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Abstract

The fuel efficiency of conventional private vehicles is a key input in the design of several economic and environmental policies. Most importantly, it provides a benchmark of CO2 emissions against which the performance of alternative fuel vehicles can be correctly measured. Therefore, reliable projections of this variable can improve the estimates on the future emission savings from policies promoting vehicle replacement, and the estimates on future tax revenues from fuel. This paper examines the evolution of fuel efficiency using data on cars entering the US market from 1984 to 2020. It uses a series of new indexes for the gasoline cost in OECD countries, the price and tax shocks that shifted user costs, and the stringency of fuel efficiency regulations. In contrast to previous contributions that downplay the role of fuel prices and taxes in shaping fuel efficiency, the study shows that their effect may be significant and robust. Doubling the user cost of gasoline with a stringent carbon tax will cause an irreversible increase in fuel efficiency, between 6% and 11%. Increasing the stringency of the US CAFE standards by 10% raises average fuel efficiency by 2-3%. The impact of cross-market regulations is ambiguous. EU standards are found to have a limited, or even negative impact on the fuel efficiency of vehicles entering the US market. The rate of autonomous technical change is shown to be low. Without the impact of price shocks and policies, such as efficiency standards and taxes, fuel efficiency would grow at an annual rate less than 0.5%.

Keywords: fuel efficiency, conventional cars, fuel taxes, gasoline prices

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Résumé

L'efficacité énergétique des véhicules individuels conventionnels est un élément clé dans la conception de plusieurs politiques économiques et environnementales. Surtout, elle fournit une référence des émissions de CO2 par rapport à laquelle les performances des véhicules à carburant alternatif peuvent être correctement mesurées. Par conséquent, des projections fiables de cette variable peuvent améliorer les estimations des futures économies d'émissions résultant des politiques favorisant le remplacement des véhicules et les estimations des futures recettes fiscales provenant du carburant. Ce rapport examine l'évolution de l'efficacité énergétique à l'aide de données sur les voitures entrant sur le marché américain de 1984 à 2020. Il utilise une série de nouveaux indices pour le coût de l'essence dans les pays de l'OCDE, les prix et les chocs fiscaux qui ont modifié les coûts d'utilisation, et la rigueur des réglementation sur l'efficacité énergétique. Contrairement aux contributions précédentes qui minimisent le rôle des prix du carburant et des taxes dans l'évolution de l'efficacité énergétique, l'étude montre que leur effet peut être significatif et robuste. Doubler le coût d'utilisation de l'essence avec une taxe carbone stricte entraînera une augmentation irréversible de l'efficacité énergétique, entre 6 % et 11 %. L'augmentation de 10 % de la rigueur des normes US CAFE augmente le rendement énergétique moyen de 2 à 3 %. L'impact des réglementations inter-marchés est ambigu. Les normes de l'UE ont un impact limité, voire négatif, sur l'efficacité énergétique des véhicules entrant sur le marché américain. Le taux de changement technique autonome s'avère faible. Sans l'impact des chocs de prix et des politiques, telles que les normes d'efficacité et les taxes, l'efficacité énergétique progresserait à un taux annuel inférieur à 0,5 %.

Mots-clés : consommation de carburant, efficacité en carburant, voitures conventionnels, taxes sur les carburants, prix de l'essence

Classification JEL : Q55, R48, Q48, H23, 031

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Executive summary

The *fuel efficiency* of conventional vehicles is a key input in the design of several economic and environmental policies. The variable is far from static, as its evolution displays a clear increasing trend. The fuel consumption of the average vehicle entering the U.S. market in 2020 was 17% lower than that of its counterpart in 1984. Reliable projections of fuel efficiency for the critical period 2021-2050 can provide a dynamic lower bound of CO_2 emissions from car use. This benchmark is necessary to estimate the emissions savings from the transition to a world where alternative fuel vehicles possess a significant, possibly dominant, share in the vehicle stock. In turn, correctly estimating the size of CO_2 emissions savings can facilitate more elaborate cost-benefit analyses. Such analyses may include various policy interventions known to accelerate the penetration of alternative fuel vehicles, and are feasible insofar as the social cost of these interventions is known. Therefore, the evolution of fuel efficiency in gasoline cars is much more than an indicator of technological progress in conventional car industry. Rather, it is a systemic component in a framework where socially desirable policies and innovations with various environmental footprints are simultaneously determined.

Generating plausible scenarios for the evolution of fuel efficiency of gasoline cars requires the analysis to distinguish its various drivers. A portion of the observed progress is driven by environmentally relevant policies. For instance, fuel efficiency *regulations* introduce penalties to manufacturers who fail to comply. In addition to regulatory standards, *gasoline taxes* increase the user cost of less efficient vehicles, incentivizing the construction of more economical alternatives. A third driver of the observed progress is the fluctuation in the price of gasoline, which has a similar effect to gasoline taxes but is beyond the control of policy makers. Part of the observed growth in fuel efficiency is *autonomous*, *i.e.* it does not stem from environmentally relevant policies or the price system. Instead, it is fuelled by pure competition between manufacturers, the growing size of the international car market, as well as from spillover effects from other industries. Consequently, “autonomous” growth can be influenced by policies of low or no environmental relevance that intensify these factors. Finally, evolving vehicle characteristics, which reflect changes in consumer preferences and manufacturing practices, underlie part of the evolution of fuel consumption.

This study estimates the contribution of the aforementioned drivers in the progress observed during the last four decades, and projects their future contribution in the period 2021-2050. It uses a longitudinal US EPA dataset with the characteristics of all vehicle models introduced in the US market during the period 1984-2020. The study controls for the evolution of Corporate Average Fuel Economy (CAFE) standards during the same period. In contrast to previous studies, the econometric estimations in this report account for non-US control variables. Fuel prices and taxes outside the US affect the fuel efficiency of vehicle models in the dataset, as some of them simultaneously enter markets other than the US. To account for that, the study develops a cost index that incorporates gasoline prices and taxes in all OECD countries.

The findings indicate that environmental policy components are responsible for a substantial part of the fuel efficiency progress realised after 1984. In particular, CAFE standards and fluctuations in gasoline costs respectively underlie 30% and 10% of it. It is shown that increasing the stringency of the US CAFE standards by 10% raises the fuel efficiency of the average car by 2-3%. The autonomous progress accounts for the remaining 60% of the fuel efficiency evolution. This finding implies that without the impact of price shocks and environmentally relevant policies, such as efficiency standards and gasoline taxes, fuel efficiency would have grown at an average annual rate that lies below 0.5%.

The study yields a series of policy-relevant long-run projections. Without a substantial policy shock, such as the phasing out of gasoline vehicles, fuel efficiency in 2050 will have increased by 4-12%. Positive shocks in the gasoline costs are estimated to raise that figure by an additional 0.9-1.4%. However, this number gets smaller if offsetting factors with a growing trend, such as vehicle weight and engine size, are considered in the projections. On the other hand, with CAFE standards continuously raising at a pace

comparable to that observed in the last decades, the fuel efficiency of future vehicle models could increase by an additional 6-7%. The implementation of a carbon tax corresponding to the high-impact scenario developed by US EPA will have a positive contribution between 0.6% and 1.3%. The predicted increase in the case of more moderate scenarios remains considerable. For the carbon tax derived in the regular scenario with an annual discount rate of 2.5%, that lies between 0.2 and 0.6%.

Importantly, the findings provide only partial support for the corresponding policies fostering innovation in the fuel efficiency of gasoline cars. This holds true in particular for CAFE standards. While the study highlights their effectiveness in boosting fuel efficiency of conventional vehicle models, the degree to which such a boost is socially desirable requires additional analysis. That should account for the rebound effects that increased fuel efficiency brings, for example by boosting higher vehicle ownership rates, inducing more vehicle use and hampering the transition towards alternative fuel vehicles.

1 Introduction

Vehicle *fuel efficiency*[1], *i.e.* the average amount of final fuel consumed per traversed kilometre, is a variable of significant environmental and socioeconomic importance. First, it directly determines total energy consumption and CO_2e emissions. In the US, on-road vehicles are responsible for approximately 60% of the total oil consumption and for over 25% of the country's greenhouse gas emissions.[2] Fuel efficiency indirectly determines the emissions of air pollutants, as vehicles of comparable filtering technologies but widely different fuel efficiency may have substantially different emission factors. Therefore, more fuel-efficient cars can contribute in solving a public health concern that has become central for policy-makers. Finally, fuel efficiency determines the fiscal bases of motor fuel taxes, which constitute primary sources of government revenue in many countries.

Fuel efficiency projections can be an important instrument in the toolkit of policy makers. In an era in which nations commit to more ambitious carbon reduction goals, it is necessary to obtain a reliable picture of how future cars will look like. The fuel consumption of internal combustion engine (ICE) vehicles entering the market in 2021-2050 will play a twofold, ambiguous role in the greenhouse gas emissions of transport sector.[3] On the one hand, less fuel-demanding ICE vehicles will save CO_2 emissions, generating a positive environmental effect. On the other hand, a gradual increase in ICE fuel efficiency will increase their use. More importantly, it will help them maintain their competitive advantages vis-à-vis electric (EVs) and other alternative fuel (AFVs) vehicles for a longer time. Thus, fuel efficiency innovation in ICE vehicles can be a "*grey innovation*", in the sense that it introduces a series of negative rebound effects that may completely offset the direct gains it generates.[4] To understand how socially (un)desirable this type of grey innovation is, policy makers need to obtain a plausible estimate about its future *scale*. Such an estimate can also indicate how intense policy interventions will need to be in order to ensure a widespread transition to electromobility. Finally, the estimate constitutes the necessary benchmark to calculate the CO_2 savings from such a transition.

This paper projects the fuel efficiency of gasoline ICE vehicles from the supply side. The projection focuses on the period 2021-2050, which constitutes the critical time window to achieve carbon neutrality. The forward projection is obtained by first performing econometric analysis using historical sales-unweighted data by US EPA on the fuel efficiency of vehicle models that entered the US market in the period 1984-2020. The analysis accounts for the effect of time-varying vehicle characteristics affecting fuel consumption, such as engine size and the number of cylinders. It also controls for pre-tax gasoline prices, as well as for policy-driven influence, in particular that from gasoline taxes and fuel efficiency regulations.

[1] This paper treats the term fuel efficiency as a synonym of fuel economy. Part of the literature distinguishes between those two terms. For example, Lutsey and Sperling (2005[1]) define fuel efficiency as being "weight-corrected" (*i.e.* as fuel economy multiplied by vehicle weight). This allows fuel efficiency to increase faster than fuel economy when mean vehicle weight increases, and *vice versa*.

[2] U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), at https://www.energy.gov/eere/about-office-energy-efficiency-and-renewable-energy.

[3] So far, these emissions display a remarkable rigidity to technological progress and relevant policy interventions (ITF Transport Outlook, 2021[21]; Energy Efficiency – IEA, 2019[19]; Tracking Transport - IEA, 2020[20]).

[4] The concept of grey innovation is comparable to that of dirty innovation discussed by Aghion et al. (2016[22]), who examine the impact of relevant policies on energy efficiency patents in car industry.

In that sense, the analysis aims to isolate the portion of the technical progress that is "autonomous" from the parts that are induced by environmentally relevant policies and market forces. That is, in the context of this paper, such progress does not occur because of peaks in crude oil prices. Neither does it manifest itself due to increases in motor fuel taxes or other factors strengthening the incentives of manufacturers to produce vehicles that economize more fuel. Rather, *autonomous technical change* is assumed to stem from spillover effects, pure competition dynamics, the size of the largest manufacturers and that of the international market for private vehicles. Existing literature estimates a statistically robust and economically substantial effect of firm[5] and market size[6] on innovation, with the former facilitating the absorption of larger upfront investment costs and the latter fostering Smith-type of specialization. The overall accumulation of knowledge in the industry, and the advances in relevant production techniques can reinforce autonomous technical change originating from market size and structure. Importantly, the channels mentioned here are still relevant for economic policy, but the present study assumes that environmentally relevant policies exert a negligible effect on them. To estimate the autonomous trend and the role of environmental policy components in the supply of more fuel-efficient cars, the study uses additional data to that by US EPA. These include pre-tax crude oil prices, gasoline taxes and the stringency of fuel efficiency standards.

The innovation generated by oil price fluctuations and that stemming from taxes and regulatory standards in the US and the EU can be used in *ex-ante* policy analysis and *ex-post* policy evaluations. From an *ex-post* viewpoint, the study computes the relative contribution of policy components in the observed technological progress regarding fuel efficiency. From an *ex-ante* viewpoint, it projects technological change beyond the sampling period (1984-2020), under different scenarios for the evolution of its key drivers. In many of these scenarios, the underlying factors evolve to obtain out-of-sample values. Most importantly, forward simulations estimate the impact of widely discussed climate-change mitigation policies on the fuel efficiency of future gasoline cars. A characteristic example of such a policy is the carbon tax, whose effect is simulated using the relevant estimated marginal effects.

The results indicate that autonomous technical change represents 60.2% of the positive contributions to fuel efficiency of cars entering the US market in the sampling period. The rest of the positive contributions originate from policy-relevant components, *i.e.* the gradual rise in Corporate Average Fuel Economy (CAFE) standards (29.7%) and the fluctuations in gasoline costs (10.1%). Since 1984, these three factors have raised average fuel efficiency by 17%. On the other hand, the characteristics of the average vehicle entering the market display systematic changes that offset part of the aforementioned progress. These changes include the increasing prevalence of automatic gearing configurations and four-wheel drivetrain systems. The growing presence of new combustion technologies, such as the turbocharger, as well as the overall evolution towards heavier cars with larger engines contribute to this offsetting mechanism.

Forward simulations indicate that if ICE cars are not phased out in the coming decades, their fuel efficiency will continue increasing. With CAFE standards raising at a pace comparable to that observed in the last decades, that fuel efficiency increase is estimated to be 6-7%. Positive shocks in the gasoline costs, stemming from either oil prices or gasoline taxes, can contribute to a further increase. That is estimated to be between 0.9% and 1.4%, depending on the scenario for the gasoline cost evolution. Furthermore, the simulations indicate that the shock in gasoline costs generated by the implementation of a carbon tax may

[5] Some notable empirical contributions (Mansfield, 1963[23])support the hypothesis that innovation in certain sectors require large upfront investment costs. That stream supports the premise that larger firms can absorb such costs more easily. Other studies suggest that innovation increases with competition (e.g. Blundell, Griffith and Van Reenen, 1999[28]). The inverted U-shape theory, hinted by Scherer (1967[24]) and formulated by Aghion et al. (2005[25]) suggests a non-monotonic relation between competition and innovation.

[6] For innovation in the pharmaceutical industry, Dubois et al. (2015[26]) keep track on the number of chemical entities per class of disease. They estimate the point elasticity of this proxy with respect to market size to be 0.23. When considering the number of approved drugs, Acemoglou and Linn (2004) find a much higher elasticity, i.e. between 4.0 and 6.0.

have an additional contribution. For the carbon tax corresponding to the high-impact scenario developed by the US EPA, this additional contribution ranges between 0.6% and 1.3%. The predicted gains remain considerable (*i.e.* 0.2-0.6%) for the implementation of a carbon tax derived in the regular scenario with an annual discount rate of 2.5%. Finally, the offsetting factors (*e.g.* vehicle weight, four-wheel drive) are expected to continue offsetting part of the progress. However, the magnitude of their negative contribution is expected to be considerably smaller than that in the sampling period.

The paper makes multiple contributions to the literature. First, it goes beyond previous attempts to estimate the relative importance of various factors affecting fuel efficiency. It provides updated estimates by improving the control variables and specifications used so far. To that end, it develops a dynamic gasoline consumer-cost index for the OECD countries, which −apart from fluctuations in oil prices− incorporates perturbations in gasoline taxes. Therefore, in contrast to previous efforts, the study controls for the effect gasoline taxes in countries other than the US may have on the fuel efficiency of automobiles entering the US market. Such a cross-market effect is possible because the automobile models in the US EPA dataset could also enter the markets where these taxes apply (*e.g*. the EU market). In addition, the econometric specifications employed in the model isolate the permanent impact of positive shocks in gasoline costs fuel efficiency from other transitory impacts. Such transitory effects may occur via changes in the manufacturing techniques, *e.g.* by using different materials or known production methods, and could result in a less energy-consuming car. However, such changes are non-permanent, as they are reversible in declining oil price periods. In contrast, the non-transitory impact estimated in this paper is not reversible and can be interpreted as a *pure innovation effect*. In this sense, the paper contributes to the existing literature on Hicksian innovation[7] by specifically examining the impact of a carbon tax on this type of innovation in automobile industry. Finally, the paper provides a dynamic benchmark for comparing the well-to-wheel CO_2 emissions of future conventional vehicles to those generated by future electric vehicles. In that sense, it contributes to a growing stream of literature attempting to estimate the economic and environmental consequences from a major proliferation of electromobility.

The rest of the paper is organised as follows. **Section 2** reviews the most relevant literature. **Section 3** presents in detail the methodological aspects of the study. It elaborates on the data and the econometric specifications used for the analysis in the sampling period (1984-2020), as well as on the projection techniques used in the forward simulations (2021-2050). **Section 4** displays the corresponding results from the econometric analysis and simulations. **Section 5** concludes.

[7] Hicksian innovation is not induced by the institutional framework that protects the post-entry rents of the innovator (Schumpeterian effect), or by policies that intensify competition in industries without a distinct technological leader. Rather, it is stems from an increase in the generalized user cost of a commodity, which generate incentives to produce cost effective alternatives. For example, Popp (2002[27]) examines the role of energy taxes in energy efficiency using US patent data for the period 1970-1994.

2 Literature review

The literature on car fuel efficiency and its evolution is voluminous and diverse. This study primarily relates to contributions attempting to explain that evolution using statistical and econometric approaches. The following review classifies these studies based on a series of features. First, it examines whether fuel efficiency is defined exclusively in the supply side, or if it includes demand by considering past and current vehicle sales. In the former case, fuel efficiency pertains to that of newly produced vehicles only. In the latter case, it refers to that of newly sold vehicles or of the circulating vehicle stock. This distinction is crucial, as predicting the latter type of fuel efficiency requires vehicle stock and sales data, as well as data tracking changes on the demand side (*e.g.* consumer preferences). Second, the review considers whether the examined studies project the fuel efficiency forward in the future, and whether they simulate a policy counterfactual scenario, within or beyond their sampling period. Finally, the review focuses on several technical aspects of pre-existing contributions, such as their geographic coverage and the treatment of time trend.

Some of the most relevant studies make use of earlier versions of the US EPA dataset used in this study. Therefore, they attempt to explain the evolution of fuel efficiency of new car models entering the market (supply-side fuel efficiency) and not that of the active vehicle fleet. Lutsey and Sperling (2005[1]) analyse the trend of fuel efficiency for light-duty vehicles in the U.S. focusing on three periods: 1975-1980, 1980-1987 and 1987-2004. They control for vehicle size, weight, engine and drivetrain efficiency, aerodynamic drag and rolling resistance. They argue that fuel efficiency has been relatively stagnant in the last two periods because fuel efficiency improvements have been largely offset by increases in vehicle size and motor power. Despite offering insights on how CAFE standards could have affected fuel efficiency in the three consecutive periods, the study does not control for them. Knittel (2011[2]) estimates fuel efficiency controlling for weight, horsepower, torque and other vehicle characteristics. Fuel prices, taxes and efficiency standards are omitted from the analysis. Therefore, the estimated time trend embodies components that are not relevant to the autonomous technical change discussed in the introduction of the present study. Such components include the impact of time-varying policies and the influence of the international environment (*e.g.* fuel prices). As a result, the econometric analysis by Knittel (2011[2]) is more suitable to uncover the impact of vehicle characteristics upon fuel efficiency, and less suitable for developing policy scenarios on the future of the latter. MacKenzie and Heywood (2015[3]) conducted another supply-side study, tracking the fuel efficiency of cars entering the US market in the period 1975-2009. The study accounts for a series of important covariates, such as the vehicle weight and acceleration, whose effect on fuel consumption has been highlighted by earlier engineering literature[8]. The statistical model they employ includes time fixed effects, which however embody the influence of policies, fuel prices and other time-varying unobserved variables. The contribution by Wang and Miao (2021[4]), which relies also on the EPA dataset, controls for CAFE standards and fuel prices, but not for fuel taxes. The study finds no significant effects of CAFE regulations on the fuel efficiency of light duty trucks. The fuel efficiency elasticities of passenger cars with respect to CAFE standards and fuel prices are found to be 0.15 and 0.03 respectively.

[8] Notable contributions with physical modelling of fuel consumption include: Wong, 2008 ([32]); Kasseris, 2006 ([31]); Leduc et al., 2010 ([33]); Rakha et al., 2011 ([34]); DeCicco, 2010 ([35]); Duarte, Gonçalves and Farias, 2016 ([36]); Orfila et al., 2017 ([37]); Fontaras, Zacharof and Ciuffo, 2017 ([38]).

Some studies control for several key variables this paper focuses on, but they estimate their impact on *vehicle stock* or *new sales*, rather than the supply side. In these studies, it is not possible to distinguish the degree to which fuel efficiency improvements in newly sold cars or existing stocks originate from the production of more fuel-efficient cars or the shift of the demand side towards them. Goldberg (1998[5]) uses US expenditure data to estimate the impact of CAFE standards on the demand side, *i.e.* on a sequence of interrelated household choices, such as vehicle ownership, type of vehicle and degree of vehicle utilisation.[9] The study contains a supply-side analysis, which is however based on simulations. Van Den Brink and Van Wee (2001[6]) study the fuel consumption of the Dutch car fleet between 1980 and 1997 using descriptive statistics and results from pre-defined statistical models. They conclude that fuel consumption has not significantly decreased since late 1980s because demand shifted towards heavier cars of higher cylinder capacity. That had an offsetting impact that neutralised improvements in fuel efficiency. They evaluate the influence of fuel taxes and car-weight tax on fuel efficiency and conclude that fuel taxes generated a 2-5% increase in that. Kwon (2006[7]) examines the separate effect of engine capacity on the fuel efficiency of UK's car stock and new sales, and extracts an aggregate time trend that does not separate policy from other time-varying components. Clerides and Zachariadis (2008[8]) use cross-country time series data to explain the fuel efficiency of *new* vehicles sold in 18 countries. Their analysis employs aggregate data rather than micro-level data from the producer side, thus it is not suitable for examining the responses of producers to policy changes. Their econometric models include a time trend and control for fuel prices, time-invariant country characteristics and income. They find that standards induced substantial fuel savings in the examined countries. Sprei, Karlsson and Holmberg (2008[9]) explore how technological attributes such as the frontal surface area, weight, maximum power and cylinder displacement volume may have affected fuel consumption of new personal cars bought between 1975 and 2002 in Sweden. They find that between 1985 and 1995 most of the technological progress was offset by an increase in consumer amenities. However, between 1995 and 2002, the demand for relevant features increased less compared to the previous period, while technological and design improvements continued. In total, Sprei, Karlsson and Holmberg (2008[9]) find that fuel consumption decreased by 12% between 1985 and 2002. Using simulation methods, they argue that fuel consumption would have increased by 23% in the same period, had it not been for specific technological developments. Using sales data, Leard *et al.* (2017[10])and Klier and Linn (2012[11]) find that prices have a non-symmetric effect on the fuel efficiency of newly purchased vehicles. That effect is statistically significant and considerable in periods of positive fuel price shocks, but negligible in periods of negative price changes. Fleet-averaged fuel efficiency responds slowly to policy changes, as it evolves only through the depreciation of older, more fuel-demanding vehicles that exit the stock and the purchase of new, less fuel-demanding vehicles entering the stock. Therefore, econometric approaches attempting to estimate the effects of policy on it (Espey, 1996[12]; Johansson and Schipper, 1997[13]) provide insightful projections, but demand long time series for the policy impacts to be identified.

Finally, earlier work has also compared the welfare impacts of fuel efficiency regulations and the fuel tax. Kleit (2004[14]) finds that the social cost of CAFE standards is 14 times bigger than that of a gasoline tax that could achieve the same reduction in gasoline consumption. Austin and Dinan (2005[15]) find that a USD 0.36 tax on gasoline could reduce gasoline consumption by the same amount as the CAFE standards, and at 58% lower cost. As none of these analyses explicitly considers the effect these policies may have on innovation, the present study can provide inputs to future contributions that may expand towards this direction.

[9] Some notable contributions specifically on the impact of fuel efficiency on vehicle utilization include: Mannering and Winston (1985[30]), Mayo and Mathis (1988[29]), Greene (1992[28]).

3 Methodology

3.1. Econometric model

3.1.1. Main components

The following econometric model is provided in a generalised form, from which the econometric specifications used in each separate model are derived with some restricting assumptions. The model predicts the fuel efficiency of vehicle i with body type x, produced by manufacturer m, appearing in the market in year y of a five-year period t:

$$\log(E_{ixmyt}) = \alpha + B_{xt} + B_m + \sum_q (\beta_q \mathrm{x}_{qi}) + \Gamma_{yt} + G_{ixmyt} + \varepsilon_{ixmyt} \qquad (1)$$

where E_{ixmyt} is expressed in kilometres per litre of gasoline. Equation (1) consists of several distinct systematic components. The first component, α, is the intercept of the regression equation representing the logarithm of the sample mean of fuel consumption. The second term is:

$$B_{xt} = \begin{cases} 0 & \text{in models without body type fixed effects} \\ \sum_x (\beta_x D_{ix}) & \text{in models with static body type fixed effects} \\ \sum_x \sum_t (\beta_{xt} D_{ix} D_{it}) & \text{in models with dynamic body type fixed effects} \end{cases} \qquad (2)$$

where D_{ix} (respectively D_{it}) is an indicator (i.e. dummy variable) that equals one if vehicle i belongs to class x (or, respectively, has entered the market during the 5-year period t), and zero otherwise. The parameter β_x represents the constant-over-time deviation of the fuel efficiency of type x vehicles from the sample mean. In specifications where the 5-year period dummies interact with body-type dummies, that deviation is dynamic. Then, the time sequence of estimated values of β_{xt} mimics a time trend that is specific to each vehicle class.

Second, fuel consumption varies at the manufacturer level, as some firms may possess relevant patents and utilise production techniques that result in more fuel-efficient cars. Comparative advantages that manifest at the firm level are captured by the term B_m:

$$B_m = \sum_m (\beta_m D_{im}). \qquad (3)$$

where β_m is a manufacturer fixed effect and D_{im} is a dummy variable that equals one if vehicle i has been constructed by manufacturer m. Due to the large number of manufacturing firms in the sample, it is not possible to estimate a reliable manufacturer-specific time trend without sacrificing a critical part of the variation of fuel efficiency in the sample. Therefore, equation (3) does not contain an interaction between manufacturer-specific and period-specific dummy variables. Overall, fixed effects β_x and β_m capture the impact of unobserved vehicle characteristics that affect fuel consumption and may systematically differ across manufacturers and body types.

Moreover, certain observable attributes of each vehicle i are related to its fuel consumption. In line with pre-existing engineering and statistical literature, the study controls for engine size and the number of cylinders in the engine. It also controls for the presence of features associated with the energy needs of a car, such as the four-wheel drivetrain, turbocharge and the automatic gear system. In equation (1), the level of any such attribute q (0 or 1 for binary variables) that is present in vehicle i is denoted by x_{qi}. The attribute is expressed in levels, so it exerts per se a marginal impact on fuel consumption that is approximately $100 * \beta_q\%$.

Importantly, the fuel efficiency of any vehicle is underpinned by an *autonomous technological trend*, here denoted by Γ_{yt}. That is, the degree and type of competition among car manufacturers may change over time, reinforcing or weakening their incentives to produce vehicles that are more economical. Improvements occur either by innovation or via use of input materials that economise fuel. This trend is captured in two different ways. In specifications with a linear time trend, autonomous technical change causes average fuel efficiency to grow at a steady annual rate that equals γ. More flexible specifications approximate the autonomous trend with 5-year period fixed effects, allowing that rate to fluctuate with time. In summary:

$$\Gamma_y = \begin{cases} \sum_t (\gamma_t D_{yt}) & \text{flexible 5} - \text{year fixed effects} \\ \gamma\,(y - y_0) & \text{linear time trend} \end{cases} \tag{4}$$

where y denotes year, y_0 is the initial year of the sampling period (1984), t is a 5-year period (e.g. from year i to year i+5), and D_{yt} is a dummy variable that equals one if year y belongs to period t (zero otherwise).

The autonomous trend is purified from the impact of international economic environment and country policies with a distinct environmental component. The latter factors may also induce or hamper innovation in the car industry. Their impact is captured by the term G_{ixmyt} in (1), which is:

$$G_{ixmyt} = Q_y + \underbrace{\left(\sum_r \beta_{US}^r\, I_{r,m}\right)\log(S_{US,y,i})}_{\text{effect of CAFE standards}} + \underbrace{\left(\sum_r \beta_{EU}^r\, I_{r,m}\right)\log(S_{EU,y})}_{\text{effect of EU standards}}.$$

(5)

In equation (5), Q_y is a component isolating the portion of fuel efficiency attributed to positive fuel cost shocks. These originate either from gasoline price or gasoline tax changes that occurred in years before y. This effect, discussed in detail in **Section 3.1.4**, is separated from those stemming from the effects US and EU regulations have on vehicle fuel efficiency, also appearing in equation (5). The model allows the latter impacts to be differentiated according to the *regional origin of a manufacturer*, denoted by r. The next section focuses on entirely on how effects from efficiency standards are modelled in this study.

3.1.2. Fuel efficiency standards

The fuel efficiency standards are modelled separately for the two largest markets of the OECD where compliance is mandatory, *i.e.* the EU and the US.

For the EU, mandatory standards are active roughly since 2008, as the Council of Environment ministers adopted a formal scheme in June 2007. Prior to that, voluntary agreements set an industry-wide target at approximately 16.6 km/litre. The EU-standard fuel efficiency target in this study sets off from this level. Subsequent targets set by the European Parliament and the Council are 17.85 km/litre for 2015, and 24.21 km/litre for 2020. The transition from 2008 to 2015, as well as from 2015 to 2020 is assumed to be linear, giving rise to the piecewise linear target scheme displayed by the solid line of Figure 3.1.

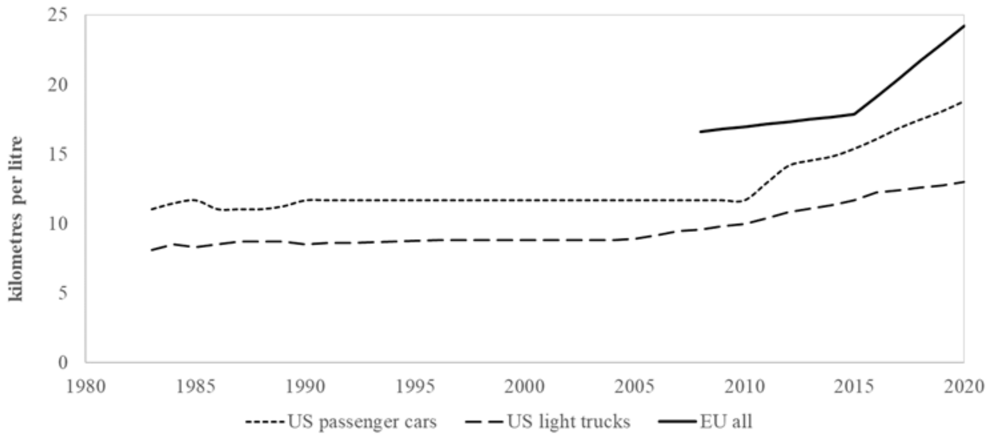
Mandatory fuel efficiency standards in the US, widely known as CAFE standards, were introduced in 1978. They are separate for cars and light duty trucks, and display a much more complex pattern. For passenger cars, they rose in the period 1978 to 1990, subsequently stagnated for twenty years, to start rising again from 2010. The evolution of standards for the light duty trucks is similar, but the stagnation period is shorter and the subsequent rate of growth slower. CAFE standards closely relate to Corporate Average Fuel Consumption (CAFC) targets set by Canada. The latter standards have been fully aligned with CAFE since 1975, but remained voluntary until 2007.

In equation (5), $S_{US,y,i}$ is the level of US CAFE standard that applies to vehicle i in year y. This is measured in kilometres per litre and is given by:

$$S_{US,y,i} = I_{iC}\, S^{C}_{US,y} + I_{iT}\, S^{T}_{US,y} \tag{6}$$

where $S^{C}_{US,y}$ and $S^{T}_{US,y}$ respectively denote the level of US CAFE standard applying to passenger cars and light trucks in year y, and I_{iC} (respectively I_{iT}) is a dummy variable that equals one if vehicle i is a passenger car (respectively light truck). The fuel efficiency standards introduced in the EU are uniform across vehicle types and equal $S_{EU,y}$. The impact exerted by the level of fuel efficiency standards on the fuel consumption of vehicle i of manufacturer m ($i.e. \beta^{r}_{US}, \beta^{r}_{EU}$) is allowed to vary across the geographical origin of the manufacturer, *i.e.* r. The dummy variable $I_{r,m}$ in equation (5) is included to this end. It equals one if manufacturer m originates from aggregate region r, and zero otherwise. The considered regions include the US, the EU and Asia, which mainly contemplates Japanese and Korean manufacturers. Parameters β^{r}_{US} and β^{r}_{EU} represent the fuel efficiency elasticity of a vehicle introduced to the US market by a manufacturer that originates from region r, with respect to CAFE (US) and EU standards respectively. According to this specification, CAFE standards have a different impact on the models of US, European and Asian manufacturers, as their market shares may substantially differ in the rest of the world (where their cars are also sold) compared to the US. Similarly, the impact of European standards is allowed to be different from this of CAFE standards. European standards exert a potential impact on their fuel efficiency because the examined vehicles are potentially sold in the European market as well.

Figure 3.1. Fuel efficiency standards in the US and the EU.



3.1.3. Construction of fuel cost index

1. The fuel price index, P_{yt}, is a weighted average of the after-tax gasoline prices in the US and the rest of the OECD countries:

$$P_y = (w_{y,US}\, p_{y,US}) + ((1 - w_{y,US})\, P_{y,R}) \quad (7)$$

where $p_{y,US}$ is the after-tax cost of gasoline in year y in the US, expressed in USD per litre; $P_{y,R}$ is a price index for the same year in the rest of the OECD countries; $w_{y,US}$ is the relative weight to $p_{y,US}$. The price index $P_{y,R}$ is a weighted average of the after-tax cost of gasoline in countries other that the US, *i.e.*:

$$P_{y,R} = \sum_{c \neq US} (w_{y,c}\, p_{y,c}). \quad (8)$$

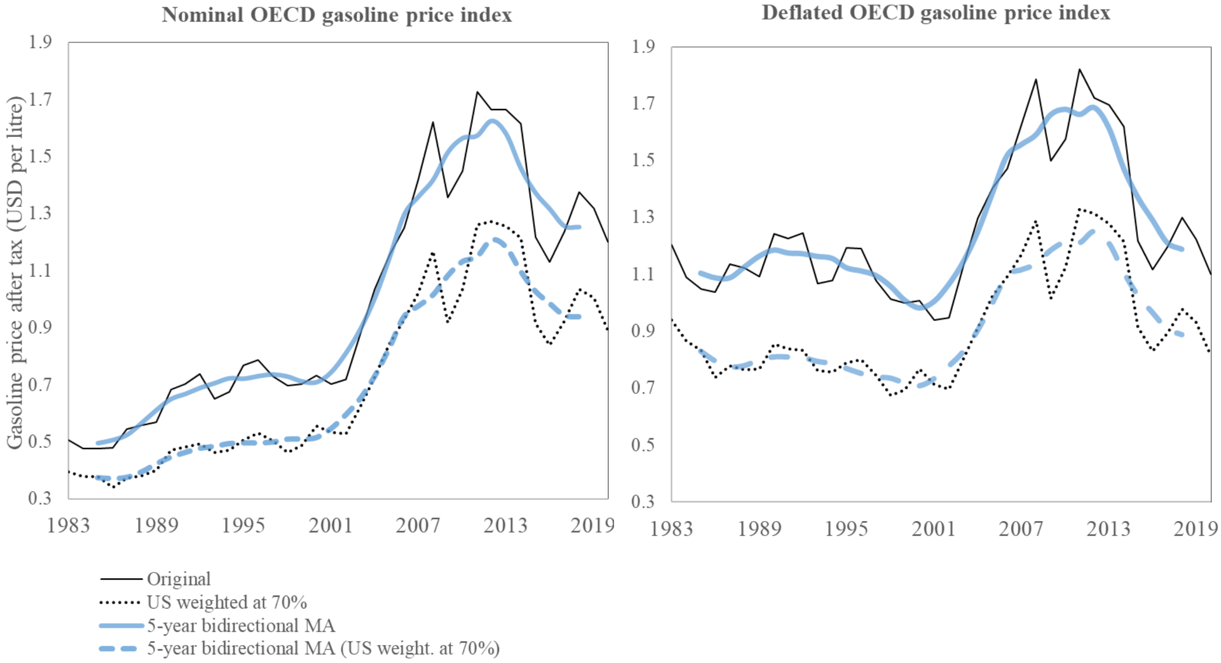
Different weights $w_{y,c}$ result in different time series of $P_{y,R}$. The weight used in this study is the share of country c in the total value of traded vehicles. These are:

$$w_{y,c} = V_{c,y} \Big/ \sum_{k \neq US} V_{k,y} \quad (9)$$

$$w_{y,US} = V_{US,y} \Big/ \sum_{k} V_{k,y}\,. \quad (10)$$

The denominator of (9) represents the total trade volume of vehicles recorded in year y in all countries of the sample except for the US. The numerator, $V_{c,y}$, is the trade volume recorded during the same year in one of these countries, c. In contrast, the denominator in equation (10) represents the corresponding volume in all countries of the sample, including the US, and the numerator, $V_{US,y}$, is the contribution of the US in that volume. An implicit assumption made here is that the larger the relative size of a country's car market, the more likely it is for an arbitrary car in the sample to be also sold there. For example, Germany possesses a relatively large market.[10] Therefore, equation (9) indicates that the fuel index should weight more the gasoline prices in Germany, compared to another country with a smaller car market. Different time series for P_y are derived by replacing the weight given to the US market in equation (7) by any exogenous weight that does not equal the one derived by (10). In general, weighting markets with larger volumes heavier implies that the manufacturers' incentives to improve fuel efficiency intensify more when the fuel tax increases in larger markets.

Figure 3.2. Gasoline price index



Note: The deflated OECD gasoline price index is expressed in 2015 USD. Bidirectional MA refers to a moving average filter that accounts for both past and future values. Graph generated by the authors.

Finally, gasoline prices $p_{y,c}$ used in equations (7) to (10) are weighted average values of the various gasoline taxes with observable values in country c and year y is:

$$p_{y,c} = \begin{cases} I_{yc}^L \, w_{Ly} \, p_{cy}^L + I_{yc}^U (1 - w_{Ly}) \, p_{cy}^U & \text{if both } p_{cy}^L \text{ and } p_{cy}^U \text{ available} \\ \left[(1 - I_{yc}^L) \, p_{cy}^U \right] + \left[(1 - I_{yc}^U) \, p_{cy}^L \right] & \text{if } p_{cy}^L \text{ or } p_{cy}^U \text{ is available} \end{cases} \quad (11)$$

where w_{Ly} is the weight given to leaded gasoline values in year y, and $(1 - w_{Ly})$ the remaining weight given to unleaded gasoline prices. The weight of the leaded gasoline price is given by the negative exponential function $w_{Ly} = e^{-\omega \cdot (y-1980)}$, implying that the importance of the leaded gasoline tax relative to the unleaded gasoline tax declines with time.[11] Variable I_{yc}^L (respectively I_{yc}^U) is an indicator obtaining the value of one if leaded (respectively unleaded) gasoline prices are available in country c during year y.

[10] Germany possessed 13.5% of the total market volume in the countries of the sample in 2020.

[11] Parameter ω is set to 0.07489, implying leaded gasoline receives full weight in year 1980, but that weight declines to 0.05 in year 2020.

The latter prices are respectively denoted by p^L_{cy} and p^U_{cy}, and are computed as weighted averages of the various types they contemplate, in particular regular and premium. It should be noted that whenever one of the two prices are not observed, equation (11) automatically assigns a full weight to the other price. Furthermore, $p_{y,c}$ is defined only if $I^L_{yc} + I^U_{yc} > 0$, *i.e.* if at least one of the two prices is observable. In the opposite case, $p_{y,c}$ is not computable. In that case, country c is excluded from the country sample for year y and equations (7)-(10) do not include its trade volume that year (*i.e.* $V_{c,y}$). Figure 3.2 displays the resulting index in nominal and real terms.

3.1.4. Modelling the effect of fuel cost shocks on innovation

To capture the effects of fuel price shocks on the fuel efficiency of vehicles, the model uses the auxiliary function:

$$Q_y = Q_0 + \sum_{j=1}^{J} \Big(\delta_j \, \Delta p_{j-1,j} \, I\big(p_j > p_{j-1}\big) \, I\big(y > y_F(j)\big) \Big) \tag{12}$$

where j is a time period from J periods of comparable length[12] (*e.g.* seven years), $\Delta p_{j-1,j}$ is the difference between the *average* value of the fuel cost index (as defined in **Section 3.1.4**) in periods j-1 and j. The indicator $I\big(p_j > p_{j-1}\big)$ obtains the value of one if that difference is positive. Similarly, the indicator $I\big(y > y_F(j)\big)$ obtains the value of one if the year of interest y precedes or equals the terminal year of period j, denoted by $y_F(j)$. Therefore, the right hand side of equation (12) can be seen as the portion of fuel efficiency that stems entirely from the positive fuel cost shocks that accumulate with time. That is, the function Q_y accumulates the innovation triggered by any positive shock that took place from the beginning of the sampling period until the end of period j in which year y belongs. The parameter δ_j transforms that aggregated shock into additional fuel efficiency. It is the percentage increase in the number of kilometres traversed per litre of fuel caused by a one USD increase in that aggregate shock. The transformation is contemporaneous and irreversible, *i.e.* negative price shocks in future periods (j+1,.., j+K) are restricted from destroying the amount of learning created due to the positive price shock in period j. Therefore, the function in (12) is non-decreasing in time. Restricting the contemporaneous effect to be equal for each period yields:

$$Q_y = Q_0 + \delta \underbrace{\sum_{j=1}^{J} \Big(\Delta p_{j-1,j} \, I\big(p_j > p_{j-1}\big) \, I\big(y > y_F(j)\big) \Big)}_{\text{accumulated positive fuel cost shocks}}. \tag{13}$$

Parameters δ and δ_j are estimated simultaneously with the rest of the parameters in the model.

3.2. Data

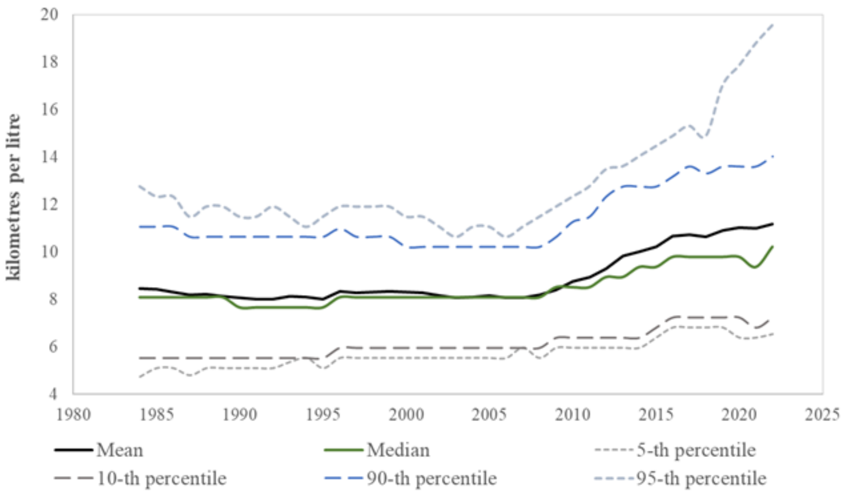
The primary data source enabling the study is the US Environmental Protection Agency (EPA) dataset on fuel efficiency. The dataset keeps track of all new vehicle models entering the US market since 1984 in a sales-unweighted fashion, records their features and provides estimates about their fuel efficiency.[13]

[12] The model accounts for a total of six periods, which are defined as: 1984-1985, 1986-1992, 1993-1999, 2000-2006, 2007-2013, 2014-2020.

[13] Those data are not sales-weighted, which means that the data is at the vehicle model level, and not at the individual vehicle level.

These estimates are generated *via* vehicle testing done at the EPA's National Vehicle and Fuel Emissions laboratory or at the manufacturer's site with oversight by EPA. The sampling period spans the years from 1984 to 2020, exploiting the latest available data. This ensures maximum comparability of fuel efficiency estimates across the years. Figure 3.3 summarizes the overall intertemporal evolution of the fuel efficiency of all vehicle models entering the US market from 1984. The mean fuel consumption of the average newly produced vehicle remained roughly stable between 1984 and 2008. During the same period, the 5th and 10th percentile increased slightly, while the 90th and 95th percentiles decreased. Since 2008, mean fuel efficiency increased substantially, and at a considerably faster pace compared to the median. The deviation of the mean from the median indicates an asymmetric technological progress, as the economy of relatively efficient vehicles increased faster than that of more fuel-demanding vehicles.[14]

Figure 3.3. Historical evolution of fuel efficiency of vehicle models entering the US market



Note: Metrics in the figure refer to the sales-unweighted distribution of vehicle fuel efficiency for models entering the U.S. market.

For the historical evolution of the gasoline tax, *i.e.* the variable T_{cy}^{G} in **Section 3.1**, the study uses data by IEA Energy Prices and Taxes Statistics dataset (2021). These data span the period from 1978 to 2021 and are available for several gasoline types, such as regular and premium leaded, regular unleaded, premium unleaded 95 and 98. The study uses the OECD Structural Analysis (STAN) Database on Bilateral Trade, which tracks the value flows of vehicle imports between pairs of OECD countries in the entire time window of the study. Data on CAFE standards are collected from the Alternative Fuel Data Centre from the US Department of Energy. They span the period from 1978 to 2025, and contain differentiated limit values for passenger cars and standards for light-duty trucks.[15] Data on EU Standards originate from the Global Fuel Economy Initiative and cover the period from 2008 to 2020.[16] The carbon tax estimates are collected from a technical support document on the social cost of carbon, methane and nitrous oxide, prepared by an interagency working group on social cost of greenhouse gases (2021[16]).[17]

[14] Therefore, the distribution of fuel economy roughly retained its shape and position in the period 1984-2008, while its right tail expanded in the period following that year.

[15] CAFE standards values can be retrieved at: https://afdc.energy.gov/data/10562.

[16] UE Standards values can be retrieved at: https://www.globalfueleconomy.org/transport/gfei/autotool/case_studies/europe/cs_eu_0.asp.

[17] The report provides different projections for the social cost of carbon based on different discount factors and scenarios. The values used here come from its latest version, which updated upwards the social cost of carbon.

3.3. Projection methods

The estimates from the regressions, which are provided in **Section 4.1**, are used in conjunction with scenarios about the evolution of the key variables entering the econometric model.

3.3.1. The impact of gasoline price shocks and the carbon tax on fuel efficiency

The impact of future shocks on the gasoline price index can be simulated using equation (13), the estimate of parameter δ, as well as additional assumptions for the evolution of the fuel cost index exhibited in **Section 3.1.3**. Three baseline scenarios are examined, all of which are based in autoregressive statistical relations between the current and the past levels of the index. **Scenario A** creates the *best possible forecast* of the index based on the partial autocorrelation function (PACF). Sequential estimation of autoregressive models AR(q) with a number of lags ranging from one ($q = 1$) to ten (q = 10) reveals that the first lag of the index, p_{y-1}, is the only robust predictor of p_y. Therefore, the econometric model used in this scenario is: $p_y = \mu + \varphi_1 \, p_{y-1} + \eta_y$. It gives rise to a non-stationary series, as both the Dickey-Fuller test and the t-test on the null hypothesis $\varphi_1 = 1$ fail to reject the non-stationary hypothesis at any conventional level of significance (p-value).[18] **Scenario B** is referred to as *almost stationary*, as it uses an autoregressive model that can generate projections that lie as close as possible to stationarity. **Scenario C** projects the index using a substantially smaller constant μ' than the respective OLS estimator μ. This somewhat judgemental scenario describes an environment where motor fuel prices decline globally, mainly because the exploitation of fossil fuels ceases. As it will be shown later, this scenario implies a stagnant innovation environment when it comes to improving fuel efficiency of conventional vehicles. The pre-carbon tax index in the three baseline scenarios is:

$$\hat{p}_y = \begin{cases} \mu + \varphi_1 \, p_{y-1} + \eta_y & \text{Scenario A: best possible forecast} \\ \mu + \varphi_1 \, p_{y-8} + \varphi_2 \, p_{y-10} + \eta_y & \text{Scenario B: (almost) stationary} \\ \mu' + \varphi_1 \, p_{y-1} + \eta_y & \text{Scenario C: declining oil prices} \end{cases} \tag{14}$$

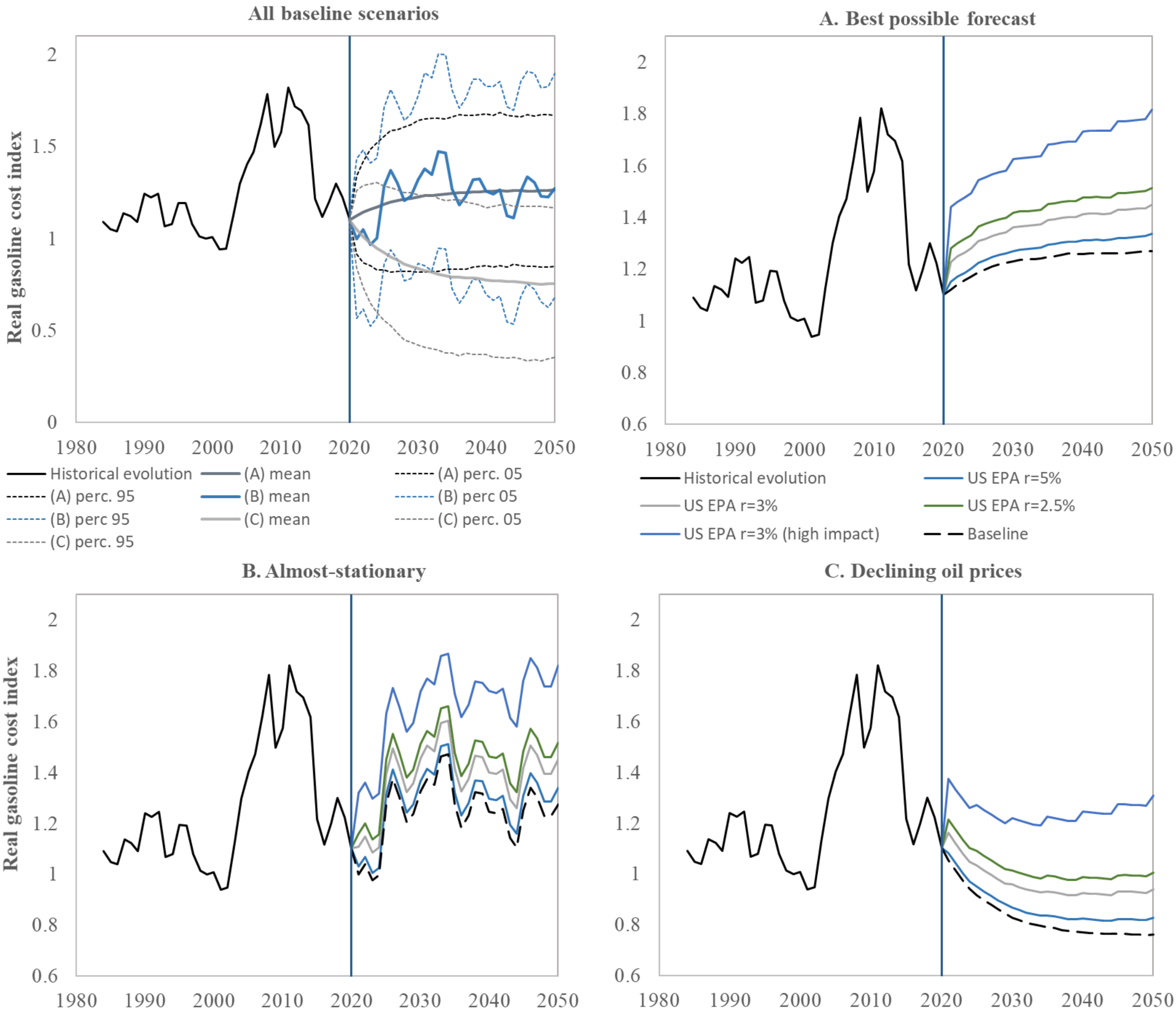
where μ and φ are parameters and η is a random term distributed $N(0, \sigma^2)$. The fuel cost index p_y includes the carbon tax ($\tau^C_{y,s}$) and is:

$$p_y = \hat{p}_y + \tau^C_{y,s} \tag{15}$$

where subscript s denotes the scenario for the evolution of the carbon tax. Therefore, $\tau^C_{y,s} = 0$ in scenarios where the carbon tax is inactive. In scenarios where it is active, its value is converted from USD per ton of CO_2 to USD per litre of gasoline. These scenarios are based on different discount rates and assumptions on the impact of climate change consequences. The first three assume a discount factor of 5%, 3% and 2.5% respectively. The fourth scenario discounts damages at an annual rate of 3%, but assumes that these damages have a higher impact (95th percentile of the impact distribution). The gasoline price index time series are simulated for the period 2020-2050. They are transformed to Q_y values, *i.e.* to percentage increases in fuel efficiency (km/litre) using equation (13), and the estimate $\hat{\delta}$. To obtain an approximation of the entire distribution of Q_y, the simulation is repeated multiple times.

[18] Dickey-Fuller test statistic is -1.7512 yielding a p-value if 0.67. The p-value for testing the hypothesis that $\varphi_1 = 1$ in a pure AR(1) model (*i.e.* no intercept) is 0.776.

Figure 3.4. Gasoline price index evolution scenarios and their inherent uncertainty



Note: Index measured in 2015 USD. Displayed results (means, percentiles) are based on forward simulations of the statistical models presented in this section and detailed in the technical appendix, using synthetic samples of 5000 observations.

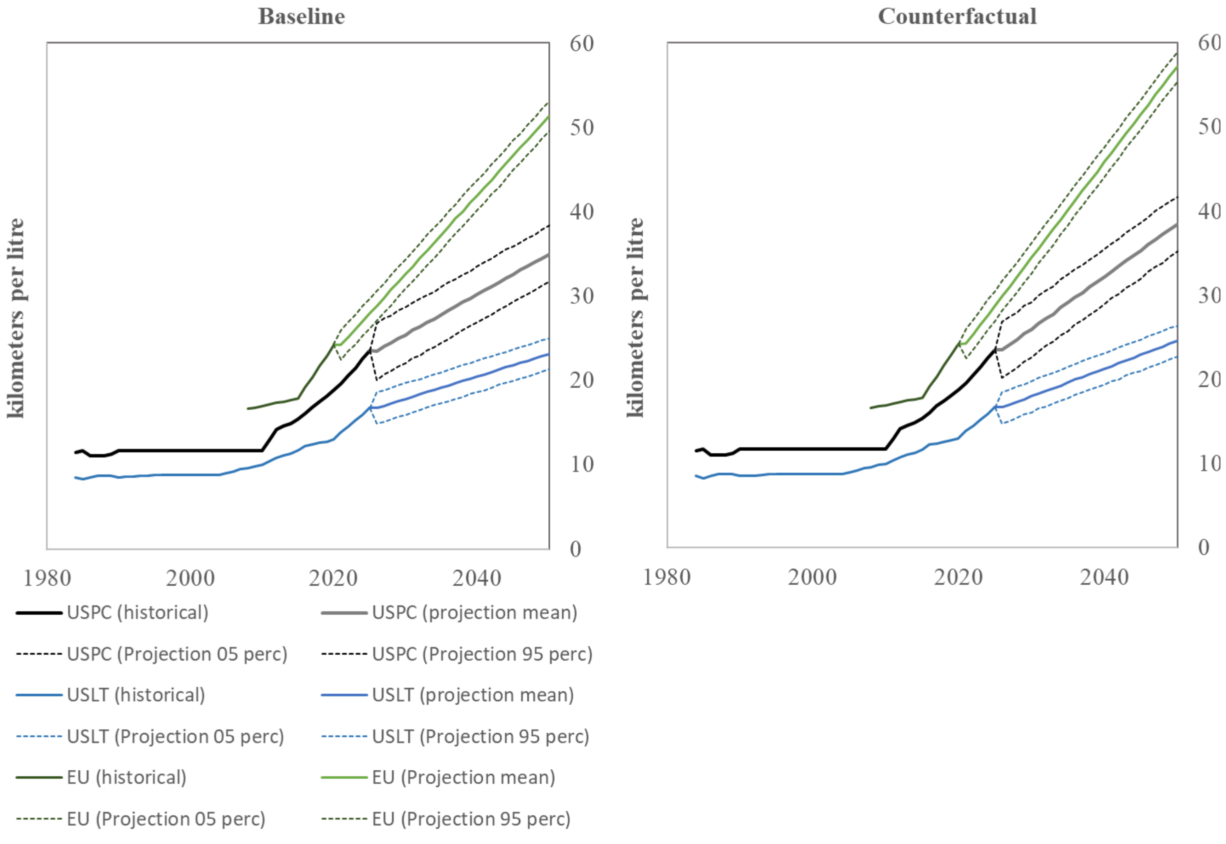
3.3.2. The impact of from more stringent fuel efficiency standards on fuel efficiency

Simulating the impact regulatory standards will have on the fuel efficiency of cars is based on equations (1) and (5). The reference projection of CAFE standards is based on the linear trend model:

$$S_{US,y}^{v} = \mu + \zeta_v \, y + \eta_y \quad (16)$$

which implies a different annual increase of required kilometres per litre for each type v (*i.e.* passenger car or light truck). The study treats announced levels of CAFE standards in the period 2021-2025 as equivalent to historical data from the period 1980-2020, thus estimations use observations between 1980 and 2025. The same model is estimated on the available historical information on EU standards. Because structural breaks are present in the observed time series (*e.g.* for US passenger cars standards were relatively stagnant before 2005), ζ_v is estimated separately for periods in which standards were stagnant and for periods in which they increased abruptly. The baseline projection uses a weighted average of estimated ζ parameters from the two aforementioned periods.[19] The counterfactual scenario involves the use of a higher slope, ζ', which are obtained by weighting more the obtained parameter from the estimating the model in years where standards increased abruptly.[20],[21] Figure 3.5 displays the projected trajectory of US and EU standards based on the estimates from the model in (16). The simulated series are translated to actual changes in the fuel efficiency of passenger cars or light trucks with the use of equation (5). The results and the associated analysis are provided in **Section 4.2**.

Figure 3.5. Fuel efficiency standard evolution scenarios



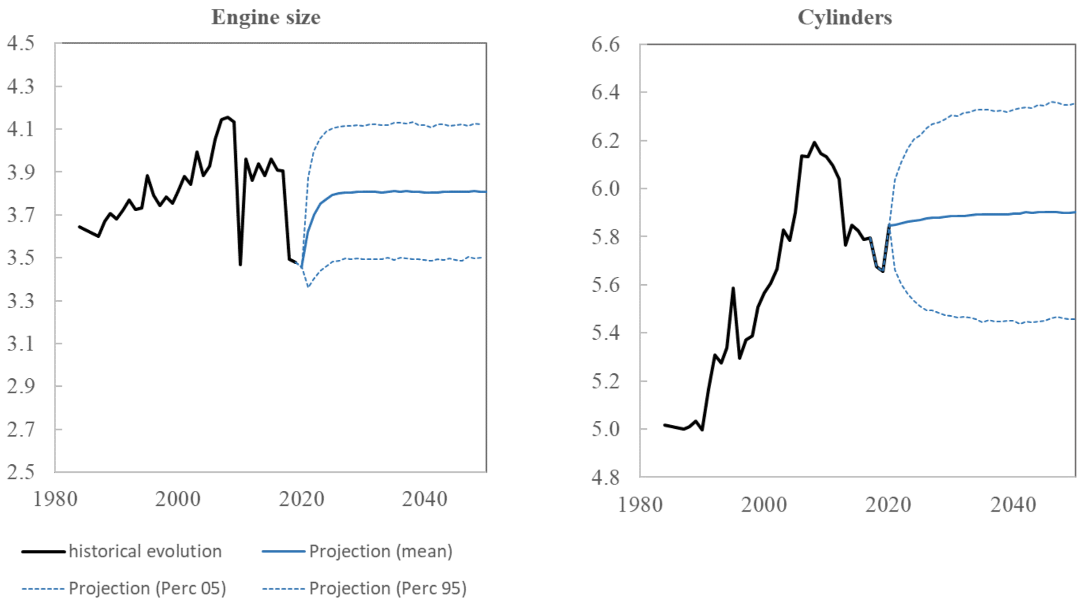
[19] For instance, treating 2026 as the beginning of the projection period for CAFE standards, it holds that $S^v_{US,2026} = S^v_{US,2025} + \zeta_v + \eta_{2026}$. Thus for an arbitrary year y in the projection period, it holds that: $S^v_{US,y} = S^v_{US,2025} + (y - 2025)\,\zeta_v + \eta_y$.

[20] Both baseline and counterfactual scenarios are hypothetical scenarios. The baseline scenario constitutes an estimation of the fuel efficiency standards trajectory; it is not an announced plan by political entities or governments.

[21] In the baseline scenario, both periods receive an equal weight (i.e. 0.5), while the counterfactual scenario weights the first period by 0.2 and the second by 0.8.

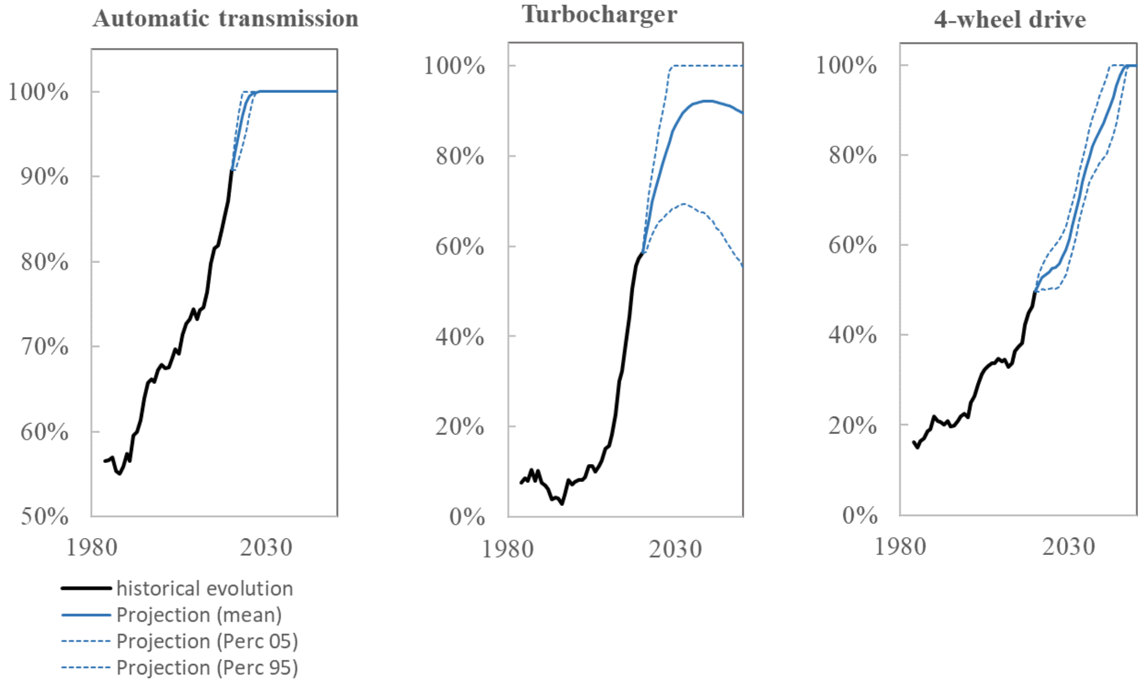
Note: USPC: CAFE levels for passenger cars in the US; USLT: CAFE levels for light trucks in the US; EU: Standards for all vehicles (uniform). Displayed results are based on simulations using synthetic samples of 5000 observations. Those simulations are based on fuel efficiency standards plan for 2017-2025, and do not take into account the 2020 SAFE rule. The reader is referred to the Appendix for a summary of the history of CAFE and EU fuel efficiency standards.

Figure 3.6. Projected evolution of the prevalence of engine size and cylinders



Note: The engine size is measured in cubic centimetres (cc). The engine size graph excludes minivans and wagons. The graph counting cylinders excludes passenger cars. Displayed results (means, percentiles) are based on forward simulations of the statistical models presented in this section and detailed in the technical appendix, using synthetic samples of 5000 observations.

Figure 3.7. Projected evolution of the prevalence of automatic gear, turbocharger and 4-wheel drivetrain



Notes: Prevalence refers to the percentage of newly produced vehicle models possessing the three displayed characteristics. Displayed results (means, percentiles) are based on forward simulations of the statistical models presented in this section and detailed in the technical appendix, using synthetic samples of 5000 observations.

3.3.3. Changes in fuel efficiency stemming from the evolution of car characteristics

Some of the vehicle characteristics that play a role in the determination of fuel efficiency are not stationary. The study attempts to remove existing trends from variables prior to projecting them, by using first differences or by directly modelling the trend. Then, continuous variables such as engine size and the number of cylinders are projected separately for each car body type, as the marginal effects of these features on fuel efficiency are available by body type. Figure 3.6 displays the projected evolution of the engine size and number of cylinders.

To keep the exercise tractable, the prevalence of the automatic transmission, turbocharger and drivetrain type in new vehicle models are not projected separately for each vehicle class. The projection of drivetrain types is complicated by the fact that the prevalence of each category (*e.g.* front wheel drive, four-wheel drive, *etc*.) correlates temporally with the rest, as the sum of their shares must add up to one at any point in time. To simplify the analysis, two aggregate categories are considered instead. The first pertains to all types of two-wheel drive systems and the second aggregates all four-wheel drive configurations. Then, projecting the prevalence of the latter automatically implies a projection for the prevalence of the former.

3.3.4. Projection of autonomous growth

Equation (4) implies two different models for the evolution of autonomous technical change Estimating the linear trend model yields a constant annual growth rate.[22] In contrast, the time fixed-effects specification allows the growth rate to increase and diminish at different periods, but does not permit a direct projection without strong additional assumptions.

Thus, a more conservative scenario for the evolution of autonomous components may assume that the estimated fixed effects originate from the following sigmoid model:

$$D_y = \alpha + \beta\left(\frac{e^{\gamma+\delta y}}{1+e^{\gamma+\delta y}}\right) + \eta_y. \tag{17}$$

That scenario accounts for the impact of an emerging electric vehicle industry, which could shift the focus of competitors from increasing the energy efficiency of conventional vehicles to increasing that of electric cars.[23] Estimates for the three parameters can be obtained *via* a non-linear least squares regression using the estimated fixed-effects from Models 1-5 as data.

[22] From (1), the growth rate is: $\frac{E_{ixmyt+1}}{E_{ixmyt}} - 1 = e^{\alpha} - 1 \approx \alpha$.

[23] At the time this study was conducted (2021), no reliable time series of considerable length regarding the evolution of fuel efficiency in electric vehicles had yet been formed. Electric vehicles enter the US EPA sample for the first time in 1998. In total, the sample contains 231 electric vehicles, a number that is insufficient to effectively control for the fact that energy efficiency innovation in them could affect fuel efficiency of conventional vehicles.

4 Findings

4.1. Estimation results and discussion

The point of departure is the basic model, whose specification includes 5-year time fixed effects to approximate the autonomous time trend (see equation 4). The basic model also contains manufacturer fixed effects (see equation 3), but not vehicle class fixed effects or vehicle type specific trends (equation 2). The rest of the econometric models provide alternative, richer specifications. Model 2 adds vehicle class (*i.e.* body type) fixed effects, Model 3 allows the fuel efficiency trend to be differentiated across different vehicle types, and Model 4 enables vehicle attributes (*e.g.* engine size) to have a different marginal effect on fuel consumption, by body type. Finally, Model 5 is a tailored model with selected fixed effects and trends. It excludes variables that have been shown to be systematically insignificant in Models 2-4, whose inclusion increases the variance of the remaining estimates. These models therefore serve as transitional specifications, in the sense that they assist in evaluating the sensitivity of the estimates from the basic model and in specifying the tailored model. All models control for real OECD income,[24] the level of CAFE and EU fuel efficiency standards and the aggregate shock index developed in **Section 3** and exhibited in equation (13). The core results from estimating the econometric model exhibited in **Section 3.1** are displayed in **Table 4.1**.

Table 4.1. *Core estimation results*

Specification	(1) Basic model	(2) Body type fixed effects	(3) Body type specific trend	(4) Body type and characteristics interactions	(5) Tailored model
δ	0.041***	0.039***	0.039***	0.039***	0.039***
β_{US}^{US}	0.366***	0.061	0.077	0.074	0.040***
β_{US}^{EU}	0.358***	0.140***	0.165*	0.170*	0.121***
β_{US}^{A}	0.334***	0.065	0.082	0.111	0.033***
β_{EU}^{US}	-0.056***	-0.033***	-0.037***	-0.036***	-0.034***
β_{EU}^{EU}	-0.028***	-0.009*	-0.011*	-0.011*	-0.009***
β_{EU}^{A}	-0.037***	0.015***	0.005*	0.005*	0.003***
γ: annual growth rate [(a)]	0.47%	0.45%	0.42%	0.42%	0.45%

Note: statistically significant at 10% (.); at 5% (*); at 1% (**); at 0.1% (***). [(a)] The annual rate of autonomous growth is the constant growth rate that replicates the level difference (1984-2020) implied by the 5-year period fixed effects.

The basic model predicts that increasing the gasoline after tax price by one USD will trigger a 4.1% increase in fuel efficiency within a maximum period of seven years. Taking into account that the sample average value of the real gasoline cost index is roughly 1.26 USD, this implies a point elasticity of 0.052. This finding is significant and robust across all model specifications, with the corresponding p-value falling

[24] Real OECD income is expressed in 2015 USD.

short of 0.001. Combining the estimate of δ with the accumulated positive gasoline price shocks suggests that these shocks increased fuel efficiency by approximately 2.7% during the sampling period. **Section 4.2** uses multiple simulations to provide insights on the effect of a carbon tax on fuel efficiency innovation. These simulations cover different scenarios on the level of the carbon tax and the evolution of fuel prices.

The obtained estimate for δ should be examined in conjunction with pre-existing literature. The figure supports the induced innovation hypothesis, i.e. that increasing the generalised user cost of a commodity leads to the invention of substitute commodities with lower such cost. In this sense, the study corroborates the findings by Crabb and Johnson (2010[17]). The latter study focuses on the impact of oil price shocks on the number of patents related to automobile energy-efficiency, rather than the energy consumption of new cars. However, the fuel efficiency elasticity obtained in the present study (i.e. 0.05) contrasts some of the values reported in earlier contributions. It lies considerably below the respective elasticity Austin and Dinan (2005[15])report, *i.e.* 0.22. This implies that indirect taxation of grey commodities may not be an effective way to accelerate the generation of environmentally friendlier alternatives, despite being an efficient tool to reduce the demand for the former. Nevertheless, the elasticity in the present study is robust and significantly different from zero in all models. This sharply contrasts the findings of Wang and Miao (2021[18]), who report an induced innovation effect that is statistically insignificant in almost all vehicle categories.

CAFE standards exert a statistically significant and economically considerable impact on the observed fuel efficiency of all manufacturers. In the basic model, the estimated elasticity of the resulting fuel efficiency with respect to the efficiency level introduced by the CAFE standard revolves around 0.35. Therefore, the model predicts that raising US CAFE standards by 10% will raise the fuel efficiency of the cars entering the US market by 3.5%. The reason for which the elasticity is considerably smaller than 1.0 is that CAFE standards apply at the level of the manufacturer and are sales-weighted. This implies that a manufacturer can comply with a more stringent value at year $y+1$ compared to year y by producing a popular fuel-efficient vehicle while producing several less fuel-efficient vehicles. In turn, this implies that the elasticity of unweighted fuel efficiency can be substantially smaller than the corresponding sales-weighted elasticity.[25]

The estimates from models 2-4 indicate that the effect of regulatory standards suggested by the basic model is possibly inflated. A plausible explanation for the upward bias is that the levels of standards temporally correlate with the relative frequency of vehicle types that are systematically more economical in terms of fuel consumption. Introducing vehicle type fixed effects deflates the relevant estimates by a factor that ranges between 2.5 and 6.0, and renders two of the three coefficients statistically insignificant. The deflated estimates remain relatively stable across refined specifications. The tailored model (Model 5) restores the statistical significance of the estimators corresponding to fuel efficiency standards by dropping plenty of insignificant covariates and interaction terms. However, the estimates indicate that the response of the vehicle fuel efficiency to standards is likely to be weak, with elasticities in the range 0.03-0.12. Calculations based on these estimates suggest that the strengthening of standards for passenger cars in the period 2010-2020 increased fuel efficiency by 8.5%, compared to 1984 levels. The raise in CAFE standards for light trucks that took place between 2005 and 2020 had a respective impact of 7%.

[25] For instance, consider a hypothetical regulation that requires a manufacturer-specific, sales-weighted minimum efficiency of 10 km/litre in year y_0 and 15 km/litre in year y_1. A manufacturer may secure compliance in year y_0 by introducing two equally popular cars, each traversing 10 km/litre. The same manufacturer secures compliance in year y_1 by producing a vehicle that traverses 15.8 km/litre and accounts for 90% of its sales, and a less efficient car with economy equal to 8 km/litre that accounts for 10% of its sales. While the elasticity of the sales-weighted fuel efficiency in this example exceeds 1.0, its unweighted counterpart is 0.38.

However, estimates from an additional regression imply that the introduction of CAFE standards possibly induced a substantial increase in the fuel efficiency of vehicle models entering the US market within a few years. That regression is the level-to-level version of the tailored model (Model 5), which yields a marginal effect of 0.17 km/litre for one km/litre increase in CAFE standards. Combining this effect with the CAFE levels in the augural year of the sampling period (1984) yields kilometric gains that correspond to 14-28% of the observed fuel efficiency of year 1984. Therefore, a key finding of the analysis is that the introduction of CAFE standards had an innovation impact that would not be possible to obtain via tax-induced increases in gasoline costs. This finding is diametrically opposite to that by Crabb and Johnson (2010[17]), although the latter study attempts to predict the number of energy-saving patents of the automobile industry.

In general, the EU efficiency standards are found to have a weak and negative impact on the fuel efficiency of cars produced by both European and US manufacturers. The corresponding elasticities are low, indicating the possibility to differentiate produced vehicles across markets. Furthermore, it also suggests the potential presence of an offsetting *cross-market effect*. That is, EU standards possibly have a positive impact on the fuel efficiency of vehicle models entering the European market, similar to that estimated here for CAFE standards on the US market. Part of this positive impact carries over to other markets, as the new, more efficient vehicles may also be attractive options for consumers there. However, strengthening EU standards could cause some of the less fuel-efficient versions of vehicles that fail to enter the home market to be supplied in other markets. The estimates suggest that this effect is possibly larger for US manufacturers. An increase in the stringency of EU standards may generate an incentive to create more fuel-efficient models for the EU market, allowing to comply to CAFE regulations with less efficient cars entering the US market. Overall, the finding suggests that the possibility of product differentiation across markets may cause leakage effects that call for better fine-tuning of regulatory frameworks.

Table 4.2. *Supplementary estimation results*

Specification	(1) Basic model	(2) Body type fixed effects	(3) Body type specific trend	(4) Body type and characteristics interactions	(5) Tailored model
Key characteristics					
Engine size	-0.371***	-0.364***	-0.366***	-0.375***	-0.365***
Number of cylinders	-0.057*	-0.065*	-0.065*	-0.018	-0.107***
Automatic transmission	-0.019***	-0.016**	-0.016**	-0.015*	-0.017***
Turbocharger	-0.072***	-0.072***	-0.073***	-0.073***	-0.071***
Drivetrain type (a)					
Four-wheel	0.018.	0.006	0.005	0.038**	-0.014
Four-wheel or all-wheel	-0.019*	-0.032***	-0.027**	0.001	-0.065***
All-wheel	0.016	0.004	0.004	0.013	-0.049***
Front-wheel	0.075***	0.055***	0.055***	0.076***	0.053
Part time four-wheel	-0.028	-0.036	-0.036.	0.038*	-0.059.
Rear-wheel	0.027**	0.016*	0.020*	0.032*	0.007

Note: statistically significant at 10% (.); at 5% (*); at 1% (**); at 0.1% (***). (a) Reference drivetrain category is two-wheel. Alternative models of the tailored version (Model 5) are used to aggregate effects and facilitate the visualization of several projections regarding impacts that are of secondary importance (see also Section 3.4.3 in Methodology).

The estimates suggest that the autonomous technological evolution is possibly smaller than previously thought. After controlling for policies, price effects, and the evolution of vehicle characteristics, findings suggest that the portion of technological progress that does not depend on environmentally relevant policies raised fuel efficiency by 15-17% in the sampling period (1984-2020). In turn, this implies an annual growth rate that falls short of 0.5%. Therefore, the overarching finding that emerges from the processing of econometric estimates is that non-technological policy components underlie 30-50% of the observed technological progress.

All models control for the drivetrain type and a series of vehicle characteristics affecting fuel consumption. The size of the engine has a robust effect on fuel efficiency with the associated elasticity placed at approximately -0.37. This implies that increasing the engine size by 10% implies a 3.7% decrease in the kilometres traversed per litre of gasoline. The number of cylinders have also a negative effect on fuel efficiency, but that is considerable smaller and less robust, *i.e.* the estimated elasticity ranges between -0.05 and -0.1. The effect of the turbocharger is similar in magnitude, but more robust across models. Since 1984, it is estimated that turbochargers decreased fuel efficiency by 3.7%. Automatic transmissions have a negative effect of fuel efficiency, but their magnitude is relatively small. Using the econometric estimates and the change in the market share of vehicles with automatic gears, the negative impact since 1984 does not exceed 0.6%. Regarding the drivetrain type, the results indicate that four-wheel vehicles are substantially less economical (5.0-6.5%) than two-wheel vehicles.

4.2. Forward simulations

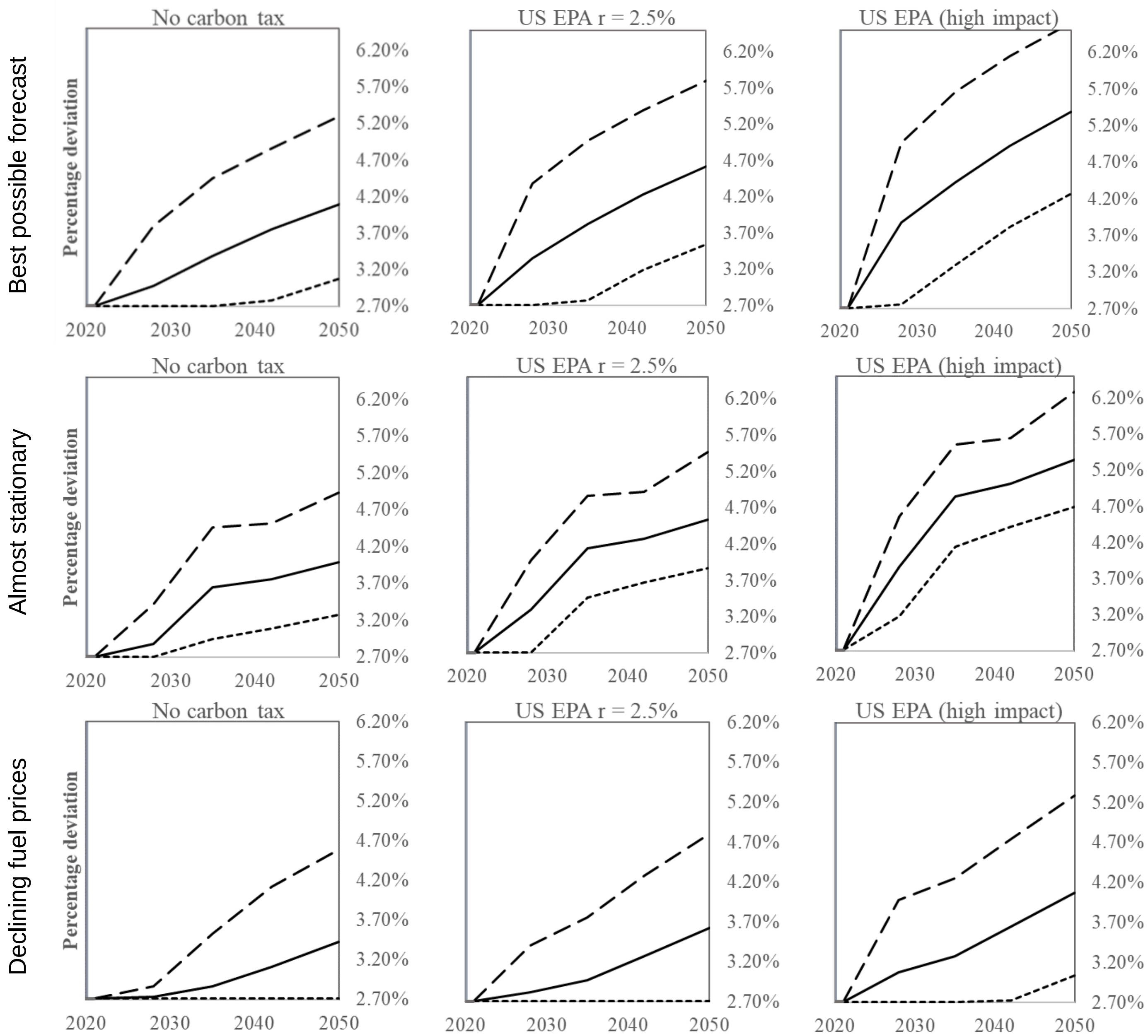
The estimated coefficients presented in **Section 4.1** are now used to simulate forward the fuel efficiency of future gasoline cars, using the methodology presented in **Section 3.4**.

The panels in Figure 4.1 display the evolution of the overall level of fuel efficiency that can be attributed to shocks in the gasoline cost index presented in **Section 3.1**. The vertical axis of all panels in Figure 4.1 represents the percentage deviation of fuel efficiency from the levels of the base year (1984) that can be attributed to changes in fuel prices and taxes, *i.e.* the gasoline cost index. Using the estimated parameters reported in **Section 4.1** that deviation in the beginning of the simulation period is estimated to be approximately 2.7%. Each row of panels corresponds to one of the three scenarios for the evolution of the gasoline cost index presented in **Section 3.4**. Each column of panels corresponds to a different scenario for the implementation of the carbon tax. That is, the first column represents the scenario of no carbon tax. The second column shows the impact of introducing a carbon tax using EPA’s regular impact scenario and an annual discount rate of climate change damages equal to 2.5%. The final column shows the impact from a carbon tax that corresponds to EPA’s high impact scenario, with damages discounted at a rate of 3%.

The simulations suggest that, in the absence of a carbon tax, gasoline price and tax fluctuations similar to those observed in the past (*i.e.* stationary) will raise fuel efficiency by 0.6 – 2.3% with a 90% probability in the projection period. The upper bound of this interval raises to 2.8% in the best possible forecast, which contains a slightly increasing trend in fossil fuel prices between 2020 and 2050. On the other hand, significant positive gasoline price shocks are much less likely to occur in the scenario of declining oil prices. In that case the expected progress reduces to 0.8% and ranges between 0% and 2%.

The net impact of the carbon pricing on fuel efficiency progress is significant, and considerably more pronounced in the case of the high-impact carbon tax scenario. In the first two scenarios for the gasoline cost evolution, a carbon tax that sets of at USD 0.35 per litre in 2020 and increases to USD 0.60 per litre in 2050 will raise fuel efficiency by 1.3%. The simulated 90% interval for this impact is 0.2-2.5%. However, in a world where oil prices have a declining trend, the same tax will be less effective in fostering Hicksian innovation (Newell *et al*., 1999). Its anticipated effect falls to 0.6%, with a 95% probability to be less than 1.9%.

Figure 4.1. Evolution of fuel efficiency under various carbon tax and gasoline price scenarios.



Note: The used carbon tax estimates are those reported by US government in 2021. The social cost of CO_2 (USD/metric ton) under the 2.5% and 3% high impact scenario is (respectively): 76 and 152 (for year 2020), and 116 and 260 (for year 2050). The high impact scenario discounts damages at an annual rate of 3%. Dashed curves represent the 5th (short dashed) and 95th (long dashed) percentiles. Percentage deviations refer to the initial year of the sampling period (1984).

Figure 4.2. Fuel efficiency under the two scenarios for the evolution of CAFE standards

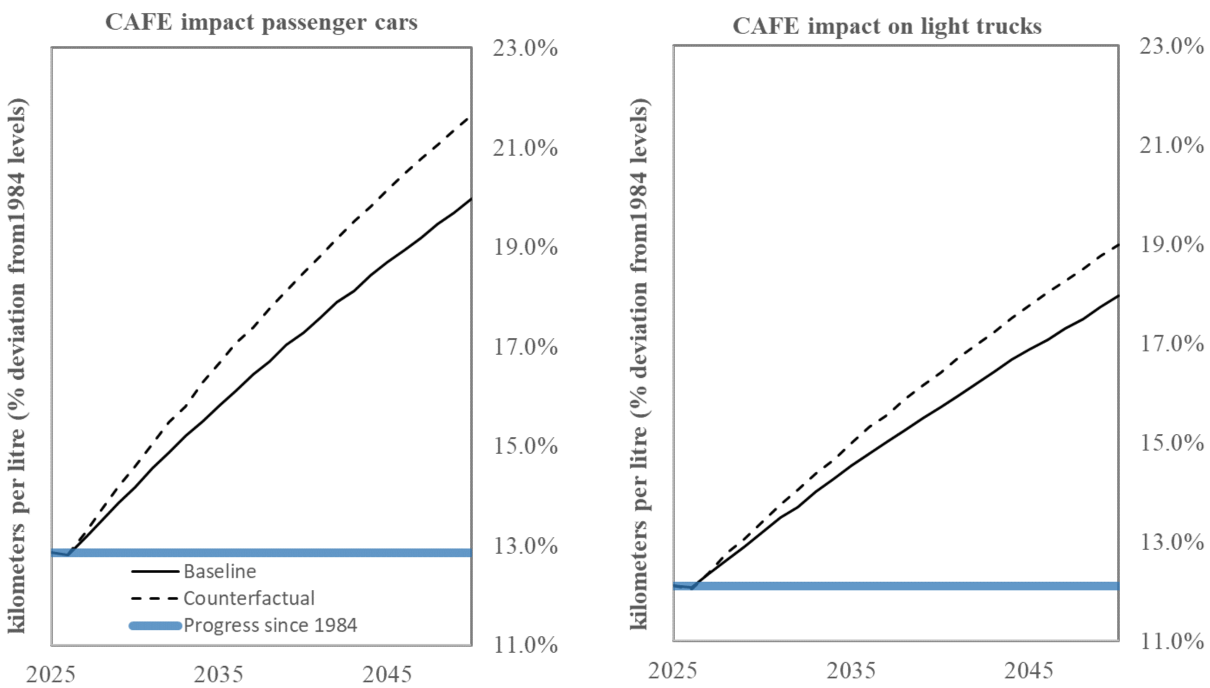
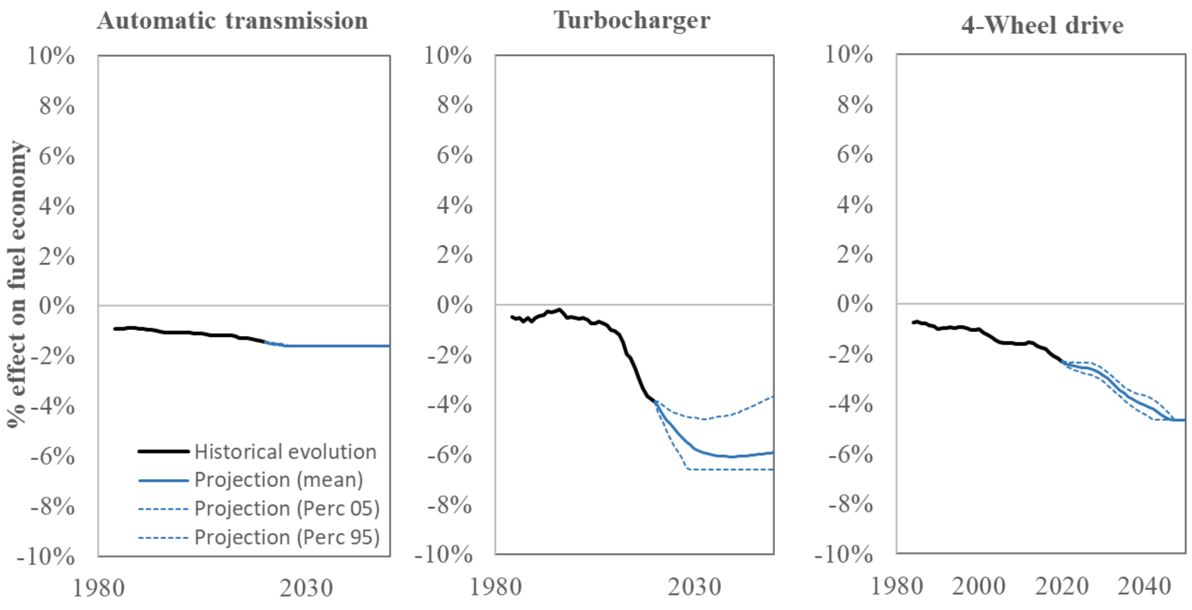


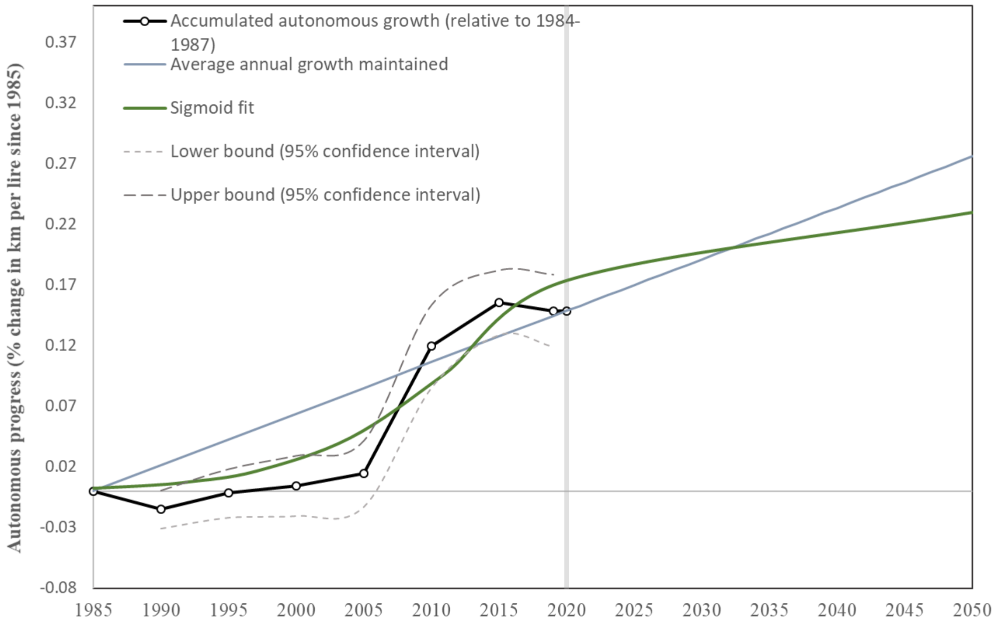
Figure 4.3. Impact of evolving prevalence of automatic gears, turbochargers and 4-wheel drive.



The simulation results suggest that stricter CAFE standards for passenger cars and light duty vehicles will have a moderate impact on fuel efficiency. The difference between the baseline and counterfactual scenario, as these scenarios were laid out in **Section 3.4**, is shown in Figure 4.2. This is approximately 1.65% for passenger cars and 1% for light trucks. However, the minimum gains predicted by the baseline scenario are approximately 11% for both passenger cars and light trucks. This suggests that the further strengthening of CAFE standards, at a pace that is comparable to that observed during the last decades, will considerably raise fuel efficiency.

Turbochargers, automatic gears and 4-wheel drivetrains will continue offsetting part of the progress predicted for the period 2021-2050, but in widely different ways. As the prevalence of automatic gears in new vehicle models appearing in the US market is already sufficiently close to 100%, their offsetting effect is highly likely to be exhausted until 2025. The prevalence of turbocharger is currently much lower. The forward simulations predict that it will continue raising until 2040, offsetting between 0.5 and 3.0% of the foreseen progress. A similar in magnitude (i.e. -2.5%), but substantially less uncertain effect is expected to originate from the increasing presence of 4-wheel drivetrains in newly produced cars. Provided that conventional vehicles remain in the market, that process is expected to span the entire time window of the forward simulation.

Figure 4.4. Estimated and projected autonomous growth in fuel efficiency



Notes: The dotted curve displays the evolution of the estimated time fixed effects. The dashed curves display the associated 5th and 95th percentile. The formula for the sigmoid fitting function is provided in Section 3.

Projecting the pace of autonomous growth, as the latter was defined in the introduction, involves a substantial amount of uncertainty. This uncertainty is greater than the one stemming from the evolution of vehicle characteristics, as it originates from the evolution of factors that are not directly observed in the study. The study approximates the autonomous growth using the estimated 5-year period fixed effects, which are displayed in the solid black curve in Figure 4.4. These do not give rise to a smooth accumulated growth path. Instead, the estimated values suggest that autonomous growth was relatively stagnant up to 2005, exploded in the period 2005-2015, before reaching a plateau. The overall evolution of period fixed effects suggests that the factors underlying autonomous growth (see **Introduction**) improved fuel efficiency by roughly 14.5% in the period 1984-2020, or at an average annual rate of 0.45%.

Different *judgemental forecasts* can be made based on hypotheses about the mechanism that generates the values of the fixed effects displayed in . Assuming that the obtained fixed effects constitute random fluctuations around a constant annual growth rate of 0.45% yields the linear projection displayed in the figure. This indicates that the same mechanisms that raised fuel efficiency by 14.5% during the sampling period will raise it by an additional 12.3% in the time window of the forward simulation (2021-2050). However, assumptions that are more conservative moderate this number substantially. For instance, assuming that autonomous growth rates are variant over time suggests fitting a sigmoid curve to the observed values (see **Section 3.4.4**). Estimating and projecting that curve with non-linear least squares produces a smaller figure for the expected progress during 2020-2050, *i.e.* just 4.5%.

5 Concluding remarks

The fuel efficiency of automobiles has increased considerably during the last four decades. This paper examined the sources of that growth using historical data on vehicle models entering the US market since 1984. It provided econometric analysis controlling for vehicle characteristics, the evolution of efficiency standards and the overall trend behind fuel efficiency growth. The analysis utilized an OECD gasoline cost index, which was developed in order to control for the effect gasoline taxes have on the fuel efficiency of new vehicle models produced for the US market. That index improves the econometric capacity of the study, as it controls for gasoline taxes in countries other than the US. Such taxes may affect the fuel efficiency of new vehicle models, especially if these are imported from or exported to countries where gasoline taxes are high. Finally, the employed econometric model is tailored to isolate the impact of gasoline costs on *actual fuel efficiency innovation* from that on *generic fuel efficiency boosts*. The latter impact is realized via changes in the production processes or used materials, and can be reversed during periods of declining gasoline costs.

The analysis revealed that 40% of the observed progress in fuel efficiency between 1984 and 2020 is driven by environmentally relevant policies. It stems from the positive shocks in the gasoline user costs, which partially originate from increases in motor fuel taxes, and from the strengthening of CAFE standards during that period. The contribution of environmentally relevant policies may become substantially bigger if the evaluation period is expanded backwards to include the initial impact of introducing CAFE standards. The results of the study suggested that the contribution of CAFE standards is roughly three times bigger than that of fuel prices, despite these variables display comparable variation in the sample. In that sense, the results contrast earlier contributions finding suggesting that the price system is more effective in (compared to command-and-control regulations) in inducing technological progress. However, the corresponding elasticities of fuel efficiency to gasoline costs and fuel standards were shown to be small enough to consider any of the two as a primary policy response to the growing emissions from private vehicles. The study finds that the combination of the two increased fuel efficiency by 10.7% in a period of 36 years, or by 0.29% on an annual basis.

Therefore, the role of both instruments in the struggle to reduce CO_2 emissions could be considerable, but is in all cases supplementary. Forward simulations suggested that the two components could increase fuel efficiency by 8.5% in the critical period (2021-2050), a number that increases to 11% in the scenario of a stringent carbon tax. Substantial *autonomous progress*, i.e. progress stemming from non-environmental policy interventions and other forces affecting international competition, is expected for the same period. The projections suggest that this number lies between 4 and 15%, a range that is somewhat wide as it involves two major uncertainties. That is, markets for conventional vehicles are expected to grow, as population and world income grows. That could possibly intensify the competition between manufacturers and the incentives to produce more economic internal combustion engine cars. On the other hand, the emerging electric vehicle industry may offset that effect by shifting competition towards the production of more efficient engines and batteries.

Importantly, the paper provides a dynamic estimate for the gasoline consumption of future cars. That estimate functions as an essential benchmark figure in the calculation of the energy consumption and CO_2 emissions savings expected from a major switch to electromobility. Additional ingredients in that exercise include projections of electric vehicle energy efficiency, country-specific projections for the carbon intensity of the electricity generation and estimates about the pace at which electric vehicles may displace conventional cars.

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