Fraction Sober	Total Fatalities per billion VMT	Fraction Sober	Total Fatalities per billion VMT
California	0.000	0.000	0.000	0.196
Connecticut	0.000	0.000	0.000	0.043
Delaware	0.113	0.000	0.000	0.000
District Of Columbia	0.000	0.255	0.000	0.108
Georgia	0.072	0.000	0.000	0.000
Hawaii	0.048	0.000	0.426	0.000
Illinois	0.000	0.000	0.341	0.000
Massachusetts	0.000	0.000	0.000	0.210
Michigan	0.000	0.275	0.000	0.000
Minnesota	0.000	0.116	0.000	0.000
Mississippi	0.000	0.092	0.000	0.000
New Hampshire	0.205	0.000	0.040	0.000
New Jersey	0.000	0.000	0.000	0.066
Ohio	0.000	0.000	0.000	0.305
Pennsylvania	0.258	0.000	0.000	0.000
Rhode Island	0.040	0.000	0.000	0.072
South Carolina	0.118	0.000	0.000	0.000
South Dakota	0.065	0.000	0.091	0.000
Texas	0.000	0.261	0.000	0.000
Vermont	0.000	0.000	0.101	0.000

This table provides the weights assigned to states for the synthetic controls used in Table 3. All states except Washington, Colorado, Oregon and Alaska were states that could have potentially received positive weight for any given synthetic control. All states that received zero weight across all four columns are excluded from this list for the sake of brevity.