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Health and economic consequences of applying the United States' $PM_{2.5}$ automobile emission standards to other nations: a case study of France and Italy

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ABSTRACT

Objectives: The US has among the world's strictest automobile emission standards, but it is now loosening them. It is unclear where a nation should draw the line between the associated cost burden imposed by regulations and the broader societal benefits associated with having cleaner air. Our study examines the health benefits and cost-effectiveness of introducing stricter vehicle emission standards in France and Italy.
Study design: Quasi-experimental study.
Methods: We used cost-effectiveness modeling to measure the incremental quality-adjusted life years (QALYs) and cost (Euros) of adopting more stringent US vehicle emission standards for $PM_{2.5}$ in France and Italy.
Results: Adopting Obama era US vehicle emission standards would likely save money and lives for both the French and Italian populations. In France, adopting US emission standards would save €1000 and increase QALYs by 0.04 per capita. In Italy, the stricter standards would save €3000 and increase QALYs by 0.31. The results remain robust in both the sensitivity analysis and probabilistic Monte Carlo simulation model.
Conclusions: Adopting more stringent emission standards in France and Italy would save money and lives.

Introduction

Air pollution remains the primary environmental source of premature mortality in the European Union (EU), causing about 400,000 deaths per year.[1] Transportation is responsible for roughly half of all airborne pollutants in the EU. Regulations on transportation have led to notable improvements in air quality in the region between 1990 and 2015.[1] Nevertheless, the United States (US) is relaxing vehicle emission standards. The impact of incremental increases or decreases in vehicle emission standards on population health is roughly known, but less is known about the trade-offs associated with such changes on macroeconomic well-being relative to health and health system costs.

This article explores the trade-off between more stringent vehicle emission standards and regulatory costs. It does so by modeling the effect of applying more stringent standards to two case study countries. We use the relatively stringent Obama era standard for particulate matter $(PM)_{2.5}$ as a reference because there are data on the macroeconomic impacts of applying these regulations over time in the US. Similarly, a number of studies have been conducted on the relationship between vehicle emissions and air quality in France and Italy.

$PM_{2.5}$ refers to air particles that are 2.5 microns in diameter or less. Particles of this size can enter the circulatory system via the respiratory system, and thereby cause cardiovascular disease, lung cancer, and premature mortality.[2–8] While deaths associated with $PM_{2.5}$

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have declined between 1990 and 2015 in the US and the EU overall, they continue to increase in Italy, Greece, and Malta.[9] The estimated number of years of life lost (YLL) from $PM_{2.5}$ in 2014 was 852 per 100,000 inhabitants in the EU, 602 per 100,000 inhabitants in France, and 1024 per 100,000 inhabitants in Italy.[1] By contrast, YLLs in the US are small and limited mostly to the greater Los Angeles area.

Cars and trucks contribute to about half of the total $PM_{2.5}$ in the EU.[1] However, there is considerable variation in the relationship between automobile emissions and $PM_{2.5}$ by geographic region, with some global cities being impacted to a greater extent by factories and power plants.[10]

Current federal regulations for vehicle emission standards set in the US by the Environmental Protection Agency[11] are stricter than the EU's current Euro Six vehicle emission standards for all major pollutants, except for carbon dioxide.[1] For $PM_{2.5}$, the target annual exposure limit defined by the US Environmental Protection Agency (EPA) in 2012 is 12 $\mu g/m^3$.[12,13]

The World Health Organization (WHO) recommends that $PM_{2.5}$ not exceed 10 $\mu g/m^3$,[14] a stringent limit for which there are few case study nations. We chose the US as a comparator rather than the WHO recommendation because there are extant data and at 12 $\mu g/m^3$, it is very close to the WHO target. The 2008 EU legislation on ambient vehicle emission sets vehicle emission limits for the entire EU and requires member states to place restrictions on harmful air pollutants, including pollutants from on-road vehicles.[15–18] Under this directive, the EU member states are required to limit population exposure to $PM_{2.5}$ to an annual average of 25 $\mu g/m^3$ by 2015 and 20 $\mu g/m^3$ by 2020.[1,15–18] In 2017, 6%–7% of the EU urban population was exposed to $PM_{2.5}$ concentrations exceeding the EU limit and about 67% were exposed to levels exceeding the WHO target.[15]

Italy and France's $PM_{2.5}$ emission exposure patterns are roughly similar to the range of emissions for other European countries. According to the European Environmental Agency (EEA), the annual mean $PM_{2.5}$ emission in 2015 was 13 $\mu g/m^3$ in France and 19 $\mu g/m^3$ in Italy,[16] compared with an average of 13.9 $\mu g/m^3$ for all EU-28 countries.[16] While France and Italy fall below the current EU limit of 25 $\mu g/m^3$, they still exceed both the US's limit of 12 $\mu g/m^3$ and the WHO Air Quality Guidelines of 10 $\mu g/m^3$.[13,14,17] Some eastern EU nations such as Poland, Serbia, and Bulgaria have emission averages that are much higher than those in Italy.[16]

In our analysis, we estimated health impacts in terms of premature deaths and years of life lost due to $PM_{2.5}$ emission exposure.[1,18] We also estimated economic costs associated with morbidity related to road traffic pollution in the EU.[18,19] Using these inputs, we developed a cost-effectiveness analysis to model the effect of applying the stricter US vehicle emission standards and enforcement to France and Italy.

Methods

Using a Markov model, we simulated relevant health and economic consequences of reduced $PM_{2.5}$ emissions associated with two scenarios in France and Italy: (1) 'keep the standard as is and (2) 'adopt and enforce US emission standards.' We estimated quality-adjusted life years (QALYs), health system costs, regulatory costs, vehicle upgrade costs, and fuel savings.[13] All parameters were derived from the existing literature and are summarized in Table 1.

We ran our model over the course of the lifetime of our standard cohort and discounted future QALYs and costs at a discount rate of 3%.[20] Final estimates of incremental costs per QALY were made in constant 2018 €. We conducted multiple one-way sensitivity analyses to quantify the robustness of our estimates against broad changes in the core parameters and assumptions of the model. In addition, we performed a Monte Carlo simulation with 10,000 random samples to capture uncertainty in our model outcomes across all variables. We built our model in TreeAge Pro 2016 software.[21]

$PM_{2.5}$ emissions regulations: US vs. France and Italy

In our model, we explored the potential impact of stricter regulations in two European countries on health and costs. We limited the regulations to only light-duty vehicles, which are defined as passenger cars for everyday use[22,23] and account for more than 80% of registered vehicles in France and Italy.[24] We omitted light- and heavy-duty trucks from our analysis, including commercial trucks, because there are limited data on upgrading costs and fuel savings. Italy and France have a similar proportion of heavy vehicles on the road, extensive rail networks, and while Italy imports a good deal of energy from France, 80% of this power comes from nuclear power generation and hydropower.[25,26] This allows for a natural control between the two case study nations.

Demographic data

We measured the impact of stricter vehicle emission standards on all residents of France and all residents of Italy as separate arms of the model. In our Markov model, the average age, population size, and age-specific mortality rates for each country were retrieved from Eurostat statistics.[27] We also applied different regulatory standards in France, Italy, and the US to a uniform, hypothetical cohort. This allows us to provide estimates of the impacts of regulatory standards on health that are independent of sociodemographic differences between the three nations.

Cost-effectiveness model

Our Markov decision-analytic model had two arms: 'keep the standard as is' and 'adopt US emission standards.' Our hypothetical regulatory changes could reduce the risk of lung cancer, stroke, asthma, and overall mortality.[18,19] However, to ensure that our numbers are conservative, we focused on two major health effects of ambient $PM_{2.5}$: asthma and cardiovascular disease (CVD). Our model, therefore, assumes five health states: perfect health, chronic asthma, chronic CVD, comorbid asthma and CVD, and death. Excluding other pollutants also helps ensure that numbers are conservative on the benefits side of the cost-effectiveness analysis.

Our Markov model simulates the impact of reduced $PM_{2.5}$ levels on the risk of developing new asthma, chronic CVD, and comorbid asthma, and CVD. We also modeled the risk of acute exacerbations for people living with chronic asthma and the risk of acute CVD events such as stroke or myocardial infarction among people living with chronic CVD. We ran the model from 2018 until 2050 to evaluate the impact of the policy over the lifetime of each standardized cohort.

We then conducted a one-way sensitivity analysis using the confidence intervals reported in the literature to see how changing a given parameter would impact the incremental cost-effectiveness ratio.[28] Finally, we developed a Monte Carlo simulation for probabilistic sensitivity analysis using a normal probability distribution based on the reported standard errors from the literature.[28] We ran the simulation with a willingness to pay (WTP) threshold of €46,000, referring to the European survey on WTP for improved air quality in an economic study[29] to assess the robustness of our analysis.

Probabilities and rates

Model parameters for the incidence rates for asthma, CVD, exacerbations, and relapses were derived from the literature. The

Table 1
List of parameters used in the Markov Model.

Description	France		Italy		Probabilistic distribution[a]
	Base value	Standard error	Base value	Standard error	
General parameters					
Average age of target population[27]	41.4	–	45.9	–	–
Total number of target population[27]	66,989,083	–	60,589,445	–	–
Chronic asthma prevalence[33] (2010)	0.06	–	0.04	–	–
Chronic CVD prevalence[32,34,35]	0.054	–	0.045	–	–
Annual discounting rate[20]	0.03	–	0.03	–	–
Ambient PM2.5 base level (μg/m^3)	13.00	–	19.00	–	–
Ambient PM2.5 benchmark level (μg/m^3)[60]	7.65		7.65		
Number of gasoline passenger cars sold in year 2017[61,62]	777,645	–	599,752	–	–
Number of diesel passenger cars sold in year 2017[61,62]	1,089,403	–	1,061,004	–	–
Total passenger vehicles on road[61,62]	32,326,000	–	37,080,753	–	–
Costs (2018 Euros)					
Cost of acute asthma ED visit or hospitalization[41,63]	399	–	1225	–	γ
On-going cost of chronic asthma	1230	6076	1407	118	γ
Cost of acute CVD attack[37,40,63]	19,279	–	23,053	20,929	γ
On-going cost of chronic CVD[37,40,63]	9358	–	5282	8539	γ
One-time facility set-up cost[11]	1,077,089	–	8,616,711	–	γ
Unit cost per vehicle for new vehicle hardware[11,b]	70.77	–	47.75	–	γ
Annual fuel savings per vehicle[b] (gasoline vehicles only)[11]	1.51	–	1.30	–	γ
Probabilities, rates, and relative risk (RR)					
Asthma ED visit or hospitalization rate[64]	0.356	–	0.356	–	β
Acute cardiovascular attack rate[32,34,35]	0.009	0.001	0.014	0.001	β
New asthma onset incidence rate[65]	0.006	–	0.004	–	β
New CVD onset incidence rate[65]	0.015	–	0.012	–	β
Case fatality rate of asthma hospitalization or ED visit[66]	0.015	–	0.015	–	β
Case fatality rate of acute CVD attack[32]	0.079	–	0.062	–	β
RR of all-cause mortality due to $PM_{2.5}$ increase[36]	1.06	0.01	1.06	0.01	γ
RR of asthma hospitalization or emergency department visit by $PM_{2.5}$[7]	1.023	0.004	1.023	0.004	γ
RR of new asthma onset due to $PM_{2.5}$ increase[3]	1.04	0.10	1.04	0.10	γ
RR of new cardiovascular disease onset due to $PM_{2.5}$ increase[6]	1.11	0.05	1.11	0.05	γ
RR of asthma emergency department visit or hospitalization rate association with CVD comorbidity[66]	2.16	0.78	2.16	0.78	γ
RR of cardiovascular attack with prior history[67]	1.97	0.17	1.97	0.17	γ
Utilities used to calculate quality-adjusted life years (QALYs)					
Annual utility of healthy resident in QALYs[42]	1.00	–	1.00	–	β
Annual utility decrement attributable to asthma ED visit or hospitalization in QALYs[39]	−0.016	0.015	−0.016	0.015	β
Annual utility decrement attributable to acute CVD attack in QALYs[48]	−0.283	0.013	−0.283	0.013	β
Utility of chronic asthma[33,39,68]	0.808	0.211	0.747	0.214	β
Utility of chronic cardiovascular disease[48]	0.844	0.010	0.844	0.010	β
Utility of chronic cardiovascular disease and asthma[43,46,47]	0.789	0.002	0.728	3.077E-06	β

CVD, cardiovascular disease; ED, emergency department.
[a] Probabilistic distribution of parameters. β denotes beta-distribution and γ stands for gamma distribution.
[b] Different cost values used per calendar year. Values in the table are the initial cost at year 2019.

life tables and demographics for France and Italy were each obtained from their national statistics bureaus.[30,31] Where a country-specific value for a given parameter was not available, we used the reported value for a demographically similar country. Where comorbid states are present, we adjusted health states to reflect independent probabilities.[32–35] We averaged the reported values from as many meta-analyses and nationwide studies as possible to improve the accuracy and generalizability of our findings.

The ‘adopt US standards’ scenario evaluates the economic costs and health benefits of reducing $PM_{2.5}$ in France and Italy to those currently seen in the US. We applied the drops in $PM_{2.5}$ levels to the relevant relative risks based on data from the literature.[3,6,7,36] We then modified the baseline risk of health states in the control arm, ‘keep the standard as is,’ to inform the corresponding probabilities in the intervention arm. For a complete list of parameters, refer Table 1.

Costs

We included health care–related costs, the costs of implementing new test facilities, and fuel savings from stricter $PM_{2.5}$ emission standards as direct costs.[11] We quantified indirect costs through health-related productivity gains associated with reduced $PM_{2.5}$ levels.[3,6,7,35] All the costs associated with this policy change were taken from the literature.

To determine the direct costs of introducing US standards to both France and Italy, we used data from the US EPA's 2014 Regulatory Impact Analysis.[11] Costs included a one-time implementation cost for $PM_{2.5}$ regulation test facilities, the unit cost of upgrading vehicles with additional hardware, the indirect cost of additional labor, and the annual fuel savings after the upgrade for gasoline vehicles.[11] To compute the total cost of vehicle upgrades, we multiplied the unit costs per vehicle by the annual number of light-duty vehicles sold in each country. For each health state, we included on-going costs of chronic asthma or CVD management,[33,37–40] costs of asthma exacerbation,[41] and costs of acute CVD events.[37,40]

Utilities

Health outcomes were measured in terms of QALYs, a measure of remaining life expectancy, adjusted to reflect the average state of health of a cohort.[42] The health state utility value for chronic asthma was derived from literature.[43,44] We multiplied the distribution of asthma health states, defined by the Global Initiative for Asthma,[45] by their corresponding utility values.[46] For CVD, we compiled the health utility values from the literature based on the EuroQol-5 Dimension scale.[47,48] All relevant asthma and CVD events were assigned a disutility value based on literature, found in Table 1.

To measure the impact of an ambient $PM_{2.5}$ decrease on quality of life, we used the reported QALY gain/loss from the literature and assumed a linear association between $PM_{2.5}$ and QALYs.

Results

In France, the added direct and indirect costs of not adopting and enforcing the US regulations (keeping the status quo) amounted to €49,000 (95% Confidence Interval (CI) = €25,000, €90,000) while adopting the US $PM_{2.5}$ emission standards would cost €48,000 (95% CI = €24,000, €88,000). The number of QALYs associated with the status quo scenario was 19.63 (95% CI = 18.47, 20.21), while the number of QALYs associated with adopting US regulations was 19.67 (95% CI = 18.50, 20.24). In Italy, the cost associated with not adopting stricter $PM_{2.5}$ regulations was €39,000 (95% CI = €6,000, €192,000), while adopting the standards was associated with a cost of €36,000 (95% CI = €5,000, €175,000). The corresponding QALYs for the status quo and new emission regulations were 27.38 (95% CI = 26.15, 28.15) and 27.69 (95% CI = 26.39, 28.45), respectively. With incremental costs of -€1000 for France and -€3000 for Italy, as well as incremental QALYs of 0.04 for France and 0.31 for Italy, adopting US emission standards saves costs and lives for both French and Italian populations. Table 2.

The one-way sensitivity analysis indicated that the results of our model were robust to changes to the parameter values, such as changes in the relative risk of CVD onset, ongoing cost of chronic asthma, new CVD onset incidence rate, and so on (the full list of model parameters subjected to the sensitivity analysis can be found in Appendix 1, Fig. S1). The parameter that affected our model the most was variability in the relative risk of asthma incidence due to an increase in $PM_{2.5}$ for France and ongoing cost of chronic CVD for Italy (Appendix 1, Fig. S1).

From the probabilistic Monte Carlo simulation (Fig. 1), 93.8% of randomly generated samples for France and 87.4% of samples from Italy were both cost- and life-saving for adopting US $PM_{2.5}$ emission standards compared with no change in air pollution policies. An additional 0.7% of French samples and 10.1% of Italian samples fell within a WTP of €46,000. Despite excluding important benefits associated with regulatory changes, less than six percent of the simulations for both France and Italy fell outside of the WTP threshold.

From the acceptability curve, with a WTP of €46,000, the intervention has 98.7% acceptability for France and 96.0% acceptability for Italy. Within the confidence interval of €27,000 - €110,000, the intervention maintained higher than 95% acceptability for both countries (Appendix 1, Fig. S2).

Discussion

We set out to illustrate the changes in societal costs and health associated with changes in $PM_{2.5}$ regulations. We used two nations as case studies to illustrate the trade-offs associated with incremental regulatory changes. Cost-saving preventive health interventions are very rare and should be implemented so long as there are no overriding ethical concerns associated with doing so.[20,49] We find that improving vehicle emission standards and enforcement is one of those rare policies that could save both money and lives. The EU has not kept pace with the US with respect to vehicle emission standards set by the US EPA. Enforcement of violations is also weak in many EU member states. As a result, the EEA reports that about 400,000 deaths occur each year as a result of long-term exposure to excessive $PM_{2.5}$.[15] This human toll also comes with an economic toll for the EU that hits health systems particularly hard. This is striking for a block of nations that also offers near universal care to its occupants.

Full quantification of the economic and health toll association with regional changes in regulation would be a massive undertaking given the large national variations in emissions, pricing of health goods, other model inputs, and mean values for EU are of little use. Given our finding that both nations would realize savings, it is likely that most EU nations would realize similar gains. However, countries with tough regulations might experience increases in costs without meaningful gains in health. Similarly, our predictions are not valid for countries with weak regulations that might enact more radical changes that could produce unforeseen and unintended macroeconomic consequences.

Our study also serves as a warning for US policy. Currently, the US is considering relaxing environmental protections, and one EPA scientific advisor has indicated that the air in the US is 'too clean' to breathe for optimal health.[50] Relaxing standards, even to a small degree, would likely lead to increases in deaths, disability, and costs. This is likely to be a bigger problem in the US than in Europe not only because driving is more prevalent but also because healthcare costs are roughly twice those of France or Italy and growing much more rapidly over time.[51–53] A recent study found that $PM_{2.5}$ concentrations are highly predictive of COVID-19 deaths in the United States.[54,55]

Our study has a number of limitations. First, we showed two case studies rather than providing mean impacts on the EU. Some nations in the EU have much higher standards than France or Italy, while others have much lower standards. Similar to the EU, US states vary with respect to enforcement of EPA vehicle emission standards. However, because the US automobile market is somewhat monolithic, automobile emissions and fuel efficiency standards in the US are driven more by the state with the toughest regulations than by EPA standards.

Another limitation is that our key model inputs—pollution-associated morbidity and mortality—are not derived from randomized trials in humans (for ethical reasons). Rather, they are

Table 2
Incremental costs, incremental quality-adjusted life years, and incremental cost-effectiveness ratios for France and Italy for current vehicle emission standards versus standards set in the United States. (Numbers are rounded to reflect the high degree of uncertainty in the estimates.)

Arm	QALY (95% CI) [a]	Incremental QALY	Cost (EUR) (95% CI)	Incremental Cost (EUR)
France				
Maintain current $PM_{2.5}$ emission standard	19.63 (18.47, 20.21)	–	49,000 (25,000, 90,000)	–
Adopt U.S. $PM_{2.5}$ emission standard	19.67 (18.50, 20.24)	0.04	48,000 (24,000, 88,000)	−1000
Italy				
Maintain current $PM_{2.5}$ emission standard	27.38 (26.15, 28.15)	–	39,000 (6,000, 192,000)	–
Adopt U.S. $PM_{2.5}$ emission standard	27.69 (26.39, 28.45)	0.31	36,000 (5,000, 175,000)	−3000

QALY, quality-adjusted life years.
[a] : Quality of life.

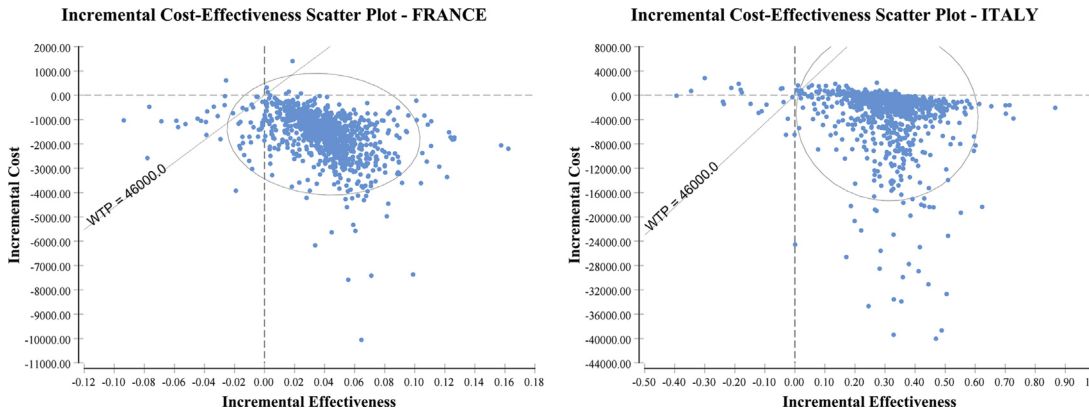

Fig. 1. Incremental cost-effectiveness scatter plot with 95% credibility interval (defined as inner space of the gray eclipse) falling within and outside of the willingness to pay (WTP) threshold of €46,000 France and Italy.

derived from observational and quasi-experimental studies of humans backed by experimental animal models. The health effects of pollution could be better or worse than those we present here. We account for error in estimates of these and other model inputs by using a broad sensitivity analysis and excluding potentially important pollutants from our estimates.

Conclusions

Most medical interventions cost well over $100,000 per QALY gained;[28] however, broader social policies such as education interventions can save both money and lives.[56–59] We show that titrating regulatory controls to optimize health could be added to the armament of policies, including vaccines and education interventions,[56–59] that improve health.

Author statements

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The research presented in this article is that of the authors. All data are available in the main text or the supplementary materials. The TreeAge model can be provided upon request. All data collection and analysis were performed in 2018, and the study is exempted from IRB approval.

Ethical approval

Not required (quasi experimental study).

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Competing interests

None declared.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2020.04.024.

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