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Abstract

Introduction: The US has among the world's strictest automobile emissions 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 emissions standards in France and Italy.

Methods: We used cost-effectiveness modelling to measure the incremental quality-adjusted life years (QALYs) and cost (EUR) of adopting more stringent US vehicle emission standards for $PM_{2.5}$ in France and Italy.

Results: Adopting Obama-era US vehicle emissions standards would likely save money and lives for both the French and Italian populations. In France, adopting US emissions standards would save €1,000 and increase QALYs by 0.04 per capita. In Italy, the stricter standards would save €3,000 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 emissions 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 emissions standards. The impact of incremental increases or decreases in vehicle emissions standards on population health is roughly known, but less is known about the trade-offs associated with such changes on macro-economic well-being relative to health and health system costs.

This paper explores the trade-off between more stringent vehicle emissions 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 macro-economic impacts of applying these regulations over time in the US. Likewise, 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 $PM_{2.5}$ 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 EPA in 2012 is 12µg/m³ [12,13].

The World Health Organization (WHO) recommends that $PM_{2.5}$ not exceed 10µg/m³ [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 12µg/m³, it is very close to the WHO target. The 2008 EU legislation on ambient vehicle emissions sets vehicle emissions 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 25µg/m³ by 2015 and 20µg/m³ by 2020 [1, 15-18]. In 2017, 6% to 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 EEA, the annual mean $PM_{2.5}$ emission in 2015 was 13µg/m³ in France and 19µg/m³ in Italy [16], compared to an average of 13.9 µg/m³ for all EU-28 countries [16]. While France and Italy fall below the current EU limit of 25µg/m³, they still exceed both the US's limit of 12 µg/m³ and the WHO's Air Quality Guidelines of 10µg/m³

[13,14,17]. Some eastern EU nations like Poland, Serbia, and Bulgaria have emissions averages that are much higher than 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 emissions 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 emissions 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. Additionally, 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 is 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 emissions 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 socio-demographic differences between the three nations.

Cost-Effectiveness Model

Our Markov decision-analytic model had two arms: “Keep the standard as is” and “Adopt US emissions 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 (ICER) [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 willingness-to-pay 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, was derived from the literature. The 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 co-morbid 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, see Table 1.

Costs

We included health care-related costs, the costs of implementing new test facilities, and fuel savings from stricter $PM_{2.5}$ emissions 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 (EQ-5D) 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.

Table 1. List of parameters used in the Markov Model

[Insert Table 1 here.]

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% 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 -€1,000 for France and -€3,000 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. Incremental costs, incremental quality-adjusted life years, and incremental cost-effectiveness ratios for France and Italy for current vehicle emissions standards versus standards set in the US.

[Insert Table 2 here]

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, etc. (the full list of model parameters subjected to the sensitivity analysis can be found in Appendix 1, Figure 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, Figure S1).

[Insert Figure 1 Here.]

Figure 1. Incremental Cost-Effectiveness Scatter Plot with 95% Credibility Interval (defined as inner space of the grey eclipse) falling within and outside of the willingness-to-pay (WTP) threshold of €46,000 France and Italy.

From the probabilistic Monte Carlo simulation (Figure 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 to 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, Figure 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 in order to illustrate the tradeoffs 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 emissions 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 emissions 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, and 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. Likewise, 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 PM2.5 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 in the EU. Some nations in the EU have much higher standards than France or Italy, while others have much lower standards. Like the EU, US states vary with respect to enforcement of EPA vehicle emissions 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 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.

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

Declarations of interest: none

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References

1. European Environment Agency. Air quality in Europe - 2017 report [Internet]. Copenhagen; 2017 [cited 2019 Jun 9]. Available from: https://www.eea.europa.eu/publications/air-quality-in-europe-2017
2. Beelen R, Raaschou-Nielsen O, Stafoggia M, Andersen ZJ, Weinmayr G, Hoffmann B, et al. Effects of long-term exposure to air pollution on natural-cause mortality: An analysis of 22 European cohorts within the multicentre ESCAPE project. *Lancet*. 2014;**383**(9919):785–95. doi:10.1016/S0140-6736(13)62158-3
3. Jacquemin B, Siroux V, Sanchez M, Carsin AE, Schikowski T, Adam M, et al. Ambient air pollution and adult asthma incidence in six European cohorts (ESCAPE). *Environ Health Perspect*. 2015;**123**(6):613–21. doi:10.1289/ehp.1408206
4. Schultz AA, Schauer JJ, Malecki KM. Allergic disease associations with regional and localized estimates of air pollution. *Environ Res*. 2017;**155**:77–85. doi:10.1016/j.envres.2017.01.039
5. Shah ASV, Lee KK, McAllister DA, Hunter A, Nair H, Whiteley W, et al. Short term exposure to air pollution and stroke: Systematic review and meta-analysis. *BMJ*. 2015;**350**:h1295. doi:10.1136/bmj.h1295
6. Wellenius GA, Burger MR, Coull BA, Schwartz J, Suh HH, Koutrakis P, et al. Ambient air pollution and the risk of acute ischemic stroke. *Arch Intern Med*. 2012;**172**(3):229–34. doi:10.1001/archinternmed.2011.732
7. Zheng XY, Ding H, Jiang LN, Chen SW, Zheng JP, Qiu M, et al. Association between Air pollutants and asthma emergency room visits and hospital admissions in time series studies: A systematic review and meta-Analysis. *PLoS One*. 2015;**10**(9):e0138146. doi:10.1371/journal.pone.0138146

8. Yang WS, Zhao H, Wang X, Deng Q, Fan WY, Wang L. An evidence-based assessment for the association between long-term exposure to outdoor air pollution and the risk of lung cancer. *Eur J Cancer Prev*. 2016;**25**(3):163–72. doi:10.1097/CEJ.0000000000000158
9. Health Effects Institute. State of Global Air 2017. Special Report. [Internet]. Health Effects Institute. 2017 [cited 2019 Jul 9]. p. 1–15. Available from: https://www.stateofglobalair.org/sites/default/files/SOGA2017_report.pdf.
10. Lau J, Hung WT, Cheung CS, Yuen D. Contributions of roadside vehicle emissions to general air quality in Hong Kong. *Transp Res Part D Transp Environ*. 2008;**13**(1):19–26. doi: 10.1016/j.trd.2007.10.004
11. United States Environmental Protection Agency. Final Rule for Model Year 2017 and Later Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards [Internet]. United States Environmental Protection Agency. 2016 [cited 2019 May 16]. Available from: https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-model-year-2017-and-later-light-duty-vehicle
12. Giannadaki D, Lelieveld J, Pozzer A. Implementing the US air quality standard for PM2.5 worldwide can prevent millions of premature deaths per year. *Environ Heal A*. 2016;**15**(1):88. doi:10.1186/s12940-016-0170-8
13. United States Environmental Protection Agency. Table of Historical Particulate Matter (PM) National Ambient Air Quality Standards (NAAQS) [Internet]. United States Environmental Protection Agency. 2018 [cited 2020 Apr 7]. Available from: https://www.epa.gov/pm-pollution/table-historical-particulate-matter-pm-national-ambient-air-quality-standards-naaqs
14. World Health Organization. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide [Internet]. Geneva; 2006 [cited 2019 May 31].

Available from: https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf;jsessionid=B69B7F29F7F6AE305EC9F1A362BD9C89?sequence=1

15. European Environment Agency. Air quality in Europe 2019 [Internet]. European Environment Agency. 2019 [cited 2020 Apr 7]. Available from: https://www.eea.europa.eu//publications/air-quality-in-europe-2019
16. European Environment Agency. Air pollutant concentrations at station level (statistics) [Internet]. European Environment Agency. 2017 [cited 2019 May 29]. Available from: https://www.eea.europa.eu/data-and-maps/data/air-pollutant-concentrations-at-station
17. European Commission. Air Quality Standards [Internet]. European Commission. 2019 [cited 2019 Jun 8]. Available from: https://ec.europa.eu/environment/air/quality/standards.htm
18. Pascal M, Corso M, Chanel O, Declercq C, Badaloni C, Cesaroni G, et al. Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project. *Sci Total Environ*. 2013;**449**:390–400. doi:10.1016/j.scitotenv.2013.01.077
19. Chanel O, Perez L, Künzli N, Medina S, Aphekom group. The hidden economic burden of air pollution-related morbidity: evidence from the Aphekom project. *Eur J Heal Econ*. 2016;**17**(9):1101–15. doi:10.1007/s10198-015-0748-z
20. Sanders GD, Neumann PJ, Basu A, Brock DW, Feeny D, Krahn M, et al. Recommendations for conduct, methodological practices, and reporting of cost-effectiveness analyses: Second panel on cost-effectiveness in health and medicine. *JAMA*. 2016:**316**(10):1093–103. doi:10.1001/jama.2016.12195
21. Treeage Software. TreeAge Pro 2016. Version R1 [software]. 2016 [cited 2019 May 17]. Available from: http://www.treeage.com/news/treeage-pro-2016-r1-0/

22. European Commission. Vehicle categories [Internet]. European Commission. [cited 2019 Apr 3]. Available from: https://ec.europa.eu/growth/sectors/automotive/vehicle-categories_en

23. Transport Policy. US: Vehicle Definitions [Internet]. 2018 [cited 2019 Apr 3]. Available from: https://www.transportpolicy.net/standard/us-vehicle-definitions/

24. European Automobile Manufacturers' Association (ACEA). Vehicles in use - Europe 2017 [Internet]. Brussels; 2017 [cited 2019 May 10]. Available from: https://www.acea.be/statistics/article/vehicles-in-use-europe-2017

25. Voorspools KR, D'haeseleer WD. Modelling of electricity generation of large interconnected power systems: How can a CO2 tax influence the European generation mix. Energy Convers Manag. 2006;47(11–12):1338–58. https://doi.org/10.1016/j.enconman.2005.08.022

26. De Beaupuy F. France's Power Emissions Fell in 2019 as Coal's Share Dipped. Bloomberg [Internet]. 2020 Feb 12 [cited 2020 Apr 10]; Available from: https://www.bloomberg.com/news/articles/2020-02-12/france-s-power-emissions-tumbled-in-2019-as-coal-s-share-slumped

27. Eurostat. Eurostat Database [Internet]. Eurostat; 2020 [cited 2019 May 7]. Available from: https://ec.europa.eu/eurostat/data/database

28. Muening P, Bounthavong M. *Cost-effectiveness analyses in health: a practical approach.* 3rd edition. San Francisco: Jossey-Bass; 2016.

29. Desaigues B, Ami D, Bartczak A, Braun-Kohlová M, Chilton S, Czajkowski M, et al. Economic valuation of air pollution mortality: A 9-country contingent valuation survey of value of a life year (VOLY). *Ecol Indic*. 2011;**11**(3):902–10. doi:10.1016/j.ecolind.2010.12.006

30. Institut national d’études démographiques (INED). Mortality rates by sex and age [Internet]. Institut national d’études démographiques (INED). 2017 [cited 2019 Apr 25]. Available from: https://www.ined.fr/en/everything_about_population/data/france/deaths-causes-mortality/mortality-rates-sex-age/

31. Ministero della Salute. Lo stato di salute della popolazione - RSSP 2012-2013 [Internet]. Ministero della Salute. 2014 [cited 2019 Apr 25]. Available from: http://www.rssp.salute.gov.it/rssp2012/paginaMenuSezioneRssp2012.jsp?sezione=statoSalute&lingua=italiano

32. Benjamin EJ, Blaha MJ, Chiuve SE, Cushman M, Das SR, Deo R, et al. Heart Disease and Stroke Statistics’2017 Update: A Report from the American Heart Association. *Circulation*. 2017;**135**:e146–603. doi:10.1161/CIR.0000000000000485

33. Demoly P, Gueron B, Annunziata K, Adamek L, Walters RD. Update on asthma control in five European countries: Results of a 2008 survey. *Eur Respir Rev*. 2010;**19**(116):150–7. doi:10.1183/09059180.00002110

34. Institut National de la statistique et des études économiques (INSEE). Population changes: Demographic balance sheet 2017 - Retrospective Tables [Internet]. Institut National de la statistique et des études économiques (INSEE). 2018 [cited 2019 Apr 25]. Available from: https://www.insee.fr/en/statistiques/2382601?sommaire=2382613#consulter-sommaire

35. Italian National Institute of Statistics (ISTAT). Demographic Indicators - Estimates for the year 2015 [Internet]. Italian National Institute of Statistics (ISTAT). 2016 [cited 2019 Apr 25]. Available from: https://www.istat.it/it/archivio/180494

36. Hoek G, Krishnan RM, Beelen R, Peters A, Ostro B, Brunekreef B, et al. Long-term air pollution exposure and cardio-respiratory mortality: A review. *Environmental Health*. 2013;**12**(1):43. doi:10.1186/1476-069X-12-43

37. Chevreul K, Durand-Zaleski I, Gouépo A, Fery-Lemonnier E, Hommel M, Woimant F. Cost of stroke in France. *Eur J Neurol*. 2013;**20**(7):1094–100. doi:10.1111/ene.12143

38. Dal Negro RW, Distante C, Bonadiman L, Turco P, Iannazzo S. Cost of persistent asthma in Italy. *Multidiscip Respir Med*. 2016;**11**(1):44. doi:10.1186/s40248-016-0080-1

39. Doz M, Chouaid C, Com-Ruelle L, Calvo E, Brosa M, Robert J, et al. The association between asthma control, health care costs, and quality of life in France and Spain. *BMC Pulm Med*. 2013;**13**(1):15. doi:10.1186/1471-2466-13-15

40. Fattore G, Torbica A, Susi A, Giovanni A, Benelli G, Gozzo M, et al. The social and economic burden of stroke survivors in Italy: A prospective, incidence-based, multi-centre cost of illness study. *BMC Neurol*. 2012;**12**(1):137. doi:10.1186/1471-2377-12-137

41. Van Ganse E, Antonicelli L, Zhang Q, Laforest L, Yin DD, Nocea G, et al. Asthma-related resource use and cost by GINA classification of severity in three European countries. *Respir Med*. 2006;**100**(1):140–7. doi:10.1016/j.rmed.2005.03.041

42. National Institute for Health and Care Excellence. The NICE Glossary [Internet]. National Institute for Health and Care Excellence. 2018 [cited 2019 Apr 25]. Available from: https://www.nice.org.uk/glossary?letter=q

43. Zafari Z, Sadatsafavi M, Marra CA, Chen W, FitzGerald JM. Cost-effectiveness of bronchial thermoplasty, omalizumab, and standard therapy for moderate-to-severe allergic asthma. *PLoS One*. 2016;**11**(1). doi:10.1371/journal.pone.0146003

44. Zafari Z, Sadatsafavi M, Mark FitzGerald J. Cost-effectiveness of tiotropium versus omalizumab for uncontrolled allergic asthma in US. *Cost Eff Resour Alloc*. 2018;**16**(1):3. doi:10.1186/s12962-018-0089-8

45. Global Initiative for Asthma. Global Strategy for Asthma Management and Prevention [Internet]. 2018 [cited 2019 May 11]. Available from: https://ginasthma.org/reports/

46. Zafari Z, Lynd LD, Fitzgerald JM, Sadatsafavi M. Economic and health effect of full adherence to controller therapy in adults with uncontrolled asthma: A simulation study. *J Allergy Clin Immunol*. 2014;**134**(4):908-915.e3. doi:10.1016/j.jaci.2014.04.009
47. Jiao B, Zafari Z, Will B, Ruggeri K, Li S, Muennig P. The cost-effectiveness of lowering permissible noise levels around U.S. airports. *Int J Environ Res Public Health*. 2017;**14**(12):1497. doi:10.3390/ijerph14121497
48. Ara R, Brazier JE. Populating an economic model with health state utility values: Moving toward better practice. *Value Heal*. 2010;**13**(5):509–18. doi:10.1111/j.1524-4733.2010.00700.x
49. Weinstein MC, Siegel JE, Gold MR, Kamlet MS, Russell LB. Recommendations of the panel on cost-effectiveness in health and medicine. *JAMA J Am Med Assoc*. 1996;**276**(15):1253. doi:10.1001/jama.1996.03540150055031
50. Brueck H. One of the EPA's newest science experts thinks 'modern air' is too clean to breathe. Business Insider [Internet]. 2017 Nov 8 [cited 2019 May 17]; Available from: https://www.businessinsider.fr/us/scott-pruitt-scientific-advisory-board-environmental-protection-agency-modern-air-robert-phalen-2017-11
51. Charlesworth A. Why is health care inflation greater than general inflation? *J Health Serv Res Policy*. 2014;**19**(3):129–30. doi:10.1177/1355819614531940
52. Dunn A, Grosse SD, Zuvekas SH. Adjusting Health Expenditures for Inflation: A Review of Measures for Health Services Research in the United States. *Health Serv Res*. 2018;**53**(1):175–96. doi:10.1111/1475-6773.12612
53. Roman BR. On Marginal Health Care — Probability Inflation and the Tragedy of the Commons. *N Engl J Med*. 2015;**372**(6):572–5. doi:10.1056/NEJMms1407446

54. Wu X, Nethery RC, Sabath BM, Braun D, Dominici F. Exposure to air pollution and COVID-19 mortality in the United States. *medRxiv*. 2020. doi: https://doi.org/10.1101/2020.04.05.20054502

55. Muennig P. Opinion | As Fears of Wuhan's Coronavirus Spread. The New York Times [Internet]. 2020 Jan 31 [cited 2020 Apr 10]; Available from: https://www.nytimes.com/2020/01/31/opinion/letters/wuhan-coronavirus.html

56. Muennig PA, Epstein M, Li G, DiMaggio C. The cost-effectiveness of New York City's Safe Routes to School Program. *Am J Public Health*. 2014;**104**(7):1294–9. doi:10.2105/AJPH.2014.301868

57. Muennig PA, Quan R, Chiuzan C, Glied S. Considering whether Medicaid is worth the cost: Revisiting the Oregon Health Study. *Am J Public Health*. 2015;**105**(5):866-71. doi:10.2105/AJPH.2014.302485

58. Muennig PA, Mohit B, Wu J, Jia H, Rosen Z. Cost Effectiveness of the Earned Income Tax Credit as a Health Policy Investment. *Am J Prev Med*. 2016;**51**(6):874–81. doi:10.1016/j.amepre.2016.07.001

59. Wu J, Dean KS, Rosen Z, Muennig PA. The Cost-effectiveness Analysis of Nurse-Family Partnership in the United States. *J Health Care Poor Underserved*. 2017;**28**(4):1578–97. doi:10.1353/hpu.2017.0134

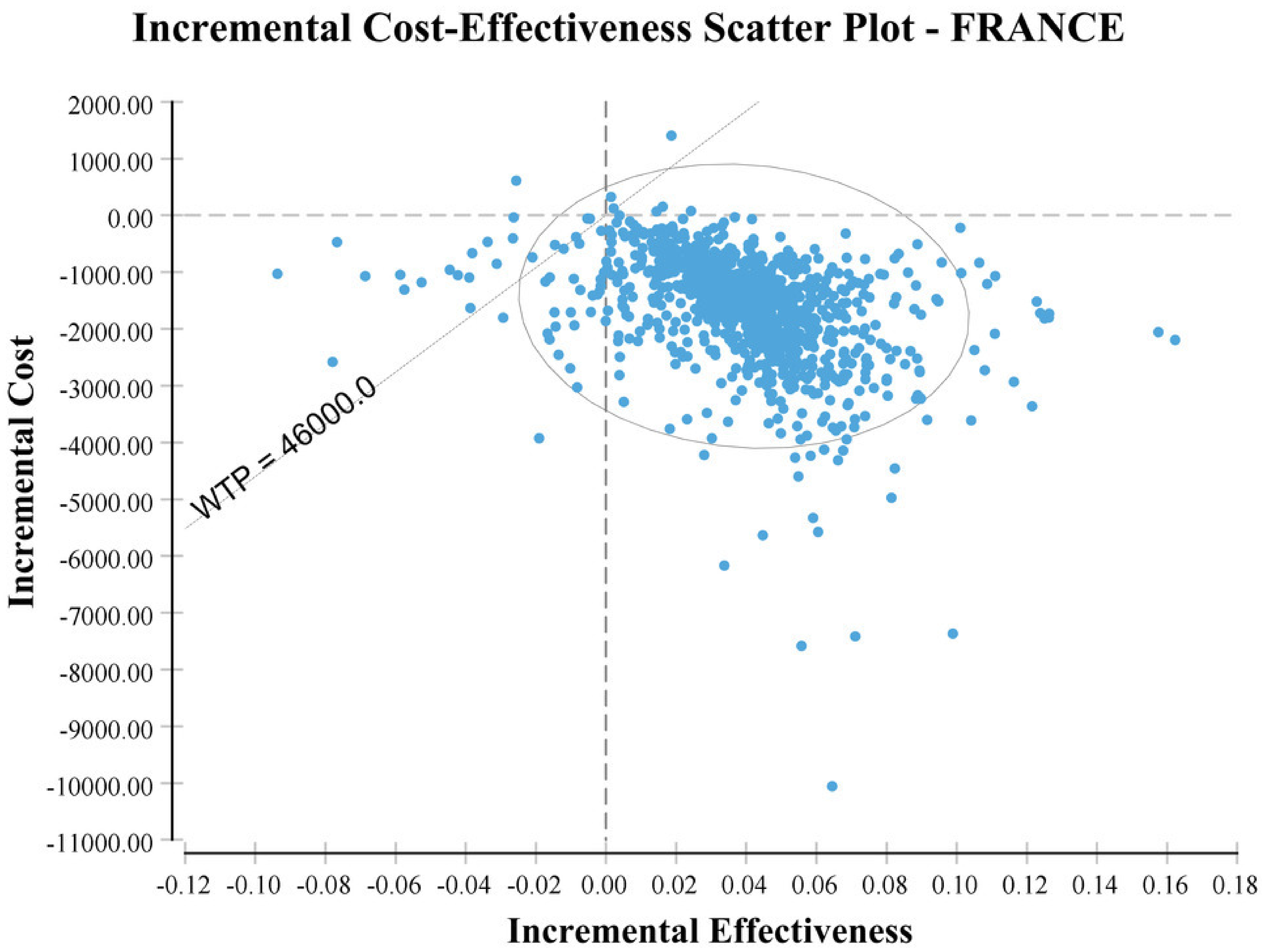
60. United States Environmental Protection Agency. Particulate Matter (PM2.5) Trends [Internet]. United States Environmental Protection Agency. 2016 [cited 2019 Jun 8. Available from: https://www.epa.gov/air-trends/particulate-matter-pm25-trends

61. Comité des Constructeurs Français d'Automobiles (CCFA). Number of passenger cars registered in France in 2013 and 2014, by fuel type [Internet]. Statista: The Statistics Portal. 2018 [cited 2019 Apr 25]. Available from:

https://www.statista.com/statistics/418737/passenger-car-registrations-in-france-by-fuel/

62. UNRAE. Number of passenger cars sold in Italy from 2014 to 2019, by fuel type [Internet]. Statista: The Statistics Portal. 2016 [cited 2019 Apr 25]. Available from: https://www.statista.com/statistics/417567/passenger-car-sales-in-italy-by-fuel-type/
63. European Central Bank. ECB euro reference exchange rate: US dollar (USD) [Internet]. European Central Bank. 2018 [cited 2019 May 5]. Available from: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html
64. Price D, Fletcher M, Van Der Molen T. Asthma control and management in 8,000 European patients: The REcognise Asthma and LInk to Symptoms and Experience (REALISE) survey. *Npj Prim Care Respir Med*. 2014;**24**(1):14009. doi:10.1038/npjpcrm.2014.9
65. Institute for Health Metrics and Evaluation. Global Burden of Disease Results Tool. Global Health Data Exchange. [Internet]. Institute for Health Metrics and Evaluation. 2018 [cited 2019 May 29]. Available from: http://ghdx.healthdata.org/gbd-results-tool
66. Aubas C, Bourdin A, Aubas P, Gamez AS, Halimi L, Vachier I, et al. Role of comorbid conditions in asthma hospitalizations in the south of France. *Allergy Eur J Allergy Clin Immunol*. 2013;**68**(5):637–43. doi:10.1111/all.12137
67. Lloyd-Jones D, Adams RJ, Brown TM, Carnethon M, Dai S, De Simone G, et al. Executive summary: Heart disease and stroke statistics-2010 update: A report from the American Heart Association. *Circulation*. 2010;**121**(7):e46-e215. doi:10.1161/CIRCULATIONAHA.109.192667
68. Terzano C, Cremonesi G, Girbino G, Ingrassia E, Marsico S, Nicolini G, et al. 1-year prospective real life monitoring of asthma control and quality of life in Italy. *Respir Res*.

2012;**13**(1):112. doi:10.1186/1465-9921-13-112


Incremental Cost-Effectiveness Scatter Plot - FRANCE
Incremental Cost
2000.00
1000.00
0.00
-1000.00
-2000.00
-3000.00
-4000.00
-5000.00
-6000.00
-7000.00
-8000.00
-9000.00
-10000.00
-11000.00
WTP = 46000.0
-0.12
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
Incremental Effectiveness

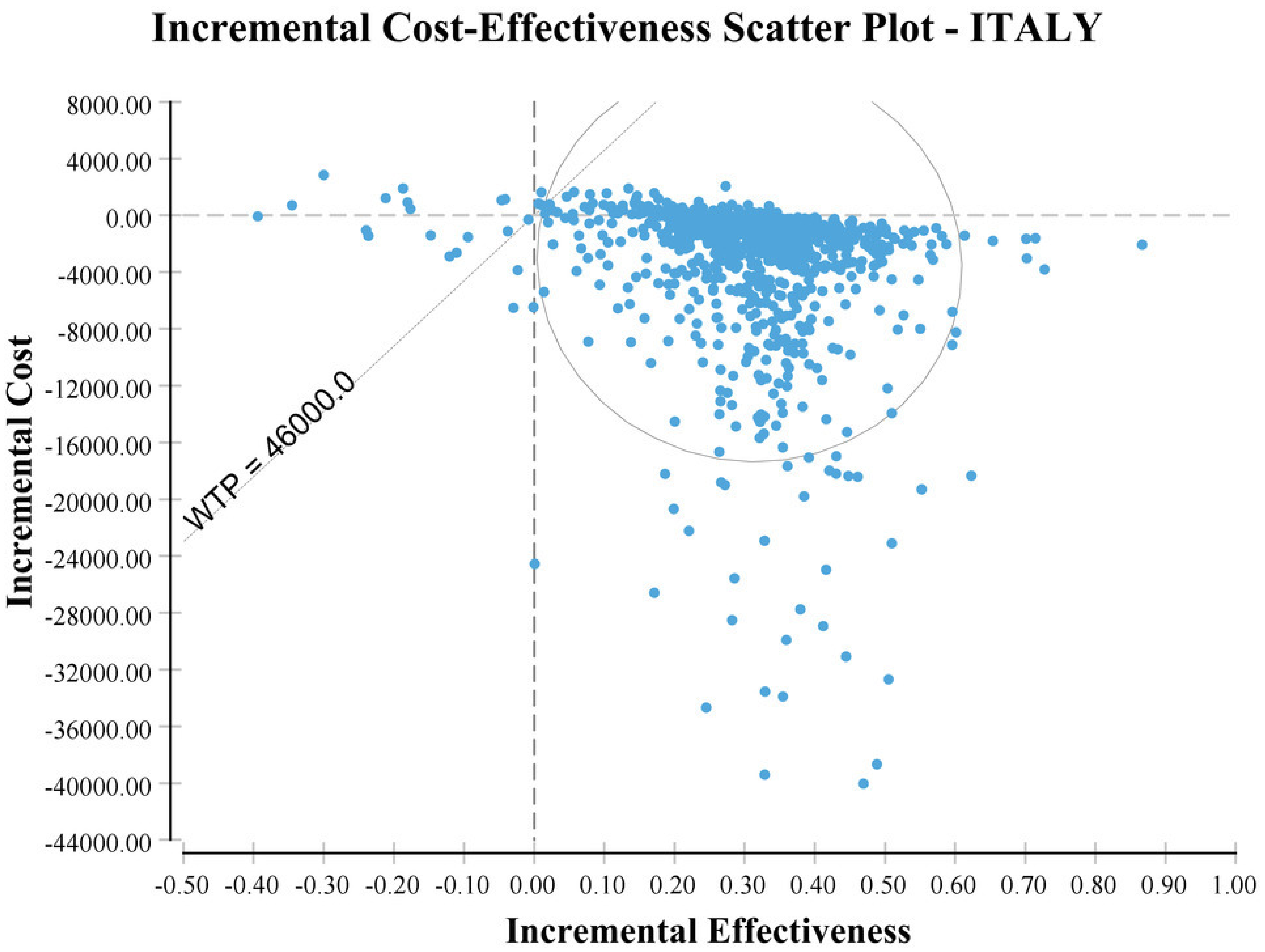

Incremental Cost-Effectiveness Scatter Plot - ITALY
Incremental Cost
8000.00
4000.00
0.00
-4000.00
-8000.00
-12000.00
-16000.00
-20000.00
-24000.00
-28000.00
-32000.00
-36000.00
-40000.00
-44000.00
WTP = 46000.0
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Incremental Effectiveness

Table 1. List of parameters used in the Markov Model

Description	France		Italy		
	Base Value	Standard Error	Base Value	Standard Error	Probabilistic Distribution[a]
General parameters					
Average age of target population [27]	41.4	-	45.9	-	-
Total number of target population [27]	66989083	-	60589445	-	-
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]	777645	-	599752	-	-
Number of diesel passenger cars sold in year 2017 [61,62]	1089403	-	1061004	-	-
Total passenger vehicles on road [61,62]	32326000	-	37080753	-	-
Costs (2018 Euro)					

Cost of acute asthma ED visit or hospitalization [41,63]	399	-	1,225	-	γ
On-going cost of chronic asthma	1,230	6,076	1,407	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]	9,358	-	5,282	8,539	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 PM2.5 increase [36]	1.06	0.01	1.06	0.01	γ
RR of asthma hospitalization or emergency department visit by PM2.5 [7]	1.023	0.004	1.023	0.004	γ
RR of new asthma onset due to PM2.5 increase [3]	1.04	0.10	1.04	0.10	γ
RR of new cardiovascular disease onset due to PM2.5 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 (QALY)					
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

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 is the initial cost at year 2019.

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.)

France				
Arm	**QALY**	**Incremental QALY**	**Cost (EUR)**	**Incremental Cost (EUR)**
Maintain Current PM2.5 Emissions Standard	19.63 (18.47, 20.21)	-	49,000 (25,000, 90,000)	-
Adopt U.S. PM2.5 Emissions Standard	19.67 (18.50, 20.24)	0.04	48,000 (24,000, 88,000)	-1,000

Italy

Arm	QALY	Incremental QALY	Cost (EUR)	Incremental Cost
Maintain Current PM2.5 Emissions Standard	27.38 (26.15, 28.15)	-	39,000 (6,000, 192,000)	-
Adopt U.S. PM2.5 Emissions Standard	27.69 (26.39, 28.45)	0.31	36,000 (5,000, 175,000)	-3,000

a: Quality of Life