Assessing California's Climate Targets and Road Transportation Policy Using Near-Real-Time Emission Estimation

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ABSTRACT

The California Air Resources Board (CARB) estimates that achieving California's 2030 emission reduction goal will require 35-40% reductions in transportation sector emissions over the next decade, requiring the rate of emission reduction to increase significantly. New analytical tools and approaches for the econometric assessment of road transportation policies can facilitate consistent evaluation of current impacts to inform future development. By estimating near-real-time, state-level, and sector-specific emissions that are not publicly available yet and applying them to policy assessment, this study offers a new dataset that captures recent and rapidly changing trends in CO_2 emissions, potentially moving up the timetable of policy developments by 1-2 years, while exploring implications for future policymaking efforts to achieve mid-century carbon neutrality goals. This study compares U.S. state-level emission reduction targets; applies an econometric model to assess the effectiveness of the Low Carbon Fuel Standard (LCFS), a major state-level road transportation policy, on CO_2 emissions from transportation; and constructs a novel dataset comprised of near-real-time daily CO_2 emissions for California's road transportation sector in 2019. California's carbon neutrality by 2045 target is one of the most ambitious long-term state-level emission reduction targets. Model results using estimated emissions for 2019 suggest that California's adoption of the LCFS decreased state emissions by approximately 14.3 million metric tons in the post-intervention period. As subnational actors continue to drive climate and energy policy, empirical studies on established targets for highly polluting sectors can clarify concrete near-term priorities and inform long-term decarbonization strategies.

KEYWORDS

carbon neutrality, daily carbon dioxide emission, econometric modeling, cumulative greenhouse gas emission, Low Carbon Fuel Standard

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) projects that meeting Paris Agreement goals will require all countries to be carbon neutral, or have net zero CO_2 emissions, by mid-century, in conjunction with reductions in non-CO_2 greenhouse gas (GHG) emissions. The United Nations Secretary-General has called for this commitment from G20 countries since 2018 and asked for greater ambition in national climate plans before the 2021 UN Climate Change Conference. The United States' Paris Agreement goal to reduce emissions by 10-17% below 1990 levels by 2025, excluding land-use, land-use change and forestry (LULUCF), is not consistent with the Paris Agreement goals of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, as recommended by the IPCC (Masson-Delmotte et al. 2018). The federal policies under the Trump Administration are projected to lead to only a 11-13% reduction in emissions below 2005 levels by 2025, excluding LULUCF. Prior to January 2021, the void left by the federal government during the Trump Administration resulted in subnational action taking the lead in climate and energy policy (America's Pledge 2020, Hsu et al. 2018). A growing number of U.S. states have set mid-century carbon neutrality targets following California's lead in 2018 and President Biden pledged a 2050 carbon neutrality target in 2021. California co-founded the United States Climate Alliance (USCA) with New York and Washington States in an effort to work towards the U.S. Nationally Determined Contribution in the absence of federal action (USCA 2020). With increased momentum on the international, national, and subnational levels to pursue mid-century carbon neutrality targets and GHG emission reduction goals, empirical research on climate policy impacts is necessary to aid future policy amendments. Studies such as E3's Pathways for Achieving Carbon Neutrality in California have broken down the specific measures applied in carbon neutrality scenarios for various sectors. In-depth exploration of decarbonization measures and policies by sector in the California context is appropriate because comprehensive policy packages are often disaggregated into specific measures along sectoral lines. A highly critical sector vital to the energy transition is transportation- especially road transportation, which currently accounts for the largest source of emissions in California, outpacing the industrial, agricultural, and residential sectors combined.

Subnational policymaking in the transportation sector is especially critical to meeting Paris Agreement goals. Emissions from the global transportation sector account for almost one-quarter of GHG emissions and approximately 72% of this amount is from road transportation (Axsen et al. 2020). Transportation accounts for 41% of California's overall emissions, due mostly to passenger vehicles, and the share rises to nearly 55% when carbon emissions from producing gasoline and diesel are included. State transportation emissions have continued to increase largely due to increased driving miles, while emissions in nearly every other sector have declined in recent years (CARB 2020). Transportation emissions are expected to grow further in scenarios produced by the International Energy Agency (IEA), even if currently announced policies are implemented (Creutzig et al. 2011). Assessing the effectiveness of current road transportation policies and comparing emission reduction ambition is critical to identifying state policy gaps, or where greater policy implementation and ambition is necessary to advance Paris goals (Creutzig et al. 2011). California's road transportation standards are pioneering- far more stringent than federal standards- and state technologies and strategies have in many cases served as a model for other states and jurisdictions around the world (Sperling and Eggert 2014). To better understand the potential for road transportation policies to reduce global emissions, it is essential to assess California's policies in the context of wider subnational policy ambitions; analyze policy effectiveness, taking into account the economic structure of jurisdictions; and utilize new emission estimation data in policy analysis.

When assessing California's policies in the road transportation sector, it is important to pay particular attention to implementation gaps for meeting emission reduction targets. California's ambitious mid-term and long-term goals for reducing GHG emissions include a 40% reduction below 1990 levels by 2030 and achieving carbon neutrality, or net zero GHG emissions, by 2045. The California Air Resources Board (CARB) estimates that achieving the 2030 goal will require 35-40% reductions in transportation sector emissions over the next decade, requiring the rate of emission reduction to increase significantly. Over the years, California has adopted a comprehensive set of policies, regulations, and incentives to reduce GHG emissions in this sector, focusing on vehicles, fuels, and mobility in the policy mix (Kern and Howlett 2009). Policy mixes- a common term referring to the presence of multiple policies implemented in the same region, during the same time period, and relating to the same objective- have been studied extensively in the literature (Axsen et al. 2020). While California drew many lessons from other regions and jurisdictions in designing climate policies, few other policy mixes are as comprehensive and ambitious (Sperling and Eggert 2014). By identifying the differences between other state policies and California's approach, researchers can better assess the level of ambition and potential room for improvement for this sector. California's Low Carbon Fuel Standard (LCFS) is a prominent climate policy, aiming to limit the state's CO_2 footprint of on-road vehicles (Creutzig et al. 2011, Sperling and Eggert 2018, USCA 2020). This regulation can play a leading role in policy mixes in many regions due to its potential effectiveness and political acceptability (Axsen et al. 2020). However, the impact of the LCFS on emissions has not been extensively studied; furthermore, the application of near-real-time emissions in policy analysis for this sector has not been greatly utilized. This data is critical because it allows researchers to identify structural changes due to recent developments, helping subnational governments to adjust ineffective policies and reinforce necessary ones more quickly (Liu et al. 2020a, Liu et al. 2020b). By using recent data and examining the ambition and effectiveness of current state policies in reducing emissions for this sector, we can better predict the outcomes of future policies. There is no recent empirical work that uses real-time daily CO_2 emissions data coupled with econometric techniques to examine the impact of U.S. state-level LCFS policies on CO_2 emissions from the road transportation sector. The question posed in this study is, how ambitious and effective are California's major climate targets and policy in the road transportation sector? Three sub-questions follow:

1. How ambitious are California's climate targets compared to other states' targets?
2. How effective are U.S. LCFS policies in reducing state-level CO_2 emissions for the transportation sector, using U.S. Energy Information Administration (EIA) transportation emissions data?
3. Can state-level real-time daily CO_2 emissions for road transportation be estimated to examine LCFS effectiveness for this sector?

I highlighted and compared major state emission reduction targets in terms of timelines and levels of commitment, with legislation and executive orders considered to be higher levels of commitment, expecting California to have more ambitious mid-term or long-term emission reduction targets and more binding commitments in the form of legislation and executive orders. I examined LCFS policy impacts on CO_2 emissions from the transportation sector using panel data for U.S. states over the period 2000–2017, Stata 16 (StataCorp 2019), and economic regressions clustered at the state level, expecting the LCFS to have been a highly effective policy that decreased transportation sector emissions. I estimated state-level real-time daily CO_2 emissions for the road transportation sector and used this data to examine LCFS policy impacts on CO_2 emissions, expecting consistent results.

BACKGROUND

State climate targets and policies

Twenty-seven states have pledged specific mid-term or long-term targets to reduce their overall GHG or carbon emissions through legislation, executive orders, announcements, or recommendations (USCA 2020). Nine states have gone further by enacting carbon neutral or net-zero commitments via legislation or executive orders. Since California's landmark Global Warming Solutions Act of 2006 (AB 32) and the 2016 Senate Bill 32 were passed, California has pioneered subnational climate action and continually extended and strengthened limits on GHG emissions. The state grew its economy while decreasing carbon pollution and strengthening its climate and energy policy portfolio. To understand the ambition and level of commitment of California's emission reduction policies, it is useful to consider the types and timelines of emission targets across different states. Because state targets use different baseline years for emission reduction, a common baseline year can be used to compare targets. Level of commitment can be approached by categorizing policies into legislation, executive orders, announced plans, and recommended goals. Binding legislation is more stringent because it generally provides tangible incentives. Recommendations and announcements can be considered less stringent as they generally do not provide tangible incentives. Executive orders have several caveats; future governors can decide not to follow through with commitments by previous governors and executive orders are rarely enforceable in court. In this study, legislation and executive orders are considered to be more stringent commitments than announced plans and recommended goals.

While carbon neutrality, net-zero, and climate neutrality are often used interchangeably, the IPCC provides a clear definition for each term. Carbon neutrality refers to a balance between the CO_2 emitted into the atmosphere and the CO_2 removed from the atmosphere; net-zero emission encompasses all GHG emissions and can refer to balancing emitted GHGs with removed GHGs within a certain period of time; and climate (GHG) neutrality goes even further by considering all human impacts that affect the climate, meaning that the targets are interpreted as implying net-zero emissions for GHG (including LULUCF). The Paris Agreement defines carbon neutrality as a balance between anthropogenic emissions by sources and removals by sinks of GHGs. The U.S. federal government has no official definition of carbon neutrality and the net-zero emissions target in President Biden's Climate Plan does not specify whether it pertains to CO_2 or all GHG gases. The distinction between carbon neutrality and GHG neutrality is important because it can result in significant differences in the estimated 2050 emissions level. This study does not seek to provide a single definition of carbon neutrality, but considers the range of state targets. California defines its carbon neutrality target as, "the point at which the removal of carbon pollution from the atmosphere meets or exceeds emissions" (EO B-55-18). Hawaii, on the other hand, in its HB 2182 and HB 1986, sets the carbon neutrality goal of "sequestering more atmospheric carbon and greenhouse gases than the State produces as quickly as practicable, but no later than 2045." Another example is Michigan's goal, which aims to end net carbon emissions by 2050 "and to maintain net negative greenhouse gas emissions thereafter." The differences in wording illustrates how carbon neutrality goals are not always defined the same way. Since in some cases, state legislation has set carbon neutrality targets in terms of total GHG emissions rather than CO_2 emissions, this study considers all state-level carbon neutrality, net-zero, and GHG neutrality target values to be 100% GHG emission reduction goals.

Low Carbon Fuel Standard (LCFS)

LCFS policies are carbon intensity standards which primarily aim to reduce emissions from transportation fuels without prescribing fuel type. An LCFS looks at the whole life cycle of the fuel, applying standards to all stages of motor fuel production, and measures intensity rather than absolute emissions. Regulated parties include all entities that either produce or import motor fuels for consumption in the jurisdiction; regulated fuel providers are usually required to reduce average fuel carbon intensity by some amount from a defined baseline year. By setting annual carbon intensity benchmarks which reduce over time for gasoline, diesel, and their replacement fuels, the LCFS provides policymakers another avenue to reduce transportation emissions and allows the market to determine the fuel mix to be used to reach targets. LCFS programs generally allow for trading and banking of emission credits to further enhance flexibility and support innovation (C2ES 2019).

California was the first state to adopt the LCFS to reduce emissions from on-road light-duty vehicles and transition away from liquid transportation fuels. In 2009, CARB approved the LCFS regulation, a key AB 32 measure, to reduce the carbon intensity of transportation fuel used in the state by at least 10% from 2010 levels by 2020 (Executive Order S-1-07). In 2018, CARB approved amendments including strengthening the carbon intensity benchmarks through 2030, with a target of 20% carbon intensity reduction from 2010 levels. As the LCFS is one of the first attempts to bring the life-cycle CO_2 emission concept into policy, it is not surprising that the life-cycle accounting was challenged by certain stakeholders until the U.S. 9th Circuit Court ruled that the LCFS would reduce CO_2 emissions and that California should be encouraged to continue expanding its efforts. Since the LCFS went into effect, low carbon fuel use has increased. Most studies have focused on the LCFS impact on intensity of motor fuels, though some have also provided evidence that the LCFS reduced carbon dioxide emissions in California's transportation sector, with one econometric study estimating the amount to be around 10%, with different modeling approaches and variables used (Holland et al. 2009, Huseynov and Palma 2019).

Other jurisdictions have planned to join California in implementing this policy. The Pacific Coast Collaborative, a regional agreement between California, Oregon, Washington, and British Columbia to align GHG reduction policies and promote clean energy, has aligned to explicitly address LCFS programs. In 2009, Oregon authorized the development of a LCFS program to reduce the average carbon intensity of conventional gasoline and diesel fuel by 10% over a ten-year period; the state fully implemented its Clean Fuels Program, targeting a 10% reduction from 2010 levels by 2025, in 2016 (C2ES 2019). New York's bill for LCFS, intended to reduce carbon intensity by 20% from the road transportation sector by 2030, failed to make it out of committee during the 2020 legislative session. The Colorado Clean Fuels Standard feasibility study, completed in September of 2020, reached the near-term decision to not implement the program at that time because the state had not made a comprehensive analysis or public process examining the tradeoffs involved with large scale use of conventional biofuels and potential for high compliance costs. While currently only California and Oregon have existing LCFS-type programs in place, other states as well as several international communities are considering programs (Figure 1). Minnesota, Iowa, and South Dakota are believed to be considering participation in a low carbon fuel program tailored for Midwestern state needs specifically. Low carbon fuel mandates similar to California's LCFS have been adopted by the Environmental Protection Agency and other jurisdictions including the European Union and the United Kingdom (CARB 2020).

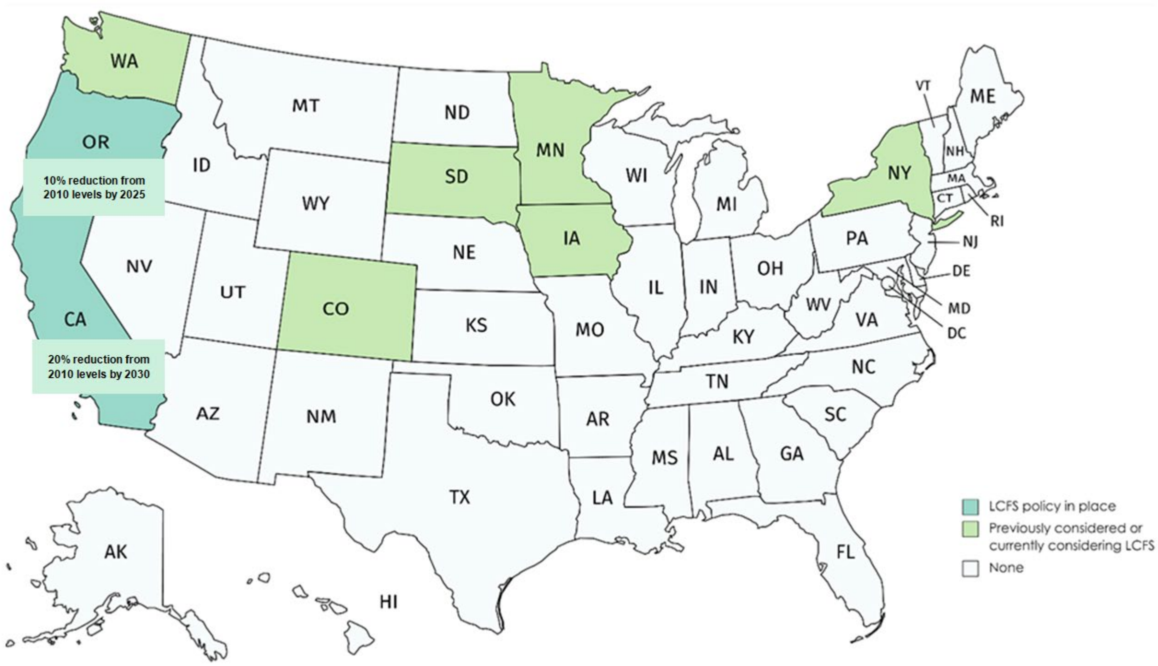

Figure 1. States which have implemented or considered LCFS policies. Oregon fully implemented its Clean Fuels Program in 2016. The Pacific Coast Collaborative, a regional agreement between California, Oregon, Washington, and British Columbia to align GHG reduction policies and promote clean energy, has aligned to explicitly address LCFS programs. Minnesota, Iowa, and South Dakota are believed to be considering participation in a low carbon fuel program tailored for Midwestern state needs specifically. Colorado considered a Clean Fuels Standard. New York's bill for LCFS failed to make it out of committee during the 2020 legislative session.

Econometric modeling

This study focused on modeling the impact of the LCFS on CO_2 emissions for the transportation sector. Population, affluence (GDP), and technology have been widely used in literature to understand CO_2 emission trends (Axsen et al. 2020, Lim and Won 2019). Carbon dioxide emission in the U.S. can be explained by the STIRPAT model (STochastic Impacts by Regression on Population, Affluence and Technology), which is an extension of the IPAT model (the Impact on the environment depends on Population, Affluence, and Technology, or Impact = Population × Affluence × Technology). The IPAT model can be used to analyze the effect of economic activity on the environment. The STIRPAT model allows for the addition of statistical assumptions and the testing of a hypothesis. Previous studies have also employed the synthetic control method and the Lasso "post-double-selection" method. The Synthetic Control Method has been utilized in environmental economics as it offers a framework to control unobservable time-variant confounders. The Lasso method allows for validation of the choice of control variables and can account for potential endogeneity in the policy treatment, specifically when there are concerns regarding lags for control variables and their interactions with trends (Huseynov and Palma 2018).

In this study, I chose to approach the question of LCFS effectiveness through a difference-in-differences (DID) econometric model and added different relevant variables used in other models such as vehicle miles traveled (VMT), representing travel demand, falling under CEQA guidelines for conducting transportation analyses. First, I assessed the average CO_2 emissions for the transportation sector (in Million Metric tons, MMT) for California and Oregon and the average for all other states to test the validity of the parallel trends assumption in the pre-intervention period for DID estimation (Figure 2). In Oregon's case, the period 2009-2016 could be considered an "anticipatory" period and was deliberately included in the analysis due to 1) Oregon's proximity to California which approved its LCFS regulation in 2009, and 2) Oregon's 2009 bill authorizing the Oregon Environmental Quality Commission to adopt rules to reduce the average carbon intensity of Oregon's transportation fuels by 10% over a 10-year period before full implementation of the program in 2016. I scaled down California's observations ten times for comparison purposes, which did not change the trend. Because states with LCFS and states without LCFS had almost identical trends during the pre-intervention period, the parallel trends assumption was satisfied for DID, so this model was appropriate for the study.

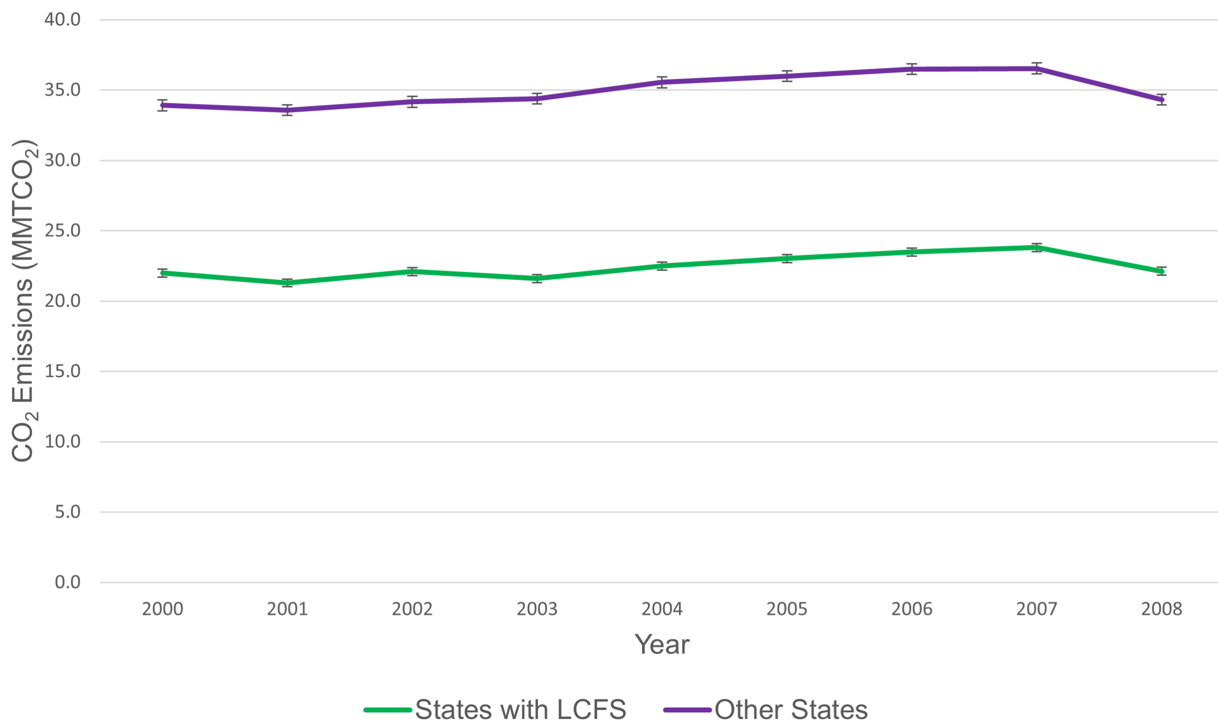

Figure 2. CO_2 emissions ($MMTCO_2$) for transportation sector during pre-intervention period. California's observations were scaled down ten times for comparison purposes, which did not change the trend. Because states with LCFS and states without LCFS had almost identical trends during the pre-intervention period, the parallel trends assumption was satisfied for DID, so this model was appropriate for the study.

Then, I assessed the average CO_2 emissions for the transportation sector (in Million Metric tons, MMT) for California and the average for nine other states to test the validity of the parallel trends assumption in the pre-intervention period for DID estimation. These states were chosen because of Carbon Monitor 2019 emission estimation data availability, which was based on alphabetical order and not based on considerations that could be tied to the LCFS. I excluded Oregon to assess the impact of California's LCFS. I again scaled down California's observations ten times for comparison purposes, which did not change the trend. Because California and other states had almost identical trends during the pre-intervention period, the parallel trends assumption was satisfied for DID, so this model was also appropriate (Figure 3).

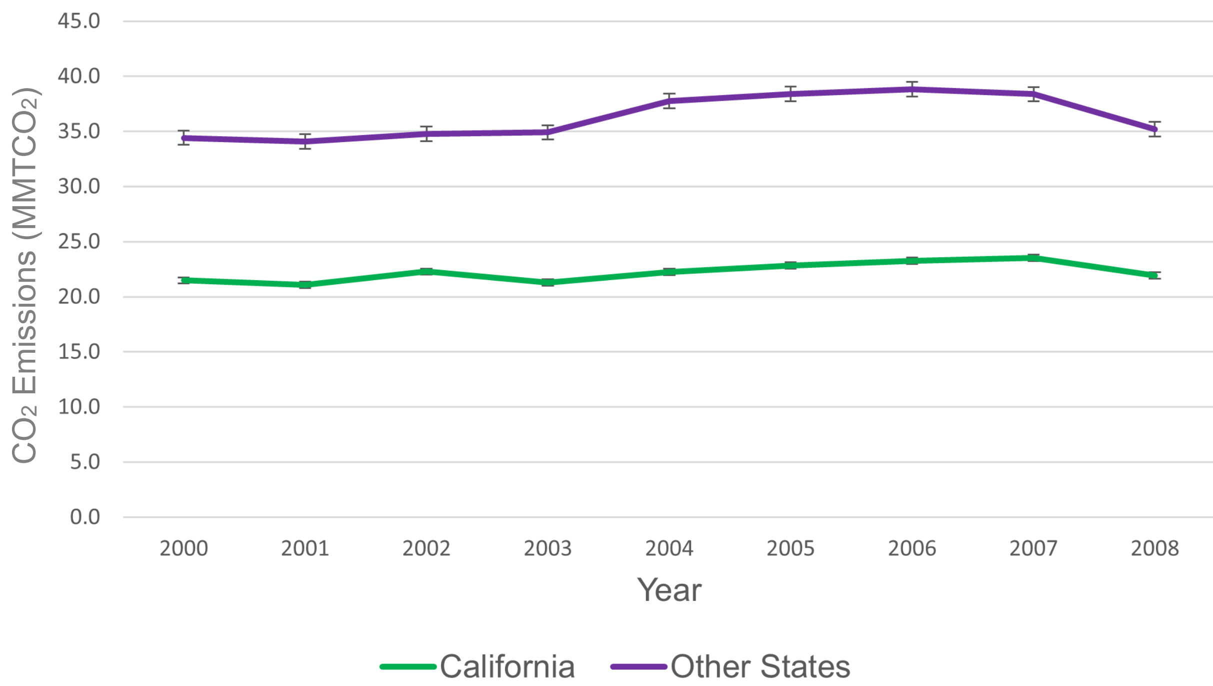

Figure 3. CO_2 emissions ($MMTCO_2$) for transportation sector during pre-intervention period for model assessing California policy only. California's observations were scaled down ten times for comparison purposes, which did not change the trend. Because California and other states had almost identical trends during the pre-intervention period, the parallel trends assumption was satisfied for DID, so this model was appropriate for the study.

Road transportation real-time emission estimation

Estimating state-level real-time daily CO_2 emissions for the road transportation sector can allow for better analyses of road transportation policy effectiveness in recent years, since most publicly available online data covers overall transportation emissions with a lag of approximately 1-2 years in publishing. Carbon Monitor (2020) estimated national-level real-time daily CO_2 emissions for the ground transportation sector. The methods used in this study were adapted from Carbon Monitor's national-level approach to be state-level and specific to the road transportation sector. Annual results prior to 2019 could be validated by comparing study estimates to publicly available data. Carbon Monitor's uncertainty analysis of the data (1-sigma uncertainties) was based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The percentage 1-sigma uncertainty that Carbon Monitor used for ground transportation was ±9.3% (Liu et al. 2020).

METHODS

Study sites

I obtained data for 27 U.S. states with mid-term or long-term emission reduction targets. Historical GHG emission data spanned the period 1990-2017. Mid-term targets included the period 2020-2030 and long-term targets included years after 2030. I collected panel data for 50 U.S. states with and without the LCFS policy for the period 2000-2018.

Data collection

I collected policy and target information including dates enacted for 27 states with emission reduction targets and for LCFS policies for the period 2000-2017 from the U.S. Climate Alliance (USCA), online publicly available information from state agencies, the Center for Climate and Energy Solutions (C2ES), and the Database of State Incentives for Renewables & Efficiency (DSIRE). I also collected data on transportation sector CO_2 emissions, end of year population, GDP percent change, and vehicle miles traveled (VMT) for 50 states in the period 2000-2017. I collected state-level publicly available online transportation CO_2 emissions data (MMT) and historical GHG emissions data for 1990-2017 from the U.S. EIA, population data from the World Population Review, gasoline tax data from the U.S. Department of Transportation Federal Highway Administration, VMT data from the Eno Center for Transportation, and GDP growth data from the U.S. Bureau of Economic Analysis (BEA). State-level monthly energy consumption data, the prime supplier sales volumes of motor gasoline and diesel, were obtained from the U.S. EIA Petroleum & Other Liquids. State-level daily indicators, the distance traveled, were obtained from Trips by Distance data from Bureau of Transportation Statistics. This included the number of trips made involving a stay of longer than 10 minutes at a location away from home.

State target analysis

To assess state-level ambition to reduce emissions, I compared state GHG emission reduction targets. I grouped cities by target years and converted emission reduction targets to the

2005 baseline to compare target ambition across states. I categorized state targets by timeframe and type to highlight levels of commitment. Mid-term and long-term emission reduction targets alongside historical emission data provided a visualization of state target ambition timelines. The analysis in this study relied on unadjusted values rather than considering the adjustment factor, which the EIA introduced to match U.S. national total emissions by distributing to states in proportion to each state's share of the total emissions. Since some state-level carbon neutrality targets are defined in terms of total GHG emissions rather than CO_2 emissions, and as the focus of this research did not involve providing a single definition of carbon neutrality, all state-level carbon neutrality, net-zero, and GHG neutrality target values were considered as 100% GHG emission reduction goals. State net-zero targets that include offsetting were graphed without the offsetting portion. Due to the uncertainty in the accounting of LULUCF emissions, I excluded this sector from emissions levels. Carbon neutrality and GHG neutrality targets take into account projections and scenarios for LULUCF emissions, mostly CO_2, meaning that there exists a level of uncertainty surrounding the precise level of mid-century emissions under a carbon or GHG neutrality target expressed excluding LULUCF.

Econometric analysis

To examine the impact of the LCFS on CO_2 emissions from the transportation sector, the dependent variable, I used a DID model and panel data for U.S. states for the period of 2000–2017 clustered at the state level (Eq. 1).

Eq. 1 $$C_{it} = \beta_1 + \beta_2 LCFS_i + \beta_3 post_t + \beta_4 (LCFS \times post)_{it} + \beta_5 X_{it} + \delta_{it}$$

In this regression, C_{it} is the dependent component, or million metric tons (MMT) of CO_2 emitted from the transportation sector; β_1 is the intercept; $LCFS_i$ is a policy indicator for the existence of the LCFS for state i with the β_2 coefficient; $post_t$ indicates post-treatment period with the β_3 coefficient; X_{it} is a vector of control variables; δ_{it} represents state-time random effects; and β_4 is the coefficient of interest for the interaction term. The timeframe for this study included the period 2000-2017 because of data availability for vehicle miles travelled (VMT) and gasoline tax. California and Oregon are the only states which experience the LCFS policy or announcement in 2009. In both models, I controlled for VMT per capita; gasoline tax in cents per gallon*;* GDP growth, or percent change; and population. I analyzed states with the policy and states without the policy using Stata 16 (StataCorp 2019). In my models, I included three specifications. The first specification included only the policy variable as the independent variable to pick up the impact of state policy in the absence of the business-as-usual trajectory created by control variables, which are key to removing confounding factors. The second specification included all variables. The third specification excluded the states that intended to adopt similar laws: Colorado, Iowa, Minnesota, New York, South Dakota, and Washington, assuming that observations for each remaining state were independent. By excluding these states, any anticipatory effects prior to policy enactment were avoided (Huseynov and Palma 2018). I clustered observations by state, expecting observations to be correlated in the same cluster and independent across clusters. The first model considered the impacts of California's LCFS and Oregon's standard, using panel data for 50 states. I included Oregon's 2009-2016 anticipatory period in the analysis for the first model. The second model considered the impacts of only California's LCFS, using panel data for 10 states. I used a subset of states because they had 2019 estimated CO_2 data and my main objective was to later use this second model to show how estimated data could aid policy effectiveness assessments.

Emission estimation

To further evaluate the effectiveness of the LCFS in reducing state-level CO_2 emissions for the transportation sector, I estimated state-level real-time daily CO_2 emissions for California's road transportation sector. Daily emissions estimates can be produced for this sector based on regularly updated activity data, made possible by the availability of recent transport activity data. I disaggregated the annual total state-level CO_2 emissions for the transportation sector in 2018, obtained from U.S. EIA and based on the EIA's comprehensive state-level annual estimates of energy consumption by sector and source, into the monthly data for the sector based on state-level monthly activity data (Eq. 2).

Eq. 2
$$Emis_{monthly,2018} = Emis_{yearly,2018} \cdot \frac{AD_{monthly,2018}}{AD_{yearly,2018}}$$

I estimated state-level road transportation CO_2 monthly emissions (*Emis*) in 2019 based on the change of monthly energy consumption data (activity data, *AD*) in 2019 compared to the same period in 2018, assuming that the corresponding emission factors (*EF*) remained unchanged (Eq.

3). Carbon Monitor (2020) assumed that the daily variation of emissions was driven by activity data and the contribution from emission factors was negligible since they evolve at longer timescales due to policy implementation and technology shifts. State-level monthly energy consumption data was comprised of the prime supplier sales volumes of motor gasoline in thousand gallons per day.

Eq. 3
$$Emis = \sum\sum\sum AD_{i,k} \cdot EF_{i,k}$$

Here, *i* refers to region and *k* refers to fuel type. *EF* is comprised of the net heating values (*v*) for each fuel type in terms of energy obtained per unit of fuel; the carbon content (*c*) per energy output in units of t C/TJ; and the oxidation rate (*o*), or the percent fraction of fuel oxidized during combustion (Eq. 4).

Eq. 4
$$Emis = \sum\sum\sum AD_{i,k} \cdot (v_{i,k} \cdot c_{i,k} \cdot o_{i,k})$$

I added monthly emissions for 2019 and allocated yearly emissions for the sector to each day using state-level daily indicators, comprised of Trips by Distance traveled data, assuming that emission factors remained unchanged in 2019 (Eq. 5).

Eq. 5
$$Emis_{daily,2019} = Emis_{yearly,2019} \cdot \frac{AD_{daily,2019}}{AD_{yearly,2019}}$$

To validate results, I compared the estimated 2018 annual emissions to EIA 2018 emissions data.

To demonstrate the viability of using state-level near-real-time daily CO_2 emission data in assessing the effectiveness of the LCFS for the period 2000-2019, I applied the California 2019 road transportation sector data estimated in this study to Equation 1. I used 2018 EIA data for emissions from the transportation sector and excluded the year 2020 due to changes in the road transportation sector during COVID-19. This exclusion also makes sense since California's original LCFS goal in 2009 used 2020 as the target year. Due to data availability issues, I used 2017 data for gasoline tax and VMT in the 2018-2019 period and used Carbon Monitor estimated data for nine other states. I considered the (1) CA Policy Only; (2) All Ten States Included; and (3) Colorado Excluded specifications, mirroring the earlier methods in the first model, to assess the impact of California's LCFS on CO_2 emissions for an extended and more recent post-intervention timeframe. This model excluded Oregon and focused on the impact of California's LCFS.

RESULTS

Data summary

There were 900 observations in the dataset for the first econometric model and 200 observations for the second. California's population steadily increased over the observed timeframe. Transportation emissions declined over the period 2007-2013, followed by annual increases through 2017. Diesel fuel blend sales decreased by 50 million gallons; sale and blending of biodiesel and renewable diesel increased by more than 60 million gallons; and emissions from gasoline used in on-road passenger cars, trucks, and SUVs were the main driver of the increases between 2013 and 2017, making up 74% of transportation emissions. Biodiesel and renewable diesel percentages in the total diesel blend increased from 0.5% to 18.5% over the period 2011-2018 in large part because of the LCFS. For the period 2000-2018, the carbon intensity of California's economy decreased by 43% and the state's GDP increased by 59% (CARB 2018). California managed to push its per capita VMT averages below the national average for the period 2001-2017; while the state's per capita VMT generally decreased over this time period, it increased between 2012 and 2016. State-level monthly energy consumption data- the prime supplier sales volumes of motor gasoline- decreased in 2020 during the COVID-19 period (EIA 2021).

State target analysis

I found that California's targets were generally more ambitious than other state-level targets. For both mid-term (2020-2030) and long-term (post 2030) targets, I documented a greater amount of legislation than executive orders, announced plans, or recommended goals (Appendix Table 1). Binding commitments were generally greater in the West Coast and Northeast regions, with some legislation and executive orders in the Midwest and Southwest regions (Figures 4 and 5).

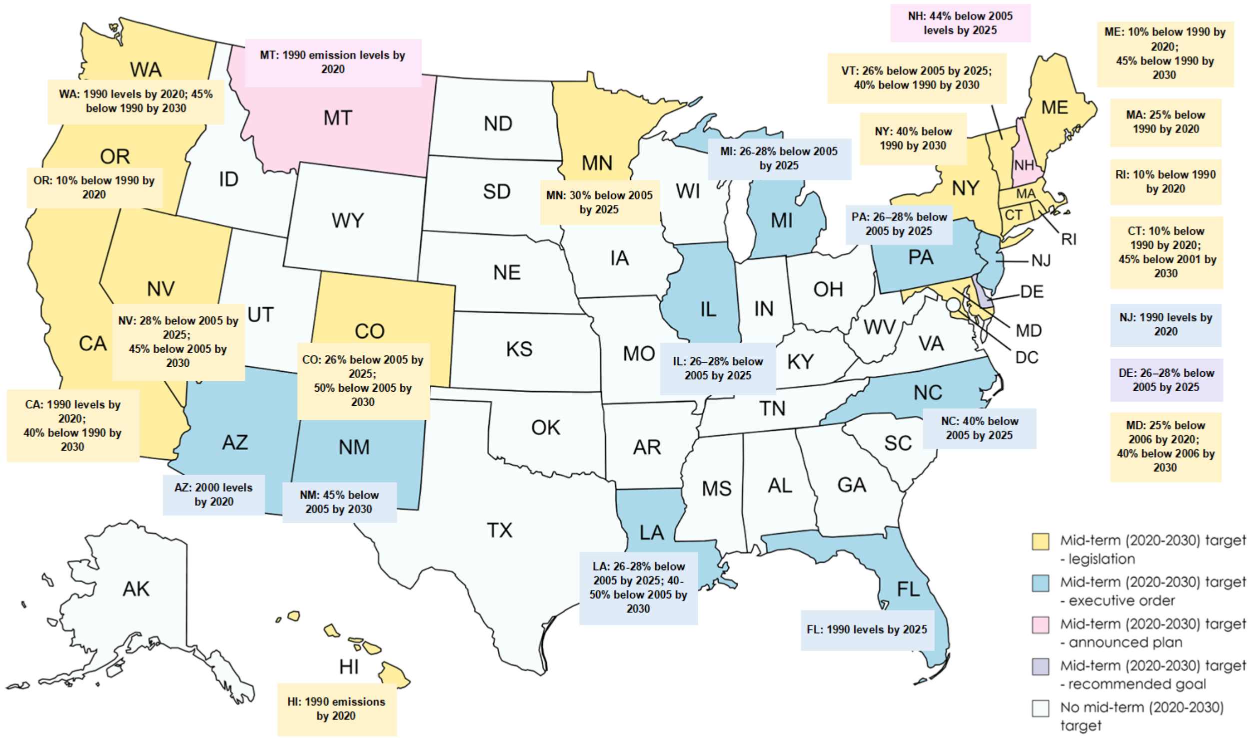

Figure 4. States with mid-term (2020-2030) GHG reduction targets. There is a greater amount of legislation than executive orders, announced plans, or recommended goals. There is greater action in the West Coast and Northeast regions, with some legislation and executive orders in the Midwest and Southwest regions.

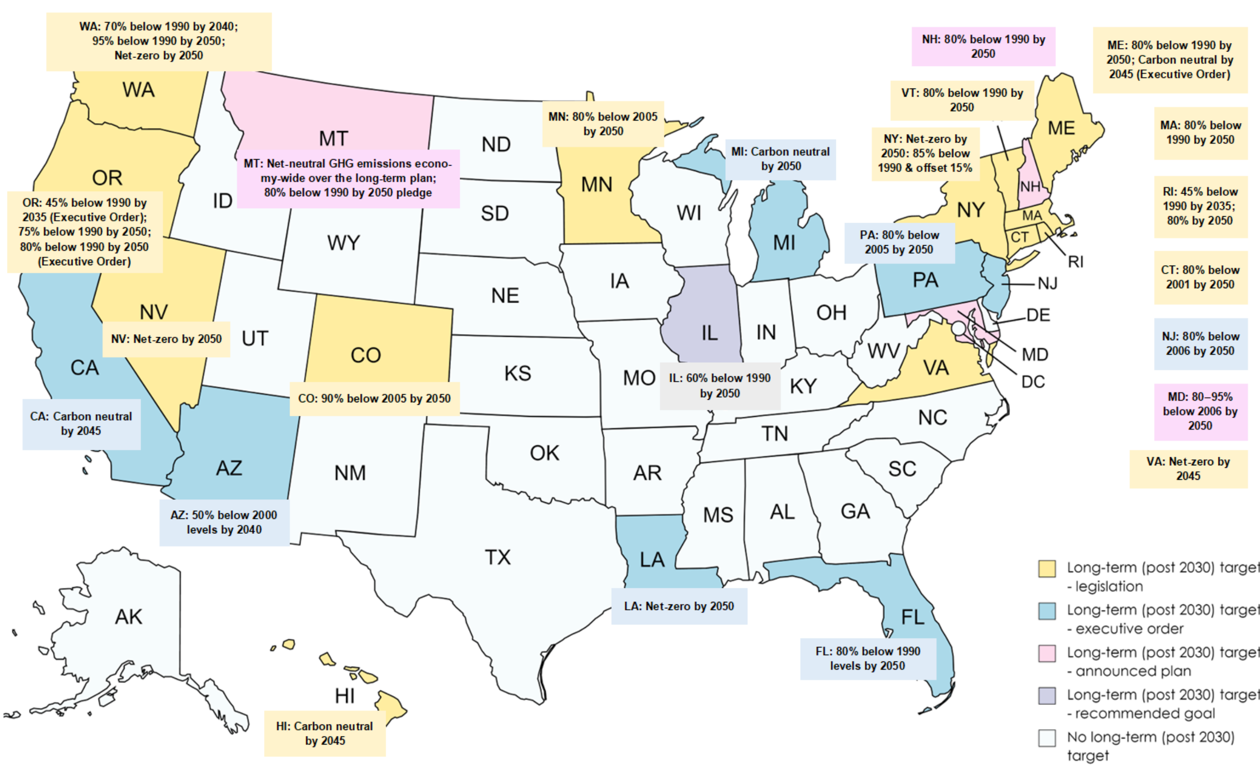

Figure 5. States with long-term (post 2030) GHG reduction targets. There is a greater amount of legislation than executive orders, announced plans, or recommended goals. There is greater action in the West Coast and Northeast regions, with some legislation and executive orders in the Midwest and Southwest regions.

California's 2030 target was middling compared to other 2030 targets, but California's carbon neutrality by 2045 goal was more ambitious than many other long-term goals (California SB 32 2016) (Figure 6).

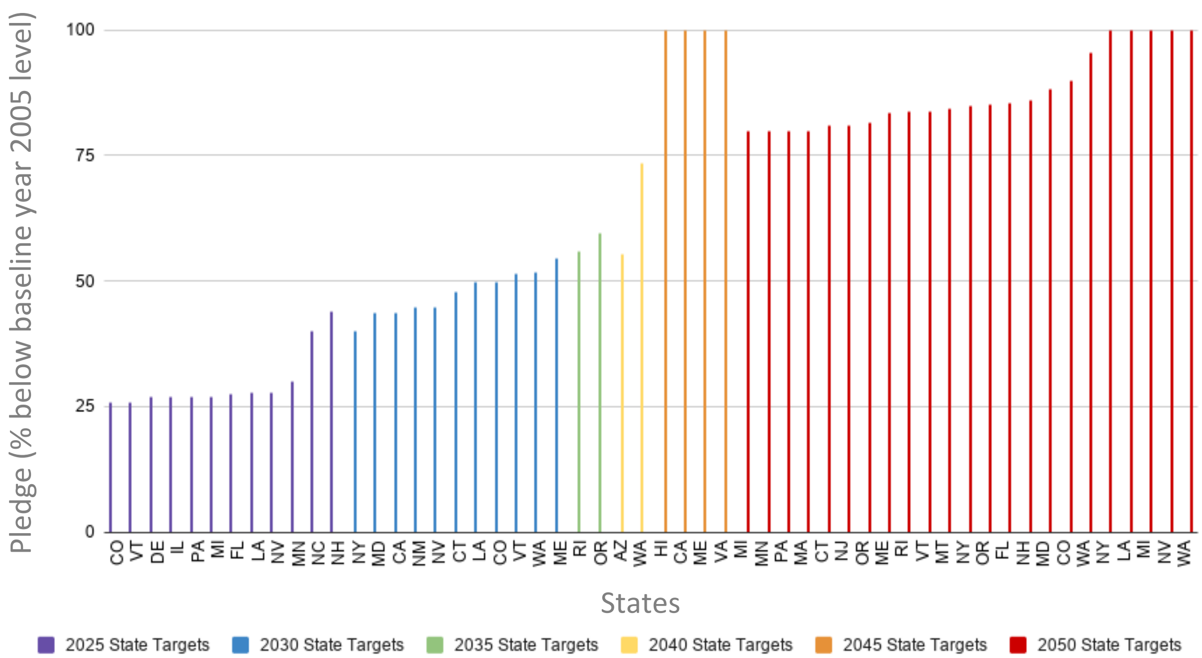

Figure 6. Pledges (% below 2005 levels) for state GHG reduction targets. The baseline year used for comparison is 2005. California's 2030 target is middling compared to other 2030 targets, but California's carbon neutrality by 2045 goal is more ambitious than many other long-term goals.

New Hampshire and North Carolina took the lead in target ambition for 2025 pledges, though North Carolina's target was an executive order- a stronger commitment than New Hampshire's announced plan (EO 80 2018). Maine and Oregon took the lead in target ambition for 2030 and 2035 pledges, respectively, though Oregon's 45% below 1990 levels by 2035 target was an executive order while Rhode Island passed 45% below 1990 levels by 2035 legislation (Maine Legislature §576-A 2019, Oregon EO 20-04 2020, Resilient Rhode Island Act 2014). California, Hawaii, Maine, and Virginia had targets to achieve carbon neutrality or net-zero GHG emissions by 2045 (Figure 7). Louisiana, Michigan, Nevada, New York, and Washington state had targets to achieve carbon neutrality or net-zero GHG emissions by 2050 (Act 15 2018, California Executive Order B-55-18 2018, Executive Directive 2020-10 2020, Executive Order 2020-182 2020, Louisiana Executive Order JBE 2020-18 2020, Maine Executive Order 9-23-2019, Office of Governor Gretchen Whitmer, Nevada Senate Bill 254 2019, New York Senate Bill S6599 2019, Virginia Chapter 1191 2020, Washington Chapter 79 2020). New York's net-zero by 2050 legislation included reducing emissions 85% below 1990 levels and offsetting 15%. For other long-term pledges, targets were comparable, with Colorado and Washington state taking the lead (Colorado House Bill 19-1261 2019, Washington Chapter 79 2020).

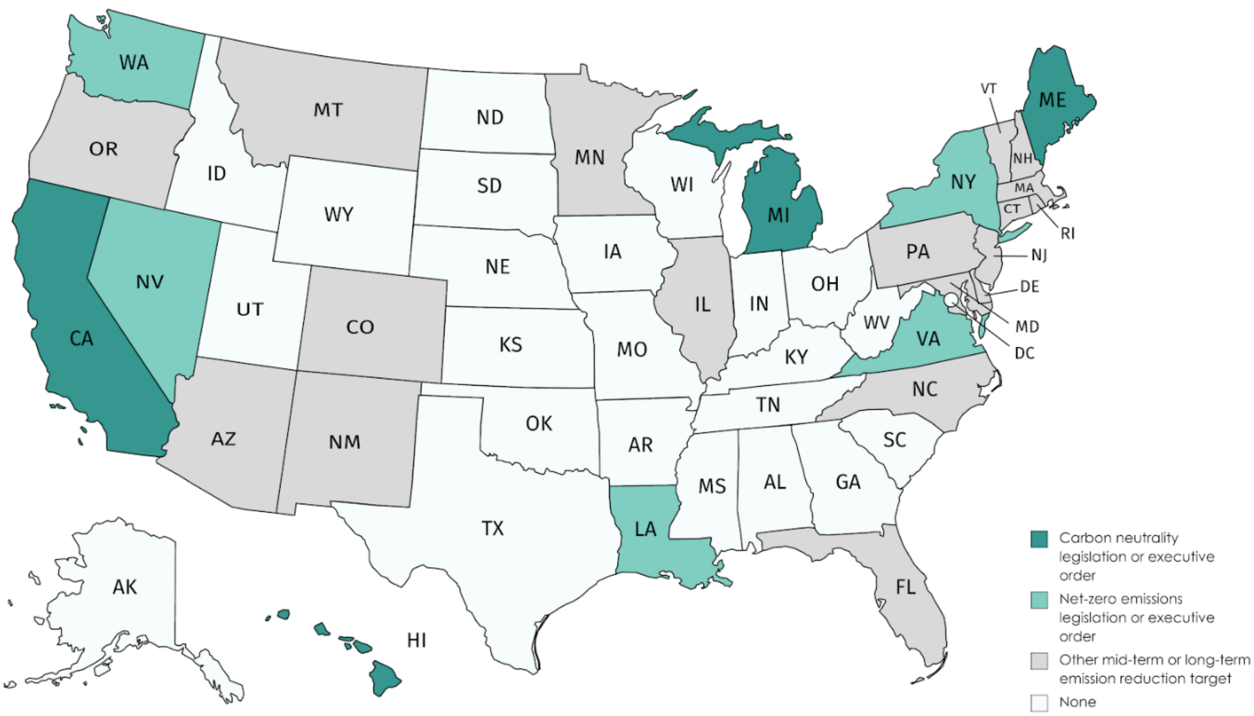

Figure 7. States with carbon neutral or net-zero GHG emissions targets. California, Hawaii, Maine, and Virginia have targets to achieve carbon neutrality or net-zero GHG emissions by 2045. Louisiana, Michigan, Nevada, New York, and Washington state have targets to achieve carbon neutrality or net-zero GHG emissions by 2050. New York has net-zero by 2050 legislation for reducing emissions 85% below 1990 levels and offsetting 15%.

I compared state-level projected GHG emissions to reach 2025-2050 emission reduction targets and found that California's carbon neutrality by 2045 goal was more ambitious than many other long-term goals (Figure 8).

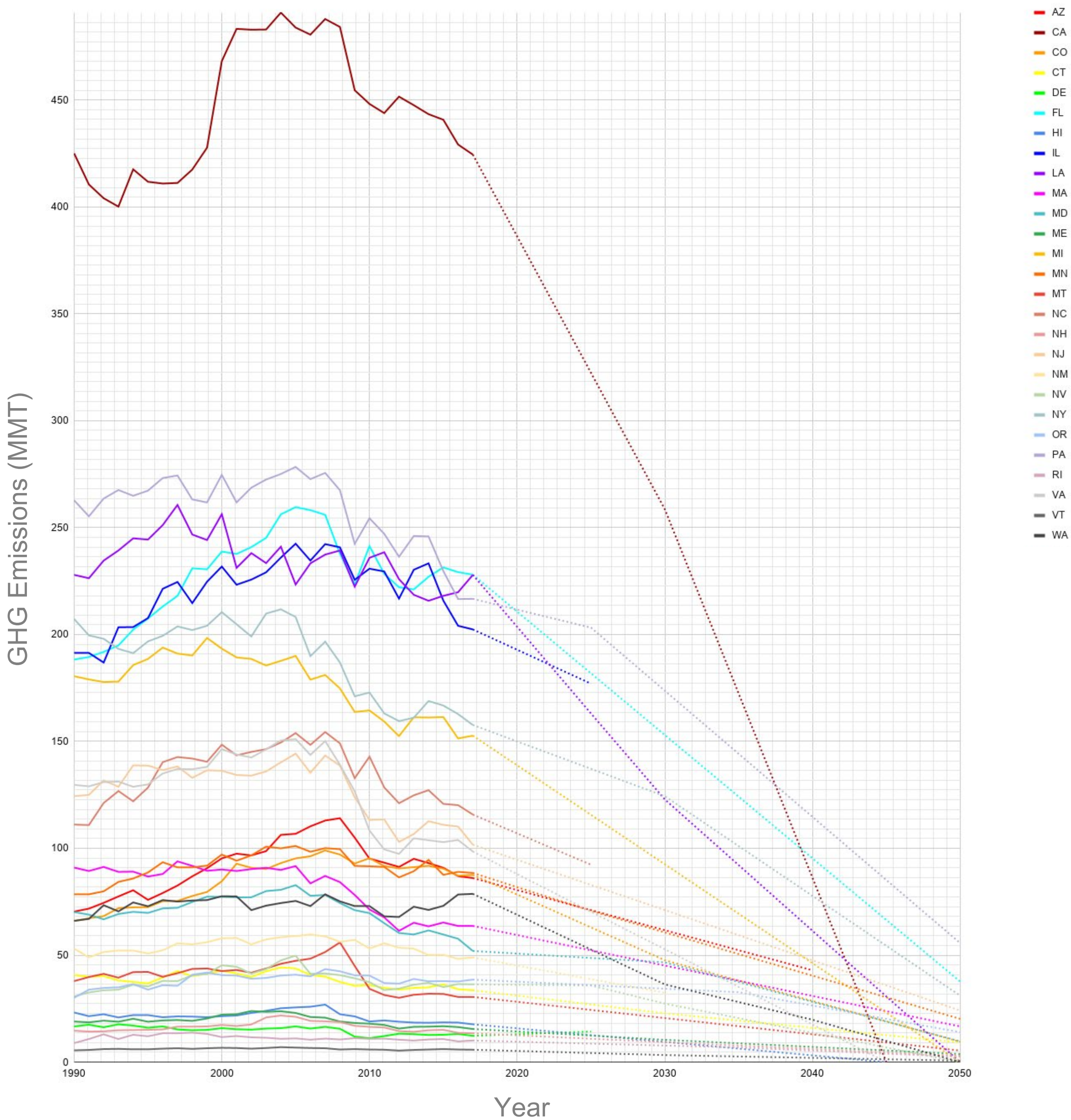

Figure 8. State-level historical emissions and projected GHG emissions to reach 2025-2035 targets. Solid lines represent historical emissions for the period 1990-2017 and dotted lines represent projected GHG emissions to reach 2025-2050 targets. For states with both legislative and executive order targets for a target year, the legislative target is graphed. For states with more than one legislative target for a target year, the more ambitious target is graphed. Since in some cases, state legislation has set carbon neutrality targets in terms of total GHG emissions rather than CO_2 emissions, this study considers all state-level carbon neutrality, net-zero, and GHG neutrality target values as 100% GHG emission reduction goals. New York's net-zero target includes offsetting and is graphed here without the offsetting portion.

Econometric analysis

When estimating the effect of California's LCFS on transportation CO_2 emissions for the period 2000-2017 using panel data for 50 states, the results predicted that the adoption of the LCFS decreased state CO_2 transportation emissions by approximately 22.9 MMT with a standard error of 2.32. The magnitude of the reduction represented around 10.5% of transportation CO_2 emissions from California in 2017. As these results only slightly exceeded the previous literature results of a 21.2 MMT reduction, I determined my model and variables to be appropriate for further analyses (Appendix Table 2).

Using the first DID model, I found that the policy treatment variable had a negative relationship to emissions for all three specifications (Table 3). The summary statistics and state dummy variables can be found in Tables 4 and 5 in the Appendix.

Table 3. Results from DID analysis for first model. To examine the impact of the LCFS in California and Oregon on CO_2 emissions from the transportation sector, I used panel data for 50 U.S. states for the period of 2000–2017, clustered at the state level, and controlled for VMT per capita; gasoline tax in cents per gallon; GDP growth; and population. I included Oregon's 2009-2016 anticipatory period in the analysis for the first model. The policy treatment variable had a negative relationship to emissions for all three specifications. Robust standard errors are in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Variables	(1) Policy Only C	(2) All States Included C	(3) Six States Excluded C
LCFS×post	-7.816	-0.606***	-0.613***
	(5.172)	(0.214)	(0.224)
LCFS	87.16	-0.341	-0.324
	(71.23)	(0.347)	(0.310)
post	-1.203**	0.297**	0.336*
	(0.489)	(0.150)	(0.172)
C_{t-1}		1.005***	1.007***
		(0.0129)	(0.0158)
POP		1.72e-08	2.16e-09
		(5.91e-08)	(8.10e-08)
GDP		0.210***	0.217***
		(0.0545)	(0.0605)
TAX		-0.00390	-0.00322
		(0.00864)	(0.0108)
VMT		2.20e-05	1.92e-05
		(1.89e-05)	(1.88e-05)
Constant	34.79***	-0.828***	-0.835**
	(4.731)	(0.296)	(0.342)
Observations	900	900	792
Number of S	50	50	44

The specification in Column 2 of Table 3, which included controls and all states, predicted that the adoption of the LCFS decreased state CO_2 transportation emissions by approximately 0.61 MMT with a standard error of 0.21. A one sample standard deviation increase led to an increase of 0.21 standard deviations in emissions, ceteris paribus. The magnitude of the reduction represented around 0.03% of transportation CO_2 emissions from the U.S. and around 0.26% of transportation CO_2 emissions from states with LCFS in 2017. In specifications 2 and 3, GDP growth had a positive relationship to emissions ($p<0.01$); population and VMT had positive relationships to emissions; and gasoline tax had a negative relationship to emissions. The coefficient for *LCFSXpost* had a negative relationship to emissions ($p<0.01$). After excluding states which considered adopting similar policies from the regression, the coefficient for *LCFSXpost* in Column 3 was similar to the coefficient for *LCFSXpost* in Column 2. The first specification, which did not include controls, produced a different result. Focusing on the two specifications with controls, I concluded that the result was robust since the coefficients both had a negative relationship to emissions ($p<0.01$).

Using the second DID model, I found that the policy treatment variable had a negative relationship to emissions ($p<0.01$) for all three specifications (Table 6). The summary statistics and state dummy variables can be found in Tables 7 and 8 in the Appendix. The specification in Column 2 of Table 6, which included controls and all ten states, predicted that California's adoption of the LCFS decreased state CO_2 transportation emissions by approximately 15.1 MMT with a standard error of 2.82. The magnitude of the reduction represented around 6.95% of transportation CO_2 emissions from California in 2017. In specifications 2 and 3, GDP growth had a positive relationship to emissions ($p<0.05$); population had a positive relationship to emissions ($p<0.01$); VMT had a positive relationship to emissions ($p<0.01$); and gasoline tax had a negative relationship to emissions ($p<0.01$). The coefficient for *LCFSXpost* had a negative relationship to emissions ($p<0.01$) for all three specifications. After excluding Colorado, which considered adopting a similar policy, the coefficient for *LCFSXpost* in Column 3 was close to the coefficient for *LCFSXpost* in Column 2. Focusing on the two specifications with controls, I concluded that the result was robust since the coefficients both had a negative relationship to emissions ($p<0.01$).

Table 6. Results from DID analysis for second model. The second model considered the impacts of only California's LCFS, using panel data for 10 states. I used a subset of states because they had 2019 estimated CO_2 data and my objective was to later use this second model to show how estimated data could aid policy effectiveness assessments. The policy treatment variable had a negative relationship to emissions ($p<0.01$) for all three specifications. Robust standard errors are in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Variables	(1) CA Policy Only C	(2) All Ten States Included C	(3) Colorado Excluded C
LCFS×post	-13.96***	-15.10***	-14.75***
	(0.609)	(2.824)	(2.839)
LCFS	185.2***	39.24***	37.88***
	(10.31)	(3.608)	(3.524)
post	-2.257***	-4.256***	-4.466***
	(0.609)	(0.973)	(1.119)
POP		4.93e-06***	4.97e-06***
		(1.38e-07)	(1.37e-07)
GDP		0.267**	0.283**
		(0.127)	(0.134)
TAX		-0.565***	-0.581***
		(0.119)	(0.118)
VMT		0.00181***	0.00176***
		(0.000570)	(0.000588)
Constant	36.10***	-0.429	0.174
	(10.31)	(6.995)	(7.496)
Observations	180	180	162
Number of S	10	10	9

Emission estimation

After estimating real-time daily CO_2 emissions for California's road transportation sector for 2019 and comparing 2018 annual estimated data to 2018 EIA data, I found that my 2018 annual emission estimate was 11.41 $MMTCO_2$ lower than the 2018 EIA annual data value (Appendix Table 9). The EIA data was specific to the transportation sector and did not focus solely on the road transportation subset like the estimated data did. The daily CO_2 emission estimates for 2019 show generally higher emissions for the period from July to October (Figure 9).

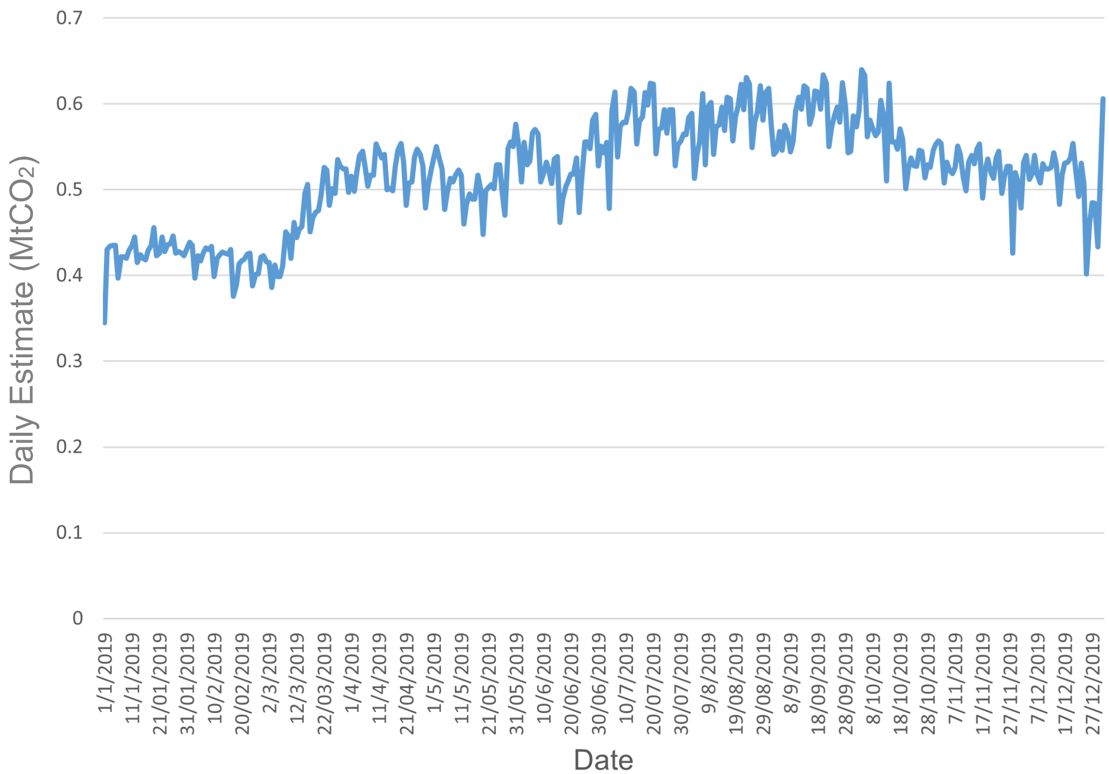

Figure 9. Near-real-time daily 2019 CO_2 emissions ($MtCO_2$) for California's road transportation sector. The daily CO_2 emission estimates for 2019 show generally higher emissions for the period from July to October.

By applying the 2019 estimated data to the second DID model, I demonstrated the viability of using state-level near-real-time daily CO_2 emission data in policy effectiveness assessments. I found that the policy treatment variable had a negative relationship to emissions ($p<0.01$) for all three specifications (Table 10). The summary statistics can be found in Table 11 in the Appendix. The specification in Column 2 of Table 10, which included controls and all ten states, predicted that California's adoption of the LCFS decreased state CO_2 transportation emissions by approximately 14.3 MMT with a standard error of 2.67. The magnitude of the reduction represented around 6.58% of transportation CO_2 emissions from California in 2017. In specifications 2 and 3, GDP growth had a positive relationship to emissions ($p<0.05$); population had a positive relationship to emissions ($p<0.01$); VMT had a positive relationship to emissions ($p<0.01$); and gasoline tax had a negative relationship to emissions ($p<0.01$). The coefficient for *LCFSXpost* had a negative relationship to emissions ($p<0.01$) for all three specifications. After excluding Colorado, which considered adopting a similar policy, the coefficient for *LCFSXpost* in Column 3 was close to the coefficient for *LCFSXpost* in Column 2.

Table 10. Results from DID analysis for second model using estimated 2019 emissions. To demonstrate the viability of using state-level near-real-time daily CO_2 emission data in assessing the effectiveness of the LCFS for the period 2000-2019, I applied the California 2019 road transportation sector data estimated in this study to Equation 1. I used 2018 EIA data for emissions from the transportation sector and excluded the year 2020 due to changes in the road transportation sector during COVID-19; used 2017 data for gasoline tax and VMT in the 2018-2019 period; and used Carbon Monitor estimated data for nine other states. The policy treatment variable had a negative relationship to emissions ($p<0.01$) for all three specifications. Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Variables	(1) CA Policy Only C	(2) All Ten States Included C	(3) Colorado Excluded C
LCFS×post	-14.19***	-14.32***	-13.88***
	(0.689)	(2.672)	(2.693)
LCFS	185.2***	41.04***	38.13***
	(10.30)	(2.910)	(2.732)
post	-2.403***	-4.691***	-4.878***
	(0.689)	(1.049)	(1.234)
POP		4.87e-06***	4.96e-06***
		(1.07e-07)	(1.01e-07)
GDP		0.252**	0.273**
		(0.121)	(0.128)
TAX		-0.618***	-0.650***
		(0.0981)	(0.0969)
VMT		0.00170***	0.00159***
		(0.000479)	(0.000454)
Constant	36.10***	2.082	3.249
	(10.30)	(5.673)	(5.862)
Observations	200	200	180
Number of S	10	10	9

Focusing on the two specifications with controls, I concluded that the result was robust since the coefficients both had a negative relationship to emissions ($p<0.01$). This iteration of the second model made variable assumptions about gasoline tax, VMT, and other data that were not present earlier in the study due to data availability issues, so while this exercise shows the viability of using 2019 estimated emissions data in policy analyses, limitations for other variables and the smaller sample size could affect the outcome of this analysis.

DISCUSSION

To achieve mid-term and long-term climate goals, subnational jurisdictions will need to overcome a range of policy and technology gaps using new economic and energy policy tools and approaches. California has pioneered new climate policies, such as the LCFS, which can serve as a reference point for the implementation of other state and federal policies (Mazmanian et al. 2020). These efforts must be matched with scientific approaches to assess mitigation strategies, document progress, and highlight implications for improvement (Hsu et al. 2019). Assessing the ambition and stringency of state targets as well as the effectiveness of policies can provide useful insights for other states considering similar strategies. It is essential to understand LCFS policy effectiveness because the main reason for the policy's legal support was a high expectation of CO_2 emission reduction. LCFS-type policies have not been widely researched using econometric methods since they are still relatively new (Huseynov and Palma 2018). Furthermore, previous LCFS policy research has not applied real-time CO_2 emission estimates to assess effectiveness over a more recent timeframe. I addressed these research gaps to inform the discussion surrounding climate targets and policy to reach Paris Agreement and carbon neutrality goals. By analyzing the ambition and stringency of state-level climate targets, assessing the effectiveness of one of California's most significant road transportation policies, and utilizing real-time emission estimates in analysis, I aimed to highlight existing potential gaps to achieve climate goals. Drawing on California's framework, U.S. states can increase emission reduction target stringency and ambition by passing legislation or executive orders to achieve mid-century carbon neutrality. The significant impact that the LCFS has had in reducing CO_2 emissions in the transportation sector underlines the effectiveness of this policy, which can serve as a reference point for future implementation by other states. Using the 2019 estimated data for real-time daily CO_2 emissions for the road transportation sector in an econometric model supported my argument for LCFS effectiveness and illustrated the usefulness of exploring different methods of emission estimation in transportation policy analyses. Daily near-real-time emissions data could aid future scientific research in this critical sector (Liu et al. 2020).

State target analysis

The comparison of state-level mid-term and long-term emission reduction targets suggests that states can increase stringency by adopting more legislation over executive orders, announced plans, or recommended targets. That there is a greater amount of legislation than executive orders, announced plans, and recommended goals for both mid-term (2020-2030) and long-term (post 2030) state targets shows that state-level targets are generally binding. It is notable that commitment levels are generally higher in the West Coast and Northeast regions, with some legislation and executive orders in the Southwest and Midwest regions. These regions may have greater commitments because they contain more states in the U.S. Climate Alliance, which requires commitments from member states to implement policies that advance the goals of the Paris Agreement by reducing GHG emissions by at least 26-28% below 2005 levels by 2025 (USCA 2020). Most states with mid-term targets also have long-term targets, suggesting that the general climate framework includes interim targets along with longer-term goals. There are fewer state targets for the period 2030-2045, which falls into the long-term category for this study, showing a potential opportunity to set more interim benchmarks and long-term targets to increase accountability. Washington, for example, has set targets for 2020, 2030, 2040, and 2050, as well as a net-zero mid-century target (Washington Chapter 79 2020). California's targets are similarly spread out, spanning 2020, 2030, and carbon neutrality by 2045 (California Executive Order B-55-18). Washington's targets are generally on the ambitious end of the spectrum for each target year and California's 2045 target outstrips many other long-term mid-century targets, demonstrating that interim benchmarks paired with ambitious longer-term goals can provide a roadmap for accelerated emission reduction.

The comparison of state-level mid-term and long-term emission reduction targets also reveals that states would be able to increase ambition by pledging mid-century carbon neutrality or net-zero long-term targets. Apart from the nine states which have pledged carbon neutrality or net-zero GHG emissions, most states with long-term targets have set comparable 2050 goals. Potential reasons for this might include the benefits of common milestones, which can provide clear policy signals and drive down costs; dialogue and technical exchange, which can create shared understanding of technology pathways and implementation experience; and state leadership, which can promote pioneering solutions and seek to align state-level interests. The states which have set more ambitious targets often have the authority to act independently within the U.S. system; have administrative and technical capacity to create pioneering policies; and have had historical success in tackling effective implementation (Mazmanian et al. 2020). As the 2050 targets generally aim for over 74% reductions below 2005 emissions levels, further ambition would involve establishing mid-century 100% GHG emission reduction targets or carbon neutrality goals. In the mid-term, greater ambition for concrete action can continue to support the pathway towards longer-term goals. Pursuing greater ambition requires a consistent reporting framework that captures both quantitative and qualitative aspects of state actions, as well as greater attention paid to implementation of subnational climate policies (Chan et al. 2015, Hsu et al. 2018).

The comparison of state-level mid-term and long-term emission reduction targets indicates that California's mid-term legislation to reduce emissions and long-term executive order to achieve carbon neutrality by 2045 can serve as a framework for subnational action (Lim and Won 2019, Sperling and Eggert 2014). California has often used executive authority to drive groundbreaking climate policy work, later codifying longer-term goals through legislation. The state has also built in mechanisms for continuous improvement; for example, when the 2045 carbon neutrality order was released, the state had recently achieved its 2020 target. If the state kept its goal of achieving the 2050 target, based on projected emission trajectory, it would have implied a slowdown in the rate of emission reduction between 2030 and 2050. Finally, in its effort to achieve long-term goals such as carbon neutrality, the state has employed a variety of emission reduction strategies. Other studies aiming to inform the discussion on carbon neutrality have focused on emission reduction in different sectors of the energy economy, exploring the unexpected synergies, counterintuitive results, and tradeoffs involved with reaching long-term goals (IPCC 2018, Larson et al. 2020, Mahone et al. 2020, Williams et al. 2021). These studies acknowledge that advanced mitigation strategies and early emission reduction targets can support potential carbon neutrality pathways (Mahone et al. 2020). California's mid-term and long-term targets are stringent and ambitious-undoubtedly necessary elements of the state's overall climate strategy.

Econometric analysis

The model results in this study demonstrated that the LCFS has greatly impacted CO_2 emission reduction in the transportation sector, though these analyses differ from the ones used by Huseynov and Palma (2018). My analyses considered different variables and groupings; included Oregon's policy in the first model; looked at a more recent timeframe; and considered impacts on transportation CO_2 emissions specifically. I also incorporated road transportation sector near-real-time emissions into the second model. These differences can account for varied results from literature, but the overall trends remain the same. As expected, the adoption of the LCFS decreased state emissions, performing best with controls present and states considering adopting similar policies, with the potential for an anticipatory period prior to policy enactment, excluded from the regression (Huseynov and Palma 2018). The results from the first model suggest that California and Oregon policy impacts may need to be examined separately, or that more research can be done to assess anticipatory period effects. The results from both models suggest that the LCFS on its own is not a silver bullet policy for addressing transportation emissions. Policy mixes- a particular strength of California's climate approach- can ensure that balanced strategies tackle emission reduction in various capacities. Certainly, the LCFS has great potential to play a major role in such a policy mix. Overall, the results make sense in the context of previous literature, which found that the LCFS is an effective policy for California's transportation sector and that cross-sector decarbonization is particularly reliant on the availability of low carbon fuels (Huseynov and Palma 2018, Mahone et al. 2020, Sperling 2016).

Emission estimation and analysis

The estimated annual 2018 data value for California's road transportation sector was lower than the EIA transportation data value, which followed expectations as the estimation focused on road transportation, a subset of the transportation sector (Liu et al. 2020). Updating the estimated daily dataset could offer a range of opportunities for related scientific research in the road transportation sector specifically (Liu et al. 2020). The detail and timeliness of these types of emissions estimates can facilitate more agile and adaptive management of CO_2 emissions during structural changes and the ongoing energy transition.

I demonstrated the viability of using my real-time 2019 emissions data estimate for California, along with Carbon Monitor's real-time data estimates for nine other states, to assess LCFS effectiveness. The model results furthered my argument for LCFS effectiveness (Huseynov and Palma 2018). My first model considered all U.S. states and a shorter timeframe; used different variable data and only general transportation sector emissions data; and did not use 2019 road transportation emissions estimates, while the second model included near-real-time road transportation data for 2019 after emission estimation; considered ten U.S. states and a longer timeframe including recent years; looked at California's LCFS specifically, excluding Oregon's policy; and excluded fewer states in the third specification due to having a narrower scope. While model differences and associated assumptions can account for the varied results from the first model in this study and from earlier literature, overall trends remained the same; as expected, California's LCFS decreased state emissions, performing best with controls present. This result makes sense in the context of previous literature and earlier results for this study, which found that the LCFS is an effective policy. The coefficients for *LCFSXpost* in this iteration of the second model were similar to the coefficients for *LCFSXpost* in the previous iteration. Results in this study were lower than results found using other approaches (Huseynov and Palma 2018). Other models with controls have previously predicted that the adoption of the California LCFS in the transportation sector decreased emissions approximately 21.19 MMT for an earlier timeframe. All models found the policy to be effective (Huseynov and Palma 2018, Mahone et al. 2020, Sperling 2016). Differences between results could be explained by the inherent difference between general transportation sector emissions and the road transportation sector emissions subset as well as the different model assumptions. The results from this model suggest that more research can be done to apply recent CO_2 emission estimates while taking into consideration data availability issues for other variables. This exercise reveals that emissions estimates for recent years can be applied to road transportation policy analyses (Liu et al. 2020). Real-time daily estimates can increase the policy-relevance of subnational emissions monitoring, potentially moving up the timetable of policy adjustments by roughly 1-2 years when compared to current available data for annual emissions.

California climate policy for road transportation

In-depth analysis of California's climate and road transportation policy microcosm can influence decision-making on larger scales. California's binding climate targets and policies are especially critical for transportation analyses, as the state has tremendous opportunities for reducing emissions in this sector (Mazmanian et al. 2020). The state's binding long-term target to achieve carbon neutrality by 2045 is more ambitious than the long-term targets of most other states. After empirically measuring the effect of one of California's major road transportation policies, the LCFS, on transportation sector CO_2 emissions, the impact is apparent and supports previous findings (Huseynov and Palma 2018). Using an alternative method of estimating state-level real-time CO_2 emissions for the road transportation sector and then conducting policy analysis with this data illustrates the opportunity for this data to be used as a tool in future assessments of climate measures for road transportation. The results support the argument that California's major climate policy for the transportation sector is highly effective and that the state's carbon neutrality target can provide a framework for ambition in other jurisdictions. While it has previously been argued that California is an outlier when it comes to environmental and energy policy, learning from California's experiences can still benefit future efforts if solid scientific approaches are used to assess mitigation effort and highlight lessons learned (Hsu et al. 2019). The results of this study, as well as future analyses in this field, can shed light on potential effective approaches in transportation and energy regulation for other jurisdictions.

Limitations and areas for further study

The limitations of this study involve the boundaries drawn around data collection and assumptions made in the analysis. For the first econometric model, I used publicly available data ending with the year 2017 and used a set of controls and variables, basing model construction on data availability and integral assumptions. For the second model using estimated emissions, further assumptions were applied due to VMT and gasoline tax data availability issues for the 2018-2019 period. This model also used a subset of U.S. states, differing from the first model. Due to these limitations, further work can be done in using econometric models and other methods to understand LCFS effectiveness and inform future policy adjustments. Nevertheless, results from econometric models can be useful because they can provide insights for future research directions as well as potential lessons learned. The limitations and results offer considerations and opportunities for further areas of research. Future research might analyze the potential interaction of the LCFS with other related programs to improve understanding of the impacts of complementary climate policies on state emissions. Other key topics could be explored including the effects of the LCFS on green technology adoption and implementation or on health co-benefits for heavily burdened communities with respect to environmental justice issues and equity (Huseynov and Palma 2018, Mahone et al. 2020). As this study focuses on state-level policy and emissions, a similar framework may be applied to other subnational jurisdictions with comparable policies (Mazmanian et al. 2020).

Policy implications

As currently there is no general consensus on a theory for carbon neutrality or states action, rigorous policy analyses are necessary to understand near-term priorities and longer-term pathways to achieve climate goals. Comparing California's climate targets with other state-level approaches and assessing climate policy effectiveness using near-real-time emission data can inform future policy directions. Dynamic information on CO_2 emissions will be critical for understanding the recent impacts of climate policies and potential for future action (Liu et al. 2020). Previous literature has pointed out the necessity of quantifying CO_2 reductions under low carbon standards and has conducted first efforts at rigorous analysis (Huseynov and Palma 2018, Yeh et al. 2016). This study builds on the literature by synthesizing and comparing state-level target data in a new format to provide context for subnational action; applying different empirical models for policy analysis; and constructing a novel dataset of daily 2019 CO_2 emissions for California's road transportation sector, adapted from national-level methods in the literature. The results underscore California's long-term target ambition and LCFS policy effectiveness while offering a new tool for future analyses. The ongoing target adjustments for both California's emission reduction targets and the LCFS reflect high adaptability and iterative increases in ambition as part of the state's climate policy framework. While environmental impact, or the effectiveness in reducing emissions, is an important metric for policy evaluation, state-level climate policy implementation needs to be evaluated based on other metrics as well: economic impact, or the extent of market stimulation, and equity, including environmental justice concerns. As the U.S. re-engages with the Paris Agreement and signals openness to pursuing a mid-century carbon neutrality goal, and as subnational actors continue to drive actionable climate policy, empirical studies on established targets for highly polluting sectors can clarify concrete near-term priorities and inform long-term decarbonization strategies.

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APPENDIX

Table 1. State mid-term (2020-2030) and long-term (post 2030) GHG reduction targets. State GHG emission reduction targets are categorized by timeframe and type to highlight levels of commitment: legislation (yellow), executive orders (blue), announced plans (pink), and recommended goals (gray).

State	2020-2030 Targets	Post-2030 Targets
AZ	2000 levels by 2020	50% below 2000 levels by 2040
CA	1990 levels by 2020 40% below 1990 levels by 2030	Carbon neutral by 2045
CO	26% below 2005 levels by 2025 50% below 2005 levels by 2030	90% below 2005 levels by 2050
CT	10% below 1990 levels by 2020 45% below 2001 levels by 2030	80% below 2001 levels by 2050
DE	26–28% below 2005 levels by 2025	N/A
FL	1990 levels by 2025	80% below 1990 levels by 2050
HI	1990 levels by 2020	Carbon neutral by 2045
IL	1990 levels by 2020 26–28% below 2005 levels by 2025	60% below 1990 levels by 2050
LA	26-28% below 2005 levels by 2025 40-50% below 2005 levels by 2030	Net-zero by 2050
MA	25% below 1990 levels by 2020	80% below 1990 levels by 2050
MD	25% below 2006 levels by 2020 40% below 2006 levels by 2030	80–95% below 2006 levels by 2050
ME	10% below 1990 levels by 2020 45% below 1990 levels by 2030	80% below 1990 levels by 2050 Carbon neutral by 2045
MI	20% below 2005 levels by 2020 26-28% below 2005 levels by 2025	Carbon neutral by 2050
MN	30% below 2005 levels by 2025	80% below 2005 levels by 2050
MT	1990 levels by 2020	Net-neutral GHG emissions economy-wide 80% below 1990 levels by 2050
NV	28% below 2005 levels by 2025 45% below 2005 levels by 2030	Net-zero by 2050
NH	20% below 1990 levels by 2025	80% below 1990 levels by 2050

NJ	1990 levels by 2020	80% below 2006 levels by 2050
NM	45% below 2005 levels by 2030	N/A
NY	40% below 1990 levels by 2030	Net-zero by 2050; 100% below 1990 levels by 2050: 85% below 1990 levels and offset 15%
NC	40% below 2005 levels by 2025	N/A
OR	10% below 1990 levels by 2020	45% below 1990 levels by 2035 75% below 1990 levels by 2050 80% below 1990 levels by 2050
PA	26–28% below 2005 levels by 2025	80% below 2005 levels by 2050
RI	10% below 1990 levels by 2020	45% below 1990 levels by 2035 80% below 1990 levels by 2050
VA	N/A	Net-zero by 2045
VT	26% below 2005 levels by 2025 40% below 1990 levels by 2030	80% below 1990 levels by 2050
WA	1990 levels by 2020 45% below 1990 levels by 2030	70% below 1990 levels by 2040 95% below 1990 levels by 2050 Net-zero by 2050

Table 2. Results from DID analysis to validate model use. When estimating the effect of California's LCFS on transportation CO_2 emissions for the period 2000-2017 using panel data for 50 states, the model predicted that the adoption of the LCFS decreased state CO_2 transportation emissions by approximately 22.9 MMT with a standard error of 2.32. The magnitude of the reduction represented around 10.5% of transportation CO_2 emissions from California in 2017. As these results only slightly exceeded previous literature results of a 21.2 MMT reduction, I determined my model and variables to be appropriate for further analyses. Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Variables	(1) Only Policy Variables C	(2) All States Included C	(3) Seven States Excluded C
LCFS×post	-15.00***	-22.90***	-23.09***
	(0.479)	(2.317)	(2.451)
LCFS	186.7***	58.12**	45.76*
	(4.641)	(27.37)	(27.16)
post	-1.216**	-2.287***	-2.526***
	(0.479)	(0.412)	(0.465)
POP		4.27e-06***	4.65e-06***
		(8.62e-07)	(8.50e-07)
GDP		0.141***	0.157***
		(0.0456)	(0.0512)
TAX		-0.153***	-0.190***
		(0.0524)	(0.0568)
VMT		0.000935*	0.000904*
		(0.000500)	(0.000547)
Constant	34.54***	5.102	4.966
	(4.641)	(6.609)	(6.731)
Observations	900	900	774
Number of S	50	50	43

Table 4. Summary statistics for model using 2000-2017 emissions.

Variables	N	Mean	Median	Std. Dev.	Min	Max
Transportation CO_2 emission (MMT)	900	37.60611	29.3	40.97445	3.3	235.2
Population	900	6078096	4337792	6716605	494300	3.94e+07
GDP growth (% change)	900	1.840778	1.8	2.661712	-8.8	22.3
Gasoline tax (cents per gallon)	900	22.09337	21.5	6.487935	2	58.2
Vehicle miles traveled per capita (miles)	900	10411.5	10411	1879.533	6259	18452
LCFS	900	0.02	0	.1400778	0	1
Year	900	2008.5	2008.5	5.191012	2000	2017
T	900	9.5	9.5	5.191012	1	18
S	900	25.5	25.5	14.43889	1	50

Table 5. State dummy variables for model using 2000-2017 emissions.

State	S	State	S	State	S	State	S	State	S
Alabama	1	Hawaii	11	Massachusetts	21	New Jersey	31	South Dakota	41
Alaska	2	Idaho	12	Michigan	22	New York	32	Tennessee	42
Arkansas	3	Illinois	13	Minnesota	23	North Carolina	33	Texas	43
Arizona	4	Indiana	14	Mississippi	24	North Dakota	34	Utah	44
California	5	Iowa	15	Missouri	25	Ohio	35	Vermont	45
Colorado	6	Kansas	16	Montana	26	Oklahoma	36	Virginia	46
Connecticut	7	Kentucky	17	Nebraska	27	Oregon	37	Washington	47
Delaware	8	Louisiana	18	Nevada	28	Pennsylvania	38	West Virginia	48
Florida	9	Maine	19	New Hampshire	29	Rhode Island	39	Wisconsin	49
Georgia	10	Maryland	20	New Mexico	30	South Carolina	40	Wyoming	50

Table 7. Summary statistics for model using 2000-2017 emissions.

Variables	N	Mean	Median	Std. Dev.	Min	Max
Transportation CO_2 emission (MMT)	180	52.99167	30.85	60.55213	4.1	235.2
Population	180	8855451	4792281	1.06e+07	627963	3.94e+07
GDP growth (% change)	180	1.791667	1.9	2.925803	-8.1	9.9
Gasoline tax (cents per gallon)	180	18.68056	18	6.945237	2	41.7
Vehicle miles traveled per capita (miles)	180	10172.81	9992.5	1731.623	6361	14498
LCFS	180	.05	0	.2185529	0	1
Year	180	2008.5	2008.5	5.202599	2000	2017
T	180	9.5	9.5	5.202599	1	18
S	180	5.5	5.5	2.880293	1	10

Table 8. State dummy variables for model.

State	S
Alabama	1
Alaska	2
Arkansas	3
Arizona	4
California	5
Colorado	6
Connecticut	7
Delaware	8
Florida	9
Georgia	10

Table 9. Near-real-time annual 2018-2019 CO_2 emissions for California's road transportation sector.

Annual Emission Estimation ($MMTCO_2$)			
	Publicly Available Data	**Study Estimate**	**Difference**
Annual 2018	217.08	205.67	11.41
Annual 2019	-	189.25	-

Table 11. Summary statistics for model using estimated 2019 emissions.

Variables	N	Mean	Median	Std. Dev.	Min	Max
Transportation/ Road Transportation CO_2 emission (MMT)	200	52.704	30.85	60.31395	4.1	235.2
Population	200	8945268	4809728	1.07e+07	627963	3.95e+07
GDP growth (% change)	200	1.84	1.9	2.809675	-8.1	9.9
Gasoline tax (cents per gallon)	200	19.0215	18	7.150696	2	41.7
Vehicle miles traveled per capita (miles)	200	10192.55	9992.5	1757.557	6361	14498
LCFS	200	0.055	0	0.2285524	0	1
Year	200	2009.5	2009.5	5.780751	2000	2019
T	200	10.5	10.5	5.780751	1	20
S	200	5.5	5.5	2.879489	1	10