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Impact of CARB's Tailpipe Emission Standard Policy on CO_2 Reduction among the U.S. States

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Abstract: U.S.Environmental Protection Agency (EPA) set the nationwide emission standard policy, but each state in the U.S. has an option to follow the higher emission standard policy set by CARB (California Air Resources Board) in 2004. There are 14 "CARB states" that follow California's more restrictive standards. The purpose of this paper is to examine the impact of CARB's tailpipe emission standard policy. Using the panel dataset for 49 U.S. states over a 28-year study period (1987–2015), this paper found the long-term policy effect in reducing CO_2 emission from CARB's tailpipe standard, and its long-run effect is 5.4 times higher than the short-run effect. The equivalent policy effect of the CARB emission standard in CO_2 reduction can be achieved by raising gasoline price by 145.43%. Also, if 26.0% of petroleum consumed for transportation is substituted by alternative clean fuels (natural gas or electricity), it will have a comparable policy effect in CO_2 reduction. Findings in this study support to continue the collaborative efforts among the EPA, National Highway Traffic Safety Administration (NHTSA), and California in order to achieve the CO_2 reduction goal set by CARB and adopted by the EPA in 2012. The packaged policy approach rooted in persistent public and political support is necessary for successful policy implementation.

Keywords: CARB; tailpipe emission standard; policy effect; transportation energy consumption; CO_2 emission; STIRPAT Model; Dynamic Panel Data GMM Model

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1. Introduction

According to *Today in Energy* (U.S. Energy Information Administration (EIA) publishes *Today in Energy*, a series of short articles with energy-related news and information and the link is https://www.eia.gov/todayinenergy/.), U.S. energy-related CO_2 emissions in 2017 fell 14% lower compared to 2005. However, the overall decrease slowed down due to the increasing CO_2 emissions in the transportation sector. While CO_2 emission from the electric power sector had lowered by 27.8%, the reduction from the transportation sector was only by 4.2% from 2005 to 2017 [1]. The dominant energy source of the transportation sector has persistently been petroleum with its share above 96%: the share in 2017 was 97.6%, compared to 96.8% in 1973. Historically, the U.S. federal government played a leading role in controlling pollutants from automobiles and other mobile sources of pollution, such as hydrocarbon and carbon monoxide emissions.

The Clean Air Act Amendments of 1965 were the first national standards set for hydrocarbon and carbon monoxide emissions from automobiles. The Clean Air Act Amendments of 1970 set a newer emission standards goal to reduce emissions by 90 percent. The automobile industry has always been in favor of federal standards with the aim to avoid each state passing varying standards. Only California can set its own standards due to its unique weather, geography, rapidly growing population, and vehicles. The CARB (California Air Resources Board) established in 1967 was tasked with setting its own stricter-than-federal vehicle emission standards. In 2004, CARB approved the nation's first GHG (Greenhouse Gas) emission standards specifically for cars [2]. CARB mandated the automakers to reduce average GHG emission (in grams) per mile by 22% for MY (Model Year) 2009–2012 compared to MY 2002. It also set the additional reduction goal for MY 2013–2016 by 30% (For details about tailpipe emission standards for states, visit https://database.aceee.org/state/tailpipe-emission-standards.). In 2012, CARB adopted a more stringent GHG standard that mandate a fleet-wide average emission reduction by approximately 4.6% annually for MY 2017–2025. California's ZEV (Zero-Emission Vehicle) program was also updated in 2012 and required an increase in the production of electric and plug-in hybrid vehicles from 2018 to 2025. There are thirteen other states (CARB states are: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington, as well as the District of Columbia.) that adopted CARB's restrictive tailpipe emission standard prior to 2010. These "CARB states" follow the California standards in order to control CO_2 emission specifically from vehicles. States in the U.S. have an option either to comply with the less restrictive EPA's standards or to adopt the more restrictive CARB's standards.

During Obama administration, the EPA's tailpipe standard was revised to correspond the increased standard for fuel economy under CAFE (Corporate Average Fuel Economy) of NHTSA (National Highway Traffic Safety Administration) [3]. The EPA's standard specifically limits the amount of carbon dioxide that can be emitted per mile and corresponds to the DOT (Department of Transportation)'s increased standard. In 2012, the EPA adopted revised GHG standards for MY 2017–2025 vehicles in line with the more stringent CARB standards. During 2016, the EPA, NHTSA, and CARB published the TAR (Technical Assessment Report) draft for the feasibility study of the currently mandated standards considering the associated cost. They concluded that the new standards would be viable and feasible by the target year of 2025. However, the EPA in Trump administration completed the new Midterm Evaluation in April 2018, and administrator Scott Pruitt announced that the new standards set by the Obama administration were too ambitious, inappropriate, and therefore should be revised. He also challenged the validity of the Clean Air Act (CAA) which granted the waiver to California to set its own stricter standards for vehicle emissions [4].

The purpose of this paper is to examine the impact of CARB's controversial tailpipe emission standard policy which leads to the conflicts between Trump administration's EPA and CARB states. Using panel data, this paper analyzed the state-level energy consumption and CO_2 emissions from the transportation sector in the U.S. during 1988–2015.

The following Section 2 reviews the previous studies on energy consumption and CO_2 emission from the transportation sector. Section 3 presents the methodology used to estimate energy consumption and CO_2 emissions in the transportation sector, followed by Section 4 which discusses the model specification and estimation results. Section 5 concludes with a summary of major findings and policy implications.

2. Literature Review

The three main sources of CO_2 emission in the world are thermal power, industry, and transportation sectors [5]. The main focus of previous studies was on the thermal power and industry sectors to understand CO_2 emission differences by sectors, while limited studies on CO_2 emission from transportation sectors mainly focus on developing countries. Saboori et al. [6] found that there is a stable relationship between the energy consumption of the transportation sector and GDP growth among OECD (The Organisation for Economic Co-operation and Development) countries, and there would be more CO_2 emission in the transportation sector with GDP growth.

Some empirical studies focused on policies designed to control carbon emissions from the transportation sector. He et al. [7] suggested multiple policies to stabilize the excessive increase in China's oil consumption for the road transport industry. The most effective policy to contain fuel consumption was to improve vehicle fuel efficiency in China. Lin and Li [8] found the effective policy impact of carbon tax among northern EU countries on CO_2 emission reduction; however, they also found that tax exemption weakened the policy effect. Siskos et al. [9] tested the policy effects of CO_2 emission standard and energy efficiency standard in the EU and found the deep emission cuts from cars in both policies. Rentziou et al. [10] tested the effects of various policies in the U.S. which govern fuel tax and population density on GHG emissions. They found that increasing the fuel tax would significantly decrease energy consumption and GHG emissions from light-duty vehicles and passenger cars. Also, it was shown that an increase in density would result in a decrease in travel demand with lowering GHG emission. The sub-national policy impact analysis focusing on a tailpipe emission standard in the U.S. is largely limited; however, at the international level, a few studies have found pieces of evidence that a more stringent standard in a country influences the policy choices in other countries. For instance, Perkins and Nuemayer [11] tested the 'California effects' thesis among countries and found the ratcheting-up effect from (1) a trading-up effect among the developing countries that export automobiles to the countries with more stringent standard and (2) investing-up dynamics through inward foreign indirect investment into developing countries that export automobiles.

Studies focusing on the development of policy approaches to mitigate CO_2 emissions from the transportation sector include the analysis of the effect of dieselization on emissions for Spanish regions by Gonzalez and Marrero [12] and the study on mitigation options for Thailand's transport sector to reduce emissions by Pongthanaisawan and Sorapipatana [13]. To control CO_2 emission from the transportation sector, some scholars suggested fuel type specific policy approaches [14,15] with the aim to promote cleaner fuel consumption. Others paid more attention to vehicle type [15,16] or transport mode [17]. Focusing on California's ZEV mandate, Greene et al. [18] analyzed the feasibility of a transition to ZEV in the U.S. and found the social benefits exceeding costs, but the transition posits new challenges for policymakers due to the time required, intercedences among regions and countries, positive feedback, and uncertainty.

However, it is hard to find empirical studies performed at the sub-national level in the U.S. for estimating factors that affect energy consumption and CO_2 emissions from the transportation sector under panel data structure. An exception is a study by Rentziou et al. [10] that forecasted GHG emission from the passenger transportation considering fuel tax's effect on vehicle miles traveled (VMT) for the 48 continental states in the U.S. The sub-national empirical studies using panel data structure are more common in other countries, including China and EU countries. In the U.S., a group of researchers had developed CO_2 emission data at a finer urban spatial level on a 100 km^2 grid, called Vulcan data (More detail about Vulcan data can be found from the following link, http://vulcan.project.asu.edu/research.php). Parshall et al. [19] suggested the use of county-level emission data in the U.S. as a preferred alternative to Vulcan data. However, county-level emission data is not feasible due to the lack of sub-state level data and does not fit well to the spatial scope of policy implementation, which is mainly at a state-level in the U.S. With the aim to build a comprehensive understanding on the trend of CO_2 emission from the transportation sector, it is also critical to consider the temporal scale in addition to the spatial scale. Wu et al. [20] showed the dynamically changing relationships among various factors and CO_2 emissions.

3. Methodology

This paper proposes two sets of policy impact models. The first model estimates the policy impacts on CO_2 emission in the transportation sector, whereas the second model estimates the policy impacts on energy consumption in the transportation sector. Dynamic panel data GMM (Generalized Method of Moments) specification is employed for estimation.

When analyzing the relationship between CO_2 emissions and key factors from the transport sectors, the following four methods are most widely employed: (1) index decomposition [5,21], (2) bottom-up sector-based analysis [22,23], (3) system optimization [24–26], and (4) econometric techniques [12,27]. Among the four methods, the econometric techniques are most suitable for panel data analysis that utilizes a stochastic process to analyze the impact of the policy factors on CO_2 emission in the transportation sectors. In this study, the econometric method is adopted for a comprehensive understanding.

CO_2 emission in the US could be explained by the STIRPAT (stochastic impacts by regression on population, affluence, and technology) model, an extension of the IPAT (the Impact on the environment depends on Population, Affluence, and Technology) model (The IPAT model which is a method to analyze the effect of economic activity on the environment [28]. CO_2 emission is one of the environmental impact variables, so previous studies applied the IPAT model to analyze CO_2 emissions [29,30].). Unlike the IPAT model, statistical assumptions are added, and the hypothesis can be tested in the STIRPAT model [31]. STIRPAT model is given by Equation (1):

$$\mathrm{I_{i.t}} = \mathrm{aP^{b}_{i.t}A^{c}_{i.t}T^{d}_{i.t}v_{i.t}} \tag{1}$$

where, I = environmental impact; P = population size; A = wealth of society; T = technology level in a society; a, b, c, and d = coefficients to be estimated as elasticities; $v_{i.t}$ = random error term; i = state (48 lower states and Washington D.C.); t = year.

Environmental impact (I) is the annual CO_2 emission from the transportation sector in state i for year t. Variable P represents the population size of state i for year t, whereas A is the wealth of society, proxied by GDP per capita of state i for year t. Technology variable (T) is usually represented by carbon intensity (CO_2 Emission/GDP). However, energy intensity (Energy Consumption/GDP) could be an instrumental variable for carbon intensity represented by T in the Equation (1) [32]. Following the suggestion by Lin et al., 2009 [32], our study employs the energy intensity (EI) as T variable. Adoption of advanced technology that decreases EI can induce the more efficient use of energy for production.

It is possible to add more variables to the STIRPAT model as long as they are relevant to the dependent variable [33]. The equation is monotonically transformed by taking the logarithm of all variables except for CARB emission standard variable (RES). To analyze the US CO_2 emission in the transportation sector, we specified the STIRPAT model as the following equation.

$$\begin{gathered}\mathrm{lnC_{i.t}} = \alpha + \beta_{\mathrm{pop}}\mathrm{lnPOP_{i.t}} + \beta_{\mathrm{gdp}}\mathrm{lnGDP_{i.t}} + \beta_{\mathrm{ei}}\mathrm{lnEI_{i.t}} + \beta_{\mathrm{vmt}}\mathrm{lnVMT_{i.t}} + \beta_{\mathrm{gp}}\mathrm{lnGP_{i.t}} + \\ \beta_{\mathrm{mix}}\mathrm{lnMIX_{i.t}} + \beta_{\mathrm{res}}\mathrm{RES_{i.t}} + \mathrm{v_{i.t}}\end{gathered} \tag{2}$$

where, $C_{i.t}$ = CO_2 emission from the transportation sector in state i and year t; POP = population; GDP = GDP per capita; EI = energy intensity; VMT = vehicle miles traveled; GP = gasoline price (in 2010 USD); MIX = ratio of alternative fuel (natural gas and electricity) consumption to petroleum consumption in the transportation sector; RES = tailpipe emission standard set by CARB.

Table 1 lists the variables in this paper with the description and measurement units. POP and GDP measure population size and wealth of society, respectively. Population variable is widely used to estimate the increasing pattern of CO_2 emissions. GDP variable is the most widely used measure representing the wealth of society, while others focus on trade openness as a wealth measure. EI, energy intensity in a society, can be measured by the ratio of total energy consumption to GDP. VMT, vehicle miles traveled, represents the travel demand. The higher ratio indicates inefficient energy consumption with low energy technology [34]. Equation (2) has three policy-related variables, GP, MIX, and RES. Gasoline price (GP) is the average per Btu price and includes the embedded tax that varies across states and by time. Davis and Killian [35] estimated the effect of gasoline tax embedded in consumer price on carbon emission. The fuel tax policy can alter the consumption of gasoline which further translated into the change in emission. MIX variable serves as a policy tool that aims to promote cleaner and alternative fuel consumption through technological advancement. The change in fuel mix can be triggered by the advanced technology in automobile manufacturing and a cleaner fuel supply system. On the demand side, the competitive prices of clean fuel and vehicle, and easier access to clean fuel may drive up the demand for clean transportation. On the supply side, reduced costs to provide clean vehicle and fuel with a public subsidy may expand the production of the clean vehicle.

RES is a dummy variable detecting a state that adopted a more restrictive tailpipe emission standard compared to EPA's standard. In 2004, CARB set its goal for California with the 2009–2012 model year vehicles, and 13 other states in the U.S. adopted CARB's policy in various years.

Table 1. Description of Variables.

Variable	Unit	Description
CO_2 emission (C)	Million Metric Ton	Total CO_2 emission from the transportation sector by state
Transportation energy (TE)	Trillion Btu	Total energy consumption in the transportation sector by state
Population (POP)	Thousand persons	State population at the end of year
Per capita GDP (GDP)	Dollars	Real GDP per capita by state in 2000 USD
Energy intensity (EI)	Thousand Btu per 1 USD	Intensity = Total energy/GDP in 2000 USD
Vehicle miles traveled (VMT)	Millions miles	Total vehicle travel miles by state
Gasoline price (GP)	Dollars per million Btu	Gasoline price in 2000 USD
Alternative fuel ratio (MIX)	Ratio (Btu/Btu)	Ratio = [(Natural gas + Electricity)/Petroleum] in the transportation sector
Tailpipe emission policy (RES)	Dummy	Adopted CARB's tailpipe emission standard

Equation (2) here is static, which cannot take into account the dynamic nature of aggregate CO_2 emission at the state-level. Using aggregate data, the dynamic nature should be considered in empirical studies [36,37]. Thus, the dynamic panel model is shown below in Equation (3).

$$\begin{aligned} \ln C_{i.t} &= \alpha + \beta_c \ln C_{i.t-1} + \beta_{pop} \ln POP_{i.t} + \beta_{gdp} \ln GDP_{i.t} + \beta_{ei} \ln EI_{i.t} + \beta_{vmt} \ln VMT_{i.t} \\ &\quad + \beta_{gp} \ln GP_{i.t} + \beta_{mix} \ln MIX_{i.t} + \beta_{res} RES_{i.t} + v_{i.t} \qquad (3) \\ \nu_{i.t} &\equiv \mu_i + \varepsilon_{i.t} \end{aligned}$$

where, $\nu_{i.t}$ = fixed effects decomposition of the error term; μ_i = state-specific error; $\varepsilon_{i.t}$ = error component, assumed to be serially uncorrelated with zero mean and independently distributed across countries.

The state-specific error term μ_i captures all of the fixed factors (time-invariant) related to CO_2 emission in the transportation sector that are not considered in the model, such as regional, social, and policy aspects, or not directly observed, such as the initial emissions technology for the vehicles in each state. With the remaining factors conditioned, all coefficients reflect a partial short-term impact between CO_2 emission in the transportation sector and all other explanatory variables. As for the long-term effect, this can be easily obtained by dividing the short-term coefficient by $1 - \beta_c$.

Additionally, Equation (4), a variation of Equation (3), is specified to estimate the energy consumption in the transportation sector with the same set of independent variables from Equation (3). This model tests the effects of three policy-related variables, GP, MIX, and RES, on total energy consumption in the transportation sector with the control of other factors. Energy policies in the transportation sector to boost energy efficiency and cleaner energy sources are expected to directly reduce energy consumption with the adoption of newer technologies among automakers. Eventually, the reduction in energy consumption from the transportation sector will lower CO_2 emission from the transportation sector.

$$
\begin{aligned}
\mathrm{lnTE}_{\mathrm{i.t}} = \alpha + \beta_{\mathrm{c}}\mathrm{lnTE}_{\mathrm{i.t-1}} + \beta_{\mathrm{pop}}\mathrm{lnPOP}_{\mathrm{i.t}} + \beta_{\mathrm{gdp}}\mathrm{lnGDP}_{\mathrm{i.t}} + \beta_{\mathrm{ei}}\mathrm{EI}_{\mathrm{i.t}} + \beta_{\mathrm{vmt}}\mathrm{VMT}_{\mathrm{i.t}} \\
+\beta_{\mathrm{gp}}\mathrm{lnGP}_{\mathrm{i.t}} + \beta_{\mathrm{mix}}\mathrm{lnMIX}_{\mathrm{i.t}} + \beta_{\mathrm{res}}\mathrm{RES}_{\mathrm{i.t}} + \mathrm{v}_{\mathrm{i.t}} \quad (4) \\
\nu_{\mathrm{i.t}} \equiv \mu_{\mathrm{i}} + \varepsilon_{\mathrm{i.t}}
\end{aligned}
$$

where, $\mathrm{TE}_{\mathrm{i.t}}$ = total energy consumption in the transportation sector in state *i* and year *t*.

The appropriate estimation method is necessary in order to obtain unbiased results. The fixed effect model (FE) and the random effect model (RE) are usually employed to analyze panel data. Depending on the results of the Hausman test, it is determined which model is more efficient. However, the dynamic panel model has a significant econometric issue that is not considered in a static panel model. Since the lagged, endogenous terms in Equations (3) and (4) are not independent of the error terms, traditional methods for estimating a panel data model, such as OLS (Ordinary Least Square), Fixed effect or Random effect, are not suited to a dynamic model [38]. The difference GMM estimator developed by Arellano and Bond [39] was designed to solve endogeneity problems. Arellano and Bond also suggested transforming the dynamic panel model into a first difference model. This transformation allowed the removal of the time-invariant state-specific error and then estimated βs by instrumental variables (IV), which is denoted by GMM-DIFF. The GMM-DIFF approach, however, poses a serious bias in small samples when the series used in the model exhibits significant persistence, as is the case with the variables considered in Equations (3) and (4). Arellano and Bover [40] and Blundell and Bond [41] offered an alternative GMM procedure (GMM-SYS) to overcome this weakness. A system of equations was estimated by combining the conditions of the first-difference estimator with those of level estimators. This procedure estimates a system of equations in both first-difference and level, where the instruments in the level equations are lagged first differences of the variables. This paper employed GMM-SYS estimator as the main approach.

Because the equation is in double logarithmic form, the coefficients were interpreted as elasticities, except for the dummy variable of 'tailpipe emission policy' (RES). In addition, it is a dynamic model, and the estimated coefficients were the short-run elasticities. Long-run elasticities could be obtained by dividing each coefficient by $(1-\beta_{\mathrm{C}})$. A further advantage of the use of differenced data is that the non-stationarity problem can be avoided [42,43].

4. Estimation Results

Most of the data in this study, spanning from 1987 to 2015, were obtained from the U.S. Energy Information Administration (EIA), EPA, and U.S. Census. Panel data analysis employs the state-level data including 48 lower states and Washington D.C. Descriptive statistics of the variables for estimation are summarized in Table 2.

Table 2. Descriptive Statistics of Variables.

Variable	Mean	Std. Dev.	Variable	Mean	Std. Dev.
CO_2 emission (C)	35.75	38.98	Vehicle miles traveled (VMT)	54,088.79	55,274.06
Transportation energy (TE)	512.87	555.65	Gasoline price (GP)	17.20	5.69
Population (POP)	5734	6,269	Alternative fuel ratio (MIX)	0.0412	0.0539
Per capita GDP (GDP)	47,130	110,338	Tailpipe emission policy (RES)	0.0894	0.2854
Energy intensity (EI)	9.34	4.28			

Source: based on authors calculation on raw data from U.S. EIA (Energy Information Administration), EPA (Environmental Protection Agency), CARB (California Air Resources Board), U.S. Census, U.S. BEA (Bureau of Economic Analysis).

For the variables, three types of panel unit root tests (LLC (Levin-Lin-Chu) [44], IPS (Im-Pesaran-Shin) [45], and Breitung [46]) were performed (see Table A1 in the Appendix A). LLC and IPS test results indicated that there was no significant evidence for the unit root in all variables, but Breitung test showed that there existed the unit root in *VMT* variable (Vehicle Miles Travelled). However, the Pedroni panel cointegration tests [47,48] found the cointegration among the variables (see Table A2 in the Appendix A). This means there are stable long-run relationships between the variables and the estimations, and analyses with the variables are meaningful. Test results are in the appendix of the paper. During the study period of 1987–2015, average annual CO_2 emission for the sample 49 states was 35.75 million metric tons (MMT). The state with the highest level of CO_2 emission was Texas with its peak of 216.9 MMT of CO_2 emissions in 2015. California had the second highest level of CO_2 emission with 206.0 MMT. The state with the least CO_2 emission was Washington D.C, followed by Vermont and Rhode Island. The average annual total energy consumption in the transportation sector was 512.87 trillion Btu among the 49 sample states between 1987 and 2015. California in 2007 had the highest transportation energy consumption of 3359.70 trillion Btu, while Washington D.C. had the lowest transportation energy consumption of 18.9 trillion Btu in 2008. Temporal trend demonstrates that transportation energy consumption is pro-cyclical to the business cycle in the U.S. After the end of the Great Recession in the U.S., it has been on a continuous rise. The gasoline price is measured by dollar/million Btu. The average motor gasoline price in panel dataset was $17.20. Energy intensity measures how much energy is used for unit production. The average energy intensity was 9.34 thousand Btu per 1 USD in the panel data, and the highest energy intensity state was Louisiana (30.10 in 1992), the lowest energy intensity state was Florida (1.66 in 2015). The higher the energy intensity, the lower the energy efficiency in the state's economic activity. Historically, energy intensity has become smaller over time due to technological advancement. Vehicle miles traveled is a direct measure of transportation demand which can be translated into a proxy for energy consumption, and in turn, this also determines the CO_2 emission level from the transportation sector. Average VMT in the sample was 54,088.79 million miles per year among the 49 states. Alternative fuel ratio is defined as the ratio of the sum of natural gas and electricity consumption to petroleum consumption in the transportation sector. The average alternative fuel ratio was 0.0412, and the ratio fluctuated over time. Tailpipe emission policy variable is a dummy showing the states that adopted more restrictive CARB's emission standards than the EPA standards during the study period. There are 14 states, including California, that had adopted CARB's GHG emission standards and all of the states adopted the standards prior to 2010.

Table 3 summarizes the estimation results of the dynamic panel data GMM system model (DPD SYS-GMM). For the GMM estimators, several specifications were tested with regards to the endogeneity of the variables. The choice of the model was based on the significance of the estimates and on the diagnostic tests result from the Arellano-Bond tests of AR (1) and AR (2), Hansen tests of overidentifying restrictions, and the Difference-in-Hansen tests of exogeneity of instruments subsets. Diagnostic tests of all the models (Hansen, AR(1), AR(2), and Difference-in-Hansen) indicated that GMM estimators are robustly supportive.

Table 3. GMM (Generalized Method of Moments) Dynamic Panel Model Estimation Results.

Panel A						
	CO_2 Emission			**Transportation Energy Consumption**		
	Coefficient	**S.E**		**Coefficient**	**S.E**	
L.lnC	0.8136	0.0089	***	-	-	
L.lnTE	-	-		0.7535	0.0148	***
lnPOP	0.0781	0.0129	***	0.1322	0.0186	***
lnGDP	0.0859	0.0103	***	0.1290	0.0167	***

Table 3. *Cont.*

Panel A						
	CO_2 Emission			**Transportation Energy Consumption**		
	Coefficient	**S.E**		**Coefficient**	**S.E**	
lnEI	0.0930	0.0090	***	0.1291	0.0123	***
lnVMT	0.1151	0.0096	***	0.1177	0.0124	***
lnGP	−0.0299	0.0028	***	−0.0191	0.0021	***
lnMIX	−0.0049	0.0015	***	−0.0009	0.0015	
RES	−0.0435	0.0069	***	−0.0484	0.0069	***

Panel B		
Diagnostic Test	**CO_2 Emission**	**Transportation Energy Consumption**
AB AR(1) †	0.001	0.001
AB AR(2) †	0.475	0.468
Hansen †	0.552	0.584
Dif Hansen †	0.894	0.399
no. Instruments	58	58
no. observations	1372	1372

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$, † p-value of chi-square test.

4.1. CO_2 Emission Model

The coefficient of the lagged variable (L.lnC) was statistically significant with a positive sign and value close to 1. This shows that the CO_2 emission of the previous year is an important factor in determining the aggregate CO_2 emission level in a state. Since the regional economic structure and human behavior in a state cannot change rapidly in a few years, the previous CO_2 emission levels in the transportation sector would be the main determinant for the current CO_2 emission level in states.

The other coefficients were significant with expected signs. All policy-related variables in the model (tailpipe emission policy (RES), high gasoline price (lnGP), and high alternative fuel ratio (lnMIX)) reduced CO_2 emission level among the 49 sample states during the study period (1987–2015). The emission control policy was found to be effective to reduce CO_2 emission in the transportation sector. Increasing gasoline price may encourage the transportation mode change (altering modal choice) with the substitution effect, which leads to CO_2 emission reduction. The growing consumption of alternative fuel also efficiently reduces CO_2 emission. The coefficients of other control variables (population (lnPOP), GDP per capita (lnGDP), energy intensity (lnEI), and vehicle miles traveled (lnVMT)) were significant with expected positive signs implying that growth in population (lnPOP), GDP per capita (lnGDP), and energy intensity (lnEI) increase CO_2 emission. The growth of population and income increase induce more transportation demand and increase CO_2 emission. Also, energy intensity, a measure of energy efficiency for total energy consumption, was found to be an important estimator demonstrating that more efficient use of energy contributes to the emission-reduction in the transportation sector among the U.S. states. Economic growth-induced CO_2 emission in the transportation sector was confirmed in the proposed model specification. Also, as predicted, the increase in travel miles rose the CO_2 emission.

4.2. Transportation Energy Consumption Model

The coefficient of the lagged variable (L.lnTE) for estimating the transportation energy consumption was also statistically significant with the value close to 1. Likewise, CO_2 emission case, transportation energy consumption level of a state in a given year is largely determined by the previous year's consumption level.

In the transportation energy consumption model, not all policy-related variables are significant. The coefficients of tailpipe emission policy (RES) and high gasoline price (lnGP) were statistically significant with the expected negative signs. However, the coefficient of the alternative fuel ratio (lnMIX) was not significant.

The emission control policy reduced transportation energy consumption. As found in the estimation model for CO_2 emission, increasing gasoline price might have induced the travelers to switch to cheaper and alternative modes of transportation. However, the growing consumption of alternative fuel in transportation have not reduced the total transportation energy consumption significantly. The alternative energies are natural gas and electricity which emit less CO_2 compared to petroleum fuels. Since energy consumption is measured by Btu (British thermal unit) for all types of energy sources in the transportation sector, the internal change in the composition of energy sources (e.g., replacement of petroleum products by alternative energy sources) does not necessarily reduce the overall energy consumption in the transportation sector. But, the growing use of alternative (cleaner) energy source has reduced the CO_2 emission from the transportation sector as found in the previous model.

The other control variables had significant positive signs as expected. Growth in population (lnPOP), GDP per capita (lnGDP), and vehicle miles traveled (lnVMT) increased transportation energy consumption. Lower energy efficiency measured by the energy intensity variable also contributed to the growing consumption of energy in the transportation sector among the U.S. states.

As explained earlier, the estimated coefficients in the model specifications showed the short-term effects of the policy variables (β_{REST}, β_{GP}, or β_{MIX}). On the other hand, the long-term effects of the policy variables could be calculated by dividing the short-term coefficients of the variables (β_{REST}, β_{GP}, or β_{MIX}) by $1 - \beta_c$. Table 4 summarizes the short-term and long-term policy effects of tailpipe emission standards, gasoline price, and alternative fuel ratio on CO_2 emission and transportation energy consumption, derived from the DPD SYS-GMM model specification.

Table 4. Estimated Short-run and Long-run Policy Effects (in %).

	CO_2 Emission			**Transportation Energy Consumption**		
	RES	**GP**	**MIX**	**RES**	**GP**	**MIX**
Short-term	−4.3544	−0.0299	−0.0049	−4.8498	−0.0192	-
Long-term	−23.3620	−0.1606	−0.0262	−19.6749	−0.0777	-

Even with almost no change in the total energy consumption, the states with CARB's stricter tailpipe emission standards had experienced the CO_2 emission reduction in the transportation sector. The states successfully achieved the main policy goal of the tailpipe emission standards in terms of CO_2 emission reduction in the transportation sector. Additionally, tailpipe emission standard policy was also effective in reducing the total transportation energy consumption. Likewise, the increase in gasoline price not only reduced the CO_2 emission but also the energy consumption from the transportation sector.

The long-term effects of the policies on CO_2 emission are 5.4 times larger than short-term effects. The impacts of independent variables on CO_2 emission last long. The largest long-term policy effect is from CARB's tailpipe emission standard (RES). If a state adopts CARB's restrictive emission standards, it can reduce the annual CO_2 emission from the transportation sector by 23.36% in the long-run. The long-term effect of gasoline price adjustment (GP) is -0.1606, showing that a 1% increase in gasoline price (with a possible increase in fuel tax) will reduce the annual CO_2 emission from the transportation sector by 0.16% in the long-run. The long-term effect of fuel mix change (MIX) is smaller compared to the other two policy effects mentioned above. With a 1% increase in alternative fuel mix ratio, a state expects to benefit from the 0.026% CO_2 emission reduction in the long-run. The average ratio of alternative energy to petroleum consumption in the transportation sector was 0.0412 in the sample. The effect of fuel mix looked very much limited; however, if 1% of petroleum consumption in the transportation sector was substituted by either natural gas or electricity, the fuel mix ratio jumped from 0.0412 to 0.0517, a 25.5% increase in fuel mix ratio (MIX). Accordingly, the 1% substitution of petroleum fuel by cleaner fuel resulted in the 0.67% annual CO_2 emission reduction in the transportation sector. Historically, the share of clean alternative energy consumption (natural gas and electricity) for the transportation sector in the U.S. has been less than 5% on average. Therefore, the policy designed to boost the increased use of clean alternative energy for the transportation sector holds great potential in the long-term.

The long-term effects of the policies on transportation energy consumption are 4.6 times larger than short-term effects. The long-term policy effect from CARB's tailpipe emission standard (RES) on transportation energy consumption is 19.67% reduction. If a state adopts CARB's restrictive emission standards, it can reduce the annual consumption from the transportation sector by 19.67% in the long-run. The long-term effect of gasoline price adjustment (GP) is -0.0777, indicating that a 1% increase in gasoline price (with a possible increase in fuel tax) will reduce the annual energy consumption from the transportation sector by 0.08 in the long-run. There is no measurable long-term effect of fuel mix change (MIX) in transportation energy consumption due to the insignificant coefficient shown in the estimation result (see Table 3).

Table 5 lists the comparative effects of the three policy instruments estimated by the DPD SYS-GMM model. If the policy effect in CO_2 emission reduction from the transportation sector by adopting CARB's tailpipe emission standards is set to be a unit (value of 1), the policy effect of a 1% increase in the gasoline price is 0.69% of the CARB tailpipe emission standard policy. In other words, the equivalent emission reduction effect of a restrictive CARB emission standard policy can be achieved by raising gasoline price by 145.43%. Policy effect of fuel mix is limited compared to the expected effect from the adoption of CARB's tailpipe emission standards. Fuel mix policy stimulating the use of clean energy for transportation (e.g., 1% increase in ratio) is found to have only 0.11% of the estimated CO_2 emission reduction from CARB's tailpipe emission standard policy. From a different angle, to attain the same amount of CO_2 emission reduction from CARB's tailpipe emission standard, a state should increase the fuel mix ratio to 888.39%. However, when approximately 26.0% of petroleum consumed for transportation is substituted by alternative clean fuels (natural gas or electricity), it will increase the ratio to roughly 888.39% that translates into the matching reduction in CO_2 emission from the transportation sector. The estimated CO_2 emission reduction from a 1% increase in gasoline price can be achieved by the 6.11% increase in the fuel mix, stimulating the use of cleaner energy sources for transportation. In other words, a 1% increase in fuel mix has only about 16.4% of the emission reduction effect from the 1% increase in gasoline price.

Table 5. Pairwise Comparative Policy Effects on CO_2 Emission.

	CO_2 Emission		
	RES	**GP**	**MIX**
RES	1.0000	0.0069	0.0011
GP	145.43	1.0000	0.1637
MIX	888.39	6.1083	1.0000

Table 6 lists the comparative effects of the three policy instruments on transportation energy consumption estimated by the DPD SYS-GMM model in this paper. If the policy effect on energy consumption from the transportation sector by adopting CARB's tailpipe emission standards is set to be a unit (value of 1), the policy effect of a 1% increase in the gasoline price is only at 0.40% of the CARB tailpipe emission standard policy. In other words, the equivalent emission reduction effect of a restrictive CARB emission standard policy can be achieved by raising gasoline price by 253.1%. There is no identified policy effect of fuel mix change (MIX) on transportation energy consumption.

Table 6. Pairwise Comparative Policy Effects on Transportation Energy.

	Transportation Energy Consumption		
	RES	**GP**	**MIX**
RES	1.00000	0.0040	N/A
GP	256.14	1.0000	N/A
MIX	N/A	N/A	1.0000

5. Conclusions and Discussion

This paper aimed to examine the effects of the controversial CARB's tailpipe emission standard on CO_2 emission and energy consumption from the transportation sector. To estimate the policy effects, this paper took comparative approaches with alternative policy instruments, such as gasoline price policy and policy to boost the use of alternative clean fuel types for the transportation sector. The main contribution of this paper is three folds: (1) evaluation of the long-term CARB's tailpipe emission standard at a sub-national level under panel data structure, (2) comparison between short-run and long-run policy effects with dynamic panel data GMM system models, and (3) pairwise comparison of relative policy effects among the three policy choices to reduce CO_2 emission from the transportation sector.

The proposed dynamic panel data GMM system models (DPD GMM-SYS) employed the panel dataset for 49 U.S. states over a 28-year study period (1987–2015) for the estimations. Estimation results clearly indicated the expected effects of all three policy-related variables for CO_2 emission model, while policy effects on transportation energy consumption are limited to tailpipe emission standard and gasoline price policy. Due to the persistent trends of CO_2 emission energy consumption in the transportation sector, the dynamic model specifications perform better than the static models. The estimation models in this paper clearly demonstrated the significant policy impact of CARB's stricter tailpipe emission standards in reducing the CO_2 emission reduction and energy consumption in the transportation sector.

In 2015, the total CO_2 emission from the transportation sector in the sample 49 states was 1831.3 MMT (million metric tons). The aggregated CO_2 emission from the transportation sector in fourteen states that currently have CARB's tailpipe standard in place was 553.4 MMT for the same year. Meanwhile, the total emission from the other thirty-five states without CARB's tailpipe emission standard was 1277.9 MMT. If all the thirty-five states had CARB's stricter emission standard in place, the estimated annual CO_2 emission reduction from the transportation sector would have been 281.7 MMT in 2015. State and local governments have implemented various tax policies to control gasoline demand and also to finance public projects through TIF (Tax Increment Financing). If there was a 1% increase in gasoline price in all the thirty-five states without CARB's tailpipe standard in 2015, a total of 2.57 MMT of CO_2 emission reduction would have been achieved. This is less than 1% of the total policy effect estimated for CARB's tailpipe emission standard policy. Fuel mix had a somewhat limited effect compared to the other alternative policies shown in this study. This is a good measure to estimate the substitution effect between conventional petroleum fuels and clean fuels, such as natural gas and electricity. To achieve the matching CO_2 emission reduction from the CARB emission standard policy, about 26.0% of petroleum fuel should be substituted by clean fuels.

The specified models in this paper confirm the effectiveness of CARB's tailpipe emission standards in reducing CO_2 emission and energy consumption in the transportation sector. CARB's stricter standards have the largest effects among the three alternative policy instruments tested in this study. During the last few years of Obama administration, EPA, NHTSA, and the State of California had collaborated by sharing their common vision to reduce GHG emission. NHTSA's CAFE has traditionally focused on reducing energy consumption in the transportation sector by increasing fuel economy. Empirical evidence on the policy impact of NHTSA's CAFE standards demonstrates why the careful design and proper implementation of fuel economy regulations are important and preferable to other policies [49]. The policy design process and implementation of the policies to reduce CO_2 emission can be further improved through the collaborative approaches among the main stakeholders. The transportation energy consumption model of this paper found that CARB's tailpipe emission standards that mainly focus on the CO_2 reduction effectively decreased the total energy consumption in the transportation sector. Historically, EPA's emission standards have been less restrictive compared to CARB's standards.

The recently developed collaborative strategies among the three players (CARB, NHTSA, and EPA) to achieve the new emission reduction goals was an appropriate and timely move in a more harmonized and comprehensive manner. Greene et al. [50], in the comprehensive policy review report, highlighted the importance of the combination of policy implementations and technological improvement to reduce GHG emissions from the transportation sector in a cost-effective way. The report recommends four paths to cut the emission dramatically by 2050: (1) vehicle efficiency improvement, (2) shift of fuel type to less carbon-intensive fuels, (3) travel behavior change, and (4) vehicle operation in more efficient ways. The findings in this study support these four paths to achieve the ambitious GHG emission reduction goal. First, the estimated policy effects of CARB's tailpipe emission standard reduced CO_2 emission through improved vehicle efficiency. It will also promote the fuel type shift to cleaner fuels through the increased production of ZEV from 2018 to 2025. Second, the estimated effect of fuel mix shift in the model of this study demonstrated the viability and importance of shift to cleaner alternative fuel types. Thirdly, the price variable in the model of this study might induce the behavioral changes of travelers by increasing gasoline price; however, the impact is limited in that changing human behavior on the demand side is much harder than controlling the emission through supply-side oriented policies.

A stricter emission standard effectively reduces CO_2 emission through the expanded supply of clean and more fuel-efficient vehicles from automakers that will stimulate the substitution effects in fuel mix towards clean fuels. On the demand side, increased gasoline price will discourage the demand for gasoline and stimulate the substitution effects when effectively combined with policies that increase the supply of more affordable clean vehicles. It will also boost the clean fuel consumption in the transportation sector. Consequently, all three policy approaches tested in this study should be packaged together to reach the CO_2 emission reduction goals in the U.S. It is highly recommended to continue the collaborative efforts among various stakeholders in order to achieve the CO_2 reduction goal set by CARB and adopted by EPA in 2012. The packaged policy ought to have higher adaptability and be rooted by the consistent public and political support, as suggested by Greene et al. [51].

Like many other studies, this study is not without limitations. More direct measures for policy variables can greatly improve the study. If it is possible to obtain the comparable tax amount on gasoline prices across all states over the study period, it will help to directly measure the effect of a state-level fuel tax policy. Additionally, the development of a variable quantifying the various state-level emission goals will enable us to estimate the diverse effects of various policy instruments using the panel data model. For the future direction of this study, it will be interesting to compare the estimated effects of policy measures in spatial panel regression with the estimation results of this study.

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Appendix A

Table A1. Unit Root Tests.

	LLC test		**IPS test**		**Breitung test**	
	level	**diff**	**level**	**diff**	**level**	**diff**
$\ln CO_2$	−1.9362 (0.0264)	−16.5443 (0.0000)	−7.1020 (0.0000)	−22.0728 (0.0000)	−2.7010 (0.0035)	−16.9693 (0.0000)
lnTE	−1.9226 (0.0273)	−16.4190 (0.0000)	−7.1037 (0.0000)	−22.1374 (0.0000)	−3.1316 (0.0009)	−17.6763 (0.0000)
lnPOP	−6.6587 (0.0000)	−26.2758 (0.0000)	−14.6148 (0.0000)	−23.6897 (0.0000)	−10.7175 (0.0000)	−27.7324 (0.0000)
lnGDP	−5.1950 (0.0000)	−22.6053 (0.0000)	−11.0513 (0.0000)	−22.5126 (0.0000)	−9.7864 (0.0000)	−24.6246 (0.0000)
lnEI	−2.5752 (0.0050)	−16.3896 (0.0000)	−7.4788 (0.0000)	−21.6953 (0.0000)	−4.4320 (0.0000)	−19.2075 (0.0000)
lnVMT	−4.6269 (0.0000)	−12.5511 (0.0000)	−5.2972 (0.0000)	−19.9103 (0.0000)	−0.0387 (0.4846)	−12.7476 (0.0000)
lnGP	−4.2073 (0.0000)	−15.9084 (0.0000)	−9.0100 (0.0000)	−21.9644 (0.0000)	−4.4244 (0.0000)	−13.0885 (0.0000)
lnMIX	−1.4813 (0.0693)	−18.5941 (0.0000)	−9.4136 (0.0000)	−22.5668 (0.0000)	−4.0984 (0.0000)	−17.7120 (0.0000)
RES	8.3330 (1.0000)	−9.4341 (0.0000)	1.0651 (0.8566)	−18.4643 (0.0000)	4.5551 (1.0000)	−19.1487 (0.0000)

Note: *p*-values in the parenthesis. LLC test. H_0: Panels contain unit roots. H_a: Panels are stationary. IPS test. H_0: All panels contain unit roots. H_a: Some panels are stationary. Breitung test. H_0: Panels contain unit roots. H_a: Panels are stationary.

Table A2. Cointegration Tests.

$\ln CO_2$			**lnTE**		
Cointegration Test	**Statistics**		**Cointegration Test**	**Statistics**	
Panel-v	−3.243	***	Panel-v	−3.368	***
Panel-rho	4.599	***	Panel-rho	4.587	***
Panel-pp	−9.822	***	Panel-pp	−9.856	***
Panel-ADF	−5.416	***	Panel-ADF	−6.635	***
Group-rho	6.755	***	Group-rho	6.690	***
Group-PP	−11.54	***	Group-PP	−11.43	***
Group-ADF	−4.902	***	Group-ADF	−6.278	***

Note: All test statistics are distributed N(0,1), under a null of no cointegration, and diverge to negative infinity (save for panel v). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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