Motor Vehicle CO₂ Emissions in the United States: Potential Behavioral Feedback and Global Warming[✉]

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ABSTRACT

The previously found correlation of average annual temperature and motor vehicle travel among U.S. states suggests amplifying feedback of increased carbon dioxide (CO₂) emissions and warming. This study employed a regression model relating average annual temperature to motor vehicle CO₂ emissions among the 48 contiguous states, controlling for other factors that affect travel. Increased emissions were associated with higher temperatures during 2000–14. Application of the model to 2015–16 data indicated that 27 million metric tons of CO₂ emissions in 2015 and 38 million metric tons in 2016 would have not occurred if the average annual temperatures among U.S. states in those years had remained at 2014 levels. A 2018 proposal by the U.S. government to reduce future vehicle fuel economy standards ignored the potential effect of warming on vehicle travel and contained erroneous analyses of the relation of vehicle weight to fatality risk, vehicle scrappage rate to new vehicle sales, and the relation of new vehicle costs to fuel economy. Huge improvement in fuel economy and reduced CO₂ emissions based on required hybrid technology are possible at reasonable cost.

1. Introduction

In its scientific meaning, feedback refers to processes in which an input to a system of variables is influenced subsequently by the variables that the input affects. Feedback is called “positive” when the net effect on the input variable is to increase it, resulting in accelerated growth of input as well as the other variables in the feedback loop. If one or more of the variables in the system is a finite resource or destroys other resources, the system is not sustainable and, without intervention, it will collapse (Barlas 2009).

Climate scientists have studied the role of such amplifying feedback on global warming in analyses of water vapor (Dessler 2013), the albedo effect (Ingram et al. 1989), and melting tundra (Schuur et al. 2009). Warming increases evaporation and thus more water vapor in the atmosphere that further retains heat in a feedback cycle.

The albedo effect occurs when warmth melts surface snow and ice that reflects heat. The resulting darker land and ocean surfaces absorb heat, further warming the atmosphere and melting more snow and ice. Arctic tundra contains huge amounts of carbon dioxide (CO₂) and methane (CH₄) that, when the tundra melts, escape into the atmosphere, trapping more heat that melts more tundra. Biological processes such as tree-killing beetle infestations manifest enhanced warming feedback as well (Kurz et al. 2008). The beetles denude the trees, reducing CO₂ uptake and reducing resistance to more beetle infestation.

Since the industrial revolution, the increased warmth that initiated these feedbacks is mainly generated by CO₂ and CH₄ emissions from human combustion of fossil fuels (Cook et al. 2016). Human behavioral responses to warming may also be part of an amplifying feedback effect on warming. For example, increased use of air conditioning powered by fossil fuels increases warming that leads to more use of air conditioning (Lundgren and Kjellstrom 2013).

Research on motor vehicle emissions has largely ignored the potential for more vehicle use and accompanying CO₂ emissions in response to warming. Comparison of travel per vehicle among the 48 contiguous U.S. states indicates that each 1°C average annual temperature increase is correlated to about 300 additional kilometers driven per

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vehicle per year (Robertson 2018a). The 2015–16 reversal of the downward trend in road deaths per population was associated with the increase in road use related to a substantial increase in temperatures in specific U.S. states in those years (Robertson 2018b). Apparently, colder temperatures inhibit discretionary driving. Also, some people let their vehicle engines run while the interior warms in winter or cools in summer before driving. Underinflation of tires results in reduced fuel economy (Waddell 2017), and people fail to adjust tire pressures that decrease in colder temperatures. That would result in more emissions in winter but apparently does not offset the effect of more miles driven when temperatures are warmer. One study of tire pressure in vehicles being serviced indicates that checking tire pressure more frequently would reduce emissions, but the temperatures at the time that the pressures were measured was not mentioned in the report (Pearce and Hanlon 2007).

The purpose of this paper is to report analyses of the potential for amplifying feedback in the use of fossil fuels to power transportation in the United States and of a proposal by the U.S. government to partially retreat from the standard for reduced fuel consumption that would reduce CO₂ emissions. To conserve fuel because of dependence on oil extracted in other countries, in the late 1970s the United States adopted Corporate Average Fuel Economy (CAFE) standards that required each corporation selling passenger cars and light trucks in the United States to achieve improved average fuel economy among its products or pay fines for noncompliance. Although the makers of some luxury vehicles chose to pay fines rather than meet the standards, the standards gradually increased fuel economy (National Highway Traffic Safety Administration 2011). To address concern about global warming related to vehicle emissions of CO₂, in 2009 an agreement was reached among the U.S. federal government, state regulators, and manufacturers of 90% of the vehicles sold in the United States to increment CAFE fuel economy requirements at a faster pace through 2025 (Union of Concerned Scientists 2018). In 2018, a new administration that is antiregulation proposed to roll back parts of the agreement. The proposal's authors argued that increased cost of more fuel efficient vehicles would retard the scrappage of older, less safe vehicles and that fuel efficient vehicles reduce affordability of new, safer vehicles (NHTSA and EPA 2018). The proposal said that manufacturers faced with fuel economy standards for new vehicles may choose to reduce vehicle weight, leading to an increase in fatalities. Actually, peer-reviewed research indicates that increases in higher-weight vehicles on U.S. roads produced more road deaths

than would have been expected without them (Anderson and Auffhammer 2014; Paulozzi 2005; White 2004). Occupants of heavier vehicles have reduced risk, but that is more than offset by increased risk to other road users. Yale University researchers recently concluded that CAFE standards had a net reducing effect on road deaths (Bento et al. 2017). Greene (2018) reviewed the literature on vehicle scrappage and the government's models. He found that they were “fraught with serious statistical problems that include misspecification, multicollinearity and overfitting.” The average life of passenger cars in the United States increased from 12.2 years in 1969 to 15.6 years in the 2000s. The life of trucks increased from 16.9 to 18.2 years. These changes rendered old statistical models of scrappage obsolete (Bento et al. 2018). Most people who drive old vehicles until they are scrapped are unlikely to be able to afford the purchase of a new vehicle.

2. Materials and methods

This study focuses on variation in CO₂ emissions among U.S. states as indicated by amount and type of fuel consumed. The large variation among U.S. states in factors that are hypothesized or known to affect motor vehicle use—temperature, precipitation, unemployment, median age of the population, insurance costs, fuel prices, registered vehicles, and kilometers traveled per liter of fuel in the extant fleet—provides the opportunity to estimate the correlation of these factors with CO₂ emissions. A least squares regression model was used to estimate the effect of differences in the hypothesized predictive factors on CO₂ emissions among the 48 contiguous U.S. states during the years 2000–14. Alaska and Hawaii were excluded because the data on temperatures in those states were not available. Weather stations are concentrated in more highly populated areas (National Oceanic and Atmospheric Administration 2017b). The regression model was then used to predict what CO₂ emissions would have been during 2015–16 in each state if each of the factors had remained at 2014 values while the others changed. The estimates for the states were then summed to gauge the difference in the national emissions associated with changes in the predictor variables when temperatures increased substantially in 2015 and 2016.

The regression model is

$$\begin{aligned} \log(\text{million metric tons of CO}_2 \text{ emitted from motor} \\ \text{vehicle use}) = & \text{intercept} + \\ & b1 \times [\text{logarithm of average annual temperature (}^\circ\text{C)}] + \\ & b2 \times (\text{logarithm of annual precipitation}) + \\ & b3 \times (\text{logarithm of percent unemployment}) + \end{aligned}$$

$b4 \times (\text{logarithm of average liability insurance expenditures per } \$10,000 \text{ median average annual income}) +$
 $b5 \times (\text{logarithm of average gasoline price per } \$10,000 \text{ median average annual income}) +$
 $b6 \times (\text{logarithm of registered vehicles}) +$
 $b7 \times (\text{logarithm of median age of the population}) +$
 $b8 \times (\text{logarithm of average kilometers driven in the state per liter of fuel consumed}).$

The values of the variables were converted to logarithms because their distributions are skewed and because the results can be stated as percent changes in emissions relative to percent changes in a given predictor. The number of observations in the regression was 720 (48 states times 15 years, 2000–14).

The number of barrels of gasoline and diesel fuel used in transportation for each of the 48 contiguous U.S. states during the years 2000–16 ([U.S. Energy Information Administration 2018b](#)) was converted to millions of metric tons of CO₂ emissions in a given state based on 159 liters of fuel per barrel, 2.35 kilograms of CO₂ emissions per liter of gasoline, and 2.68 kilograms of CO₂ emissions per liter of diesel fuel. The average annual temperature (°C) and centimeters of precipitation for each included state in each year were respectively calculated from average monthly temperatures and precipitation in each state and year ([National Oceanic and Atmospheric Administration 2017a](#)). The weather and other data sources include different codes for states, so they were matched by a computer routine. The annual state unemployment rates were copied from a compilation by the [Rhode Island Department of Labor and Training \(2017\)](#) using U.S. Department of Labor Statistics. Median age of the population in each state per year was obtained from the U.S. Census Bureau's American Community Survey ([U.S. Census Bureau 2017](#); [ProximityOne 2017](#)). Median annual income per household was obtained from the [Federal Reserve Bank of St. Louis \(2018b\)](#). Average insurance expenditures for liability coverage by state and year were obtained from data compiled by the National Association of Insurance Commissioners available from the [Insurance Information Institute \(2018\)](#). Number of kilometers driven and vehicles registered in each state per year were calculated from data in the U.S. Department of Transportation's annual Highway Statistics ([Federal Highway Administration 2019](#)). Differences in retail fuel prices among the states by year were derived from energy cost data in U.S. states ([U.S. Energy Information Administration 2018a](#)).

To examine the U.S. government's claims regarding vehicle scrappage and affordability, the percentages of vehicles scrapped per year were examined in relation to

TABLE 1. Percent change in million metric tons of CO₂ emissions per year per state in relation to percent change in predictor variables for the 48 contiguous U.S. states for 2000–14. Here, CI is confidence interval.

	Coeff	Lower 95% CI	Upper 95% CI
Temperature	0.162	0.125	0.199
Vehicles (millions)	0.927	0.913	0.941
Median age (yr)	−0.565	−0.626	−0.524
KPL	−0.679	−0.803	−0.591
Insurance/\$10,000 income	−0.091	−0.152	−0.030
Intercept	−8.246	—	—

vehicle sales and the manufacturer's suggested retail price was examined in relation to fuel efficiency ratings by the U.S. Environmental Protection Agency. New vehicle sales during each year, 2000–16, were obtained from the [Federal Reserve Bank of St. Louis \(2018a\)](#). The percent scrapped in a given year P is calculated by

$$P(2) = -100 \frac{[R(2) - S(2) - R(1)]}{R(1)},$$

where R is total registered vehicles in consecutive years 1 and 2 and $S(2)$ is new vehicle sales in the second of each pair of years. The manufacturer's suggested retail price of 2018 model year, including 296 automobiles, pickup trucks, vans, sport utility vehicles, and crossover vehicles, were obtained from [J.D. Power \(2018\)](#). The combined urban–rural fuel efficiency rating of these vehicles was obtained from the fuel economy guide published by the [U.S. Department of Energy \(2018\)](#).

The data (in logarithmic form) used to develop the regressions are available in the online supplemental material and from the author.

3. Results

The initial regression estimates indicated that the 95% confidence intervals for precipitation, unemployment, and retail fuel prices per \$10,000 of median family income overlapped zero, so regression coefficients were re-estimated without these variables. The regression coefficients and 95% confidence intervals of the remaining predictor variables are presented in [Table 1](#). Corrected for number of vehicles in a state in a given year and the effects of other factors, each percent increase in temperature (°C) is associated with an additional 0.162% increase in CO₂ emitted per year per state. A 1% increase in total vehicles registered is associated with a 0.927% increase in emissions. States with older median-aged populations had fewer emissions: −0.565% per 1% increase in median age (older).

TABLE 2. Predicted millions of metric tons of CO₂ emissions in 2015–16 if each predictive factor did not change from 2014 as compared with expected emissions in 2015–16 for the 48 contiguous U.S. states.

Predictor	2015			2016		
	Predicted if no change	Diff from expected	Percent diff	Predicted if no change	Diff from expected	Percent diff
Temperature	1649	27	1.6	1672	38	2.2
Vehicles	1656	20	1.2	1659	51	3.0
Median age	1676	0	0.0	1709	0	0.0
KPL	1693	−17	−1.0	1743	−33	−1.9
Insurance/\$10,000 income	1679	−3	−0.2	1705	5	0.3

Some 0.697% of emissions per year were prevented for each increase in a percent of fuel economy per state. A percent increase in liability insurance expenditure per \$10,000 of median income was associated with a reduction of 0.091% reduction in emissions. The fit of the data to the model was excellent (coefficient of variation $R^2 = 0.968$). When the correlations among predictor variables were examined for collinearity it was found to be low and not likely to distort the regression coefficients (Stewart 1987). The maximum found was $R^2 = 0.24$ between temperature and insurance costs per income, the latter higher in warmer areas, which is consistent with their higher death rates.

The predicted emissions nationally during 2015 and 2016 and the percent difference from those expected if the variables had not changed from 2014 are shown in Table 2. The average temperature among the 48 states was 10.61°C in 2014, 11.7°C in 2015, and 12.17°C in 2016. If the temperatures had remained at the 2014 average, some 27 000 000 tons of CO₂ emissions would have been avoided in 2015 and 38 000 000 tons in 2016. Aging of the population had little effect in 2015 or 2016. Increased fuel economy reduced emission by 17 000 000 tons in 2015 and 33 000 000 tons in 2016. Fluctuating insurance costs were associated with a reduction of 3 000 000 tons in 2015 and an increase of 5 000 000 tons in 2016.

The percent of vehicles scrapped in relation to the numbers of new vehicles sold per year is displayed in Fig. 1. There is no significant correlation between vehicle sales and the percent scrapped. The lowest scrappage (3.4%) occurred in 2001 when annual vehicle sales were near a high point, and the large drop in vehicle sales during the “Great Recession” that began in 2008 did not reduce the percent of vehicles scrapped.

Figure 2 depicts EPA composite rated fuel economy converted to kilometers per liter (KPL) in relation to manufacturers’ suggested retail prices for 296 new makes and models in 2018 among vehicles that had data available on both variables. The average price of \$36,000 indicated in the government proposal is skewed by high-priced sports cars and luxury

vehicles. The median price is \$33,400. The majority of vehicles with the highest fuel economy are among the lower-priced vehicles but not the lowest. One-half of the 14 vehicles rated at 30 KPL or better were priced below the median.

4. Discussion

As predicted from the correlation of temperature and travel per vehicle in previous research, increases in temperature are related to increased CO₂ emissions. This suggests that a feedback of warming and vehicle use is occurring. The effect of increased fuel economy was more than offset by the temperature increases in 2015 and 2016, and increased numbers of registered vehicles further contributed to increased emissions. The effect of aging of the population was nil and the effect of cost of insurance reversed in 2016 as insurance rates declined. The aging of the U.S. population is substantially a result of the post–World War II bulge in births of people who are now entering their retirement years. When most of them will have died in 30 years or so, the effect of aging on emissions will likely diminish. Insurance costs are based on injury and vehicle damage that may be reduced by wider adoption of vehicles with increased crash avoidance technology. The most reliable way to reduce emissions is to improve fuel economy.

The U.S. government’s 2018 proposal to modify previously agreed upon efforts to increase fuel economy

FIG. 1. Percent of vehicles scrapped in relation to new vehicle sales.

FIG. 2. Fuel economy rating in relation to manufacturer's suggested retail price for 2018 models.

ignored the research on increased vehicle use and fatalities in relation to temperature. It included erroneous assumptions regarding the effect of vehicle weight on fatalities, vehicle scrappage, and affordability of highly fuel efficient vehicles. As indicated in Fig. 1, the percent scrapped is unrelated to the sales of new vehicles. Vehicles are scrapped because their remaining usefulness is not worth the cost of repairing or maintaining them (except for “antique” vehicles maintained by restoration enthusiasts), and it has no apparent effect on sales of new vehicles, which most people replacing old vehicles probably cannot afford.

As indicated in Fig. 2, the availability of hybrid gasoline–electric and all-electric engines provides a huge leap in fuel economy at prices comparable to lower-than-average-priced vehicles. While the cost of the fuel saving technology adds to the initial cost of vehicles of the same make and model, that cost is partially offset by the lower operating cost due to fuel economy and would likely decrease because of economies of scale when larger numbers are produced. As more hybrid and electric powered vehicles become available in the used vehicle markets, they become affordable for more people.

The most astonishing government document supposedly in support of the reduced requirements for fuel efficiency states that a rise in average worldwide temperatures of about 4°C by the year 2100 is virtually inevitable and that the proposed change in fuel standards would have little effect on that inevitability (National Highway Traffic Safety Administration 2018). Most climate scientists agree that warming may occur to that extent if there is no mitigation but that such a view is short sighted. The effects of emissions occurring now will last far longer than the end of the twenty-first century. Without mitigation, the effects are cumulative and eventually catastrophic, especially so for populations concentrated on ocean and river shorelines (Clark et al. 2016). Assuming that disaster is inevitable is a self-fulfilling prophecy.

The extent of the correlation of vehicle use and temperature is unknown for vehicles in countries outside the United States. Vehicles in use are expanding rapidly worldwide. There are more than a billion vehicles in use and as many as 2 billion or more are projected by 2040. Even without a feedback effect, the CO₂ emissions from such growth will hasten warming beyond most expectations (Sperling and Gordon 2009).

To meet new challenges, governments often tweak old policies rather than review all of the available options. Rather than modify CAFE standards from the 1970s, a far more effective policy for governments worldwide would be to require all new vehicles to employ hybrid technology with the exception of all-electric vehicles in areas where electricity is generated primarily by sustainable methods (Harvey 2018). Economists prefer economic incentives or increased taxes on carbon emissions to reduce their harmful effects (e.g., Anderson et al. 2011), but the lack of correlation of fuel prices/income with emissions when controlling statistically for other factors suggests that the taxes would have to be a lot higher than those prevalent in the United States during the early twenty-first century to have any meaningful effect.

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