Project Title	**Welfare Effects of Future Medium and Heavy-Duty Vehicle Tailpipe Nitrogen Oxides Emissions Standards**
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Conflict of interest statement	The principal investigator and other project members have no conflicts of interest to declare.

Proposal Summary

The Environmental Protection Agency recently finalized standards for tailpipe emissions of nitrogen oxides (NOx) emitted by medium and heavy-duty trucks. Using newly available truck survey data, we will estimate how economic activity and other factors determine truck utilization by age, region, and category of truck. We will use these estimates to forecast future truck utilization and estimate emissions reductions of the NOx standards, as well as uncertainty of those emissions reductions. The Department of Transportation sets many regulations for trucks, such as safety and fuel consumption standards, and the benefits and costs of these regulations depend on truck utilization. The modeling for this project can help the Department of Transportation improve estimates of future truck utilization and the welfare effects of its regulations. The data and econometric analysis rely partly on the recently resumed Vehicle Inventory and Use Survey, and the project can also help the agency assess the quality of the survey data.

Research Question

Emissions of NOx from medium and heavy-duty trucks contribute significantly to ground-level ozone and fine particulates, and the Environmental Protection Agency (EPA) has been regulating NOx emissions for decades. In 1985, EPA set NOx standards and tightened them again several times over the coming decades. These standards have reduced NOx emissions dramatically. Then, in 2022, EPA finalized new NOx emission standards for heavy-duty trucks that reduce average emissions rates by roughly three-fourths. The agency claims these standards will reduce NOx emissions from the heavy-duty truck fleet by 48 percent in 2045 and result in widespread air quality improvements across the US. Millions of US residents, particularly lower-income and other disadvantaged groups, live in areas that exceed air quality standards. The agency expects the regulations to improve air quality and health outcomes, and it anticipates annual benefits, net of costs, of up to $29 billion in 2045 (EPA 2023).

The standards are a form of vintage-differentiated regulation, as they apply only to trucks when they are first produced and exempt older trucks. As such, emissions reductions from tightening the standards depend on how much newer trucks, which are subject to the new standards, are driven relative to older trucks, which are not. Because the standards affect up-front purchase and operating costs, the stricter standards can also increase utilization of older trucks, as truck owners may delay purchasing new vehicles to replace the older ones (Gruenspecht, 1982; Jacobsen and van Benthem, 2015; Rittenhouse and Zaragoza-Watkins, 2018).

When EPA finalized the standards, the agency had to justify their stringency by demonstrating that their benefits are likely to exceed the costs and by characterizing uncertainty of those estimates. Such ex-ante analysis is challenging because emissions reductions depend on how trucks are utilized, creating the need to predict aggregate miles traveled; and, because of the vintage-differentiated regulation, it is also necessary to predict how aggregate miles traveled will be allocated across different vintages of trucks. Historically, truck activity is closely connected to overall economic activity (that is, Gross Domestic Product) as well as manufacturing activity. Predicting these determinants of truck activity far into the future is quite difficult. For example, in 2003, the Energy Information Administration projected GDP and manufacturing activity for 2022 that were 20 and 55 percent higher than actual 2022 levels. Projected miles traveled were about 10 percent higher than actual 2022 levels.

Unfortunately, when the agency analyzed the 2022 standards, it had to rely partly on data from the 1990s to forecast miles traveled. The Census Bureau and Department of Transportation collected survey data on medium and heavy-duty trucks in 1963 and every 5 years starting in 1967, but data collection ended in 2002. The hiatus made it impossible to update projections of truck utilization by age, and researchers had to develop workarounds using aggregated data from other sources, such as fuel consumption estimates from the Federal Highway Administration. However, the agencies recently resumed the survey, and data from the 2021 survey were just recently made public. These data are available now, but they were not available when the agency predicted the emissions benefits of the 2022 standards. The new data make it possible to update forecasted truck activity and emissions reductions and to quantify which regions and demographic groups will experience the largest pollution reductions and air quality improvements.

The project will use the newly available data to improve forecasts of the 2022 standards on emissions reductions and to quantify uncertainty around those reductions. We will combine the new survey data with historical survey data back to 1992. The nearly thirty-year period of analysis includes extensive variation in economic activity, fuel costs, and truck utilization and technology, such as the 2008-2009 economic recession, periods of low and high diesel fuel prices, and the growth of online shopping for consumer goods.

The proposed project builds on an extensive two-year data collection and modeling effort funded by the Alfred P. Sloan Foundation. In the proposed project, we will model a truck's vehicle miles traveled as function of its per-mile fuel costs, long-distance shipping demand, and local shipping demand (including online shopping). Model parameters will vary with truck age and other truck attributes. We will estimate the parameters using data collected in our prior work.

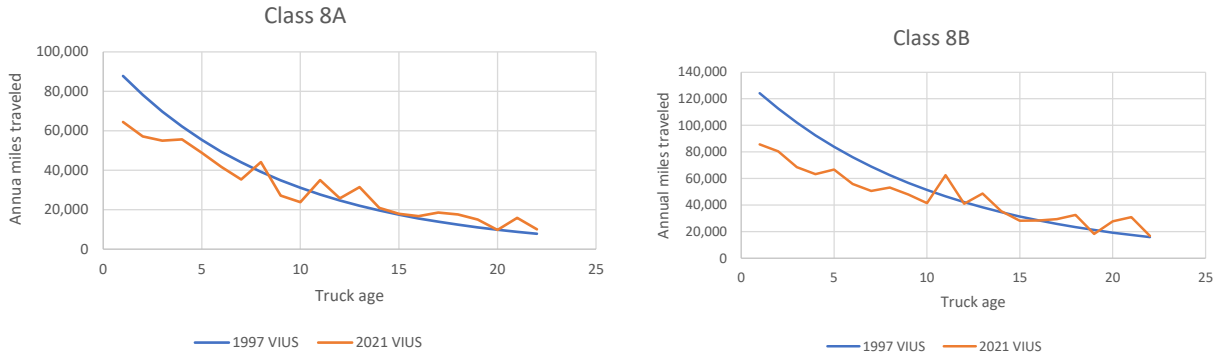
Having estimated the model, we will predict future miles traveled and emissions by age and truck type and region, with and without the tighter standards. We can also characterize the uncertainty of the predictions based on uncertainty over determinants of miles traveled and parameter estimates. The proposed analysis improves on the EPA forecasts and economics literature in four ways by: 1) updating forecasts using the newly available data; 2) incorporating the effects of the regulations themselves on operating costs and truck utilization (EPA assumes the regulations do not affect utilization); 3) quantifying local emissions reductions and correlating those improvements with demographics; and 4) quantifying uncertainty in future emissions reductions.

Data

We have completed nearly all the data assembly for this project. The main data source will be the Vehicle Inventory and Use Survey from 1992, 1997, 2002, and 2021. These data are collected for thousands of individual trucks and allow us to characterize the makeup of the on-road stock of trucks, including their fuel economy, miles traveled, vehicle type (e.g., local delivery truck), and major use (e.g., long-distance transport of refrigerated goods).

An initial look at the 2021 data indicates the importance of using the new data to predict future miles traveled by truck age. The two figures below show average miles traveled by truck age for trucks with weight ratings above 33,000 pounds. Class 8a trucks have weight ratings of 33,000-60,000 pounds, and class 8b trucks have weight ratings above 60,000 pounds; the latter are primarily used for long-distance shipping. The 1997 numbers are fitted values using a polynomial approximation, whereas the 2021 numbers are the averages for each age rather than fitted values. For both weight groups, there has been a pronounced shift in utilization: compared to 1997, in

2021, trucks tend to be used less at young ages and more at older ages. Because of the vintage-differentiated regulation, this shift reduces the emissions benefits of the standards, as older trucks that are subject to weaker emissions standards account for a larger share of miles traveled than they used to.



A second data source is the Commodity Flow Survey, which was administered in 1993 and every five years from 1997-2022. We use the data to estimate demand for shipping across geographic regions. We also utilize the Consumer Expenditure Survey, which provides estimates of household expenditures on online shopping; we estimate demand for local deliveries associated with online shopping with these data.

We have obtained EPA's engine certification data to estimate the NOx emission rates of trucks when they are first produced. We use emissions rates for trucks manufactured after 1998. Unfortunately, we are not aware of comprehensive estimates of on-road NOx emissions from trucks, and we use the EPA tested emissions and degradation rates to impute a truck's emissions rates as it accumulates miles over its lifetime.

We also use data on state-level truck registrations from 2002-2022 from IHS Markit. The data include registrations of new and older trucks, and they allow us to examine the entry and exit of trucks over time, estimate scrappage rates, and characterize the age distribution of trucks on the road.

Finally, we will obtain the EPA's assumptions about emissions per ton-mile, truck utilization, scrappage rates, technology cost, and market evolution from the agency's 2022 benefit-cost analysis.

Methods

Model and Estimation

The methodology builds on Leard et al. (2015) using new data and more precise shipping demand variables. A market skt is defined by state (s), body type and weight class (k), and year (t). The model determines truck utilization conditional on the number of trucks in operation, the attributes of those trucks, and demand for trucking services. The trucking services market is defined by weight class and body type, state, and year. Within a market, we assume that each truck's shipment is homogeneous, and that each shipment has an exogenous number of ton-miles associated with it; the equilibrium ton-miles of shipments is thus proportional to the number of shipments.

Each market contains many trucks that are differentiated by multiple characteristics. On the supply side, fleet owners take shipping prices as exogenous and compete to transport shipments.

The supply of vehicle ton-miles travelled (VTMT) by a specific truck (j) for a particular market depends on factors affecting the per-mile cost of making the shipment. Cost factors include fuel and operator costs per ton-mile (cpm_{jskt}), maintenance expenses (influenced by the truck's physical attributes like age, mileage, axle configuration, cab and trailer types), and state-specific costs. This supply function is represented as

$$vtmt_{jskt} = S(cpm_{jskt}, y^{S}_{jskt})$$

where y^{S}_{jskt} includes supply-side factors that affect the truck's VTMT supply.

On the demand side, the VTMT of truck j in year t depends on factors that affect the willingness to pay for ton-miles, such as the regional economic activity (measured by Gross State Product or shipments originating in the state in year t). Because shipments in a market are homogeneous, each truck's VTMT depends on equilibrium shipments and the total number of trucks in operation in the market (Q_{skt}). The demand function is denoted as

$$vtmt_{jskt} = D(GSP_{st}, y^{D}_{jskt}, Q_{skt})$$

where y^{D}_{jskt} includes demand-side factors besides GSP and the number of trucks in the market.

In equilibrium, the per-truck VTMT adjusts until per-truck VTMT demand equals supply.

$$vtmt^{*}_{jskt} = S\left(cpm_{jskt}, y^{S}_{jskt}\right) = D(GSP_{st}, y^{D}_{jskt}, Q_{skt})$$

These two equalities indicate a reduced-form relationship that defines VTMT as a function of the variables that appear in the supply function as well as the variables that appear in the demand function. We assume that the function defining equilibrium per-truck VTMT takes the form:

$$vtmt_{jskt} = (cpm_{jskt})\beta GSP_{st} \exp\left(\alpha + \theta y^{S}_{jskt} + \rho y^{D}_{jskt} + \delta Q_{skt} + \epsilon_{jskt}\right) \quad (1)$$

Equation (1) links each truck's equilibrium VTMT with demand and supply-side variables. To estimate parameters in equation (1), we regress equilibrium VTMT on demand and supply side variables:

$$\ln\left(vtmt_{jskt}\right) = \gamma_a ln\left(cpm_{jskt}\right) + \beta_a \ln(GSP_{st}) + \theta y^{S}_{jskt} + \rho y^{D}_{jskt} + \delta Q_{skt} + \epsilon_{jskt} \quad (2)$$

The a subscripts on the parameters indicate that we allow the parameters to vary by truck age. We compute fuel costs as the weighted average of the price in the truck's home state and other states, divided by the truck's average shipment weight and fuel economy, where the weights are the share of miles the truck drives within its home state.

The fuel cost variable may be endogenous because the weights used to construct the fuel price and average truck weight may respond to fuel prices and because the truck's fuel economy may be correlated with unobserved truck attributes that affect the costs of providing truck services (such as reliability or maintenance costs). To address the potential endogeneity, cost per ton-mile is instrumented by averaging fuel prices and weights across trucks belonging to the same category. Other demand and supply side variables include the truck's odometer reading, age fixed effects, indicators for whether the truck was purchased or disposed during the survey year, estimated shipments originating in the truck's home state from the Commodity Flow Survey, estimated expenditure on online shopping in the truck's home state from the Consumer

Expenditure Survey, and fixed effects for operator-class, body type, cab type, fleet size, axle configuration, number of engine cylinders, state, and survey year.

Forecasting Emissions

We forecast emissions and quantify forecast uncertainty in three steps. First, using the IHS registrations and estimated scrappage rates, we predict counts of trucks by state and weight class for future years. This step is similar to the methodology EPA uses to predict emissions reductions from the standards.

Second, we use forecasts of GSP and extrapolate trends in shipments and online shopping to predict ton-miles traveled for each truck according to equation (2). Using the average weight by truck age reported in the Vehicle Inventory and Use Survey, we convert vehicle ton-miles traveled to vehicle miles traveled, since the emissions standards are denominated in grams per mile rather than per ton-mile. Combining these predictions with the truck counts from the first step allows us to estimate miles traveled by truck category and age.

Third, we estimate the emissions reductions caused by the standards by computing total emissions in two scenarios: a) recently adopted standards and b) if the prior standards continue unchanged into the future (that is, the same baseline scenario the EPA uses). We disaggregate the emissions reductions by region (for example, Census division or state, depending on data quality), and we report correlations among the emissions reductions and household demographics. This allows us to quantify how NOx regulations affect environmental justice outcomes. Finally, we conduct a Monte Carlo analysis that incorporates uncertainty in future GSP, shipments, online shopping, and parameter estimates. The uncertainty would be estimated based on a forecast model that we estimate for these determinants of miles traveled.

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