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When standards have better distributional consequences than carbon taxes[*]

Jiaxin Zhao[†] and Linus Mattauch[‡]

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Abstract

Carbon pricing is the efficient instrument to reduce greenhouse gas emissions. Nevertheless, the geographical and sectoral coverage of substantial carbon pricing remains low, often due to concerns about increasing economic inequality. Regulations such as fuel economy standards are more popular. Could the reason be that they have an equity advantage over carbon pricing? We develop two models, one representing energy services and the other the carbon-intensity of consumption, to identify the economic situations in which this is the case. First, we prove that an efficiency standard can be more equitable than carbon pricing when consumers prefer high-carbon technology attributes. Evidence from the US vehicle market confirms this finding. Second, we show theoretically, and through a numerical application to the Chinese transport sector, that intensity standards are preferable when richer households consume a greater share of high-emissions goods. Our results hold when the redistribution of carbon pricing revenue is not progressive. These insights may help advance decarbonisation when pricing instruments remain unpopular.

Keywords: Incidence; Distributional effects; Carbon pricing; Efficiency standards; Intensity standards

JEL codes: H22, H23, Q52, Q54

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[†] School of Public Policy and Management, Tsinghua University, China; Environmental Change Institute, School of Geography and the Environment, University of Oxford, UK; Email: *zhaojx22@mails.tsinghua.edu.cn.*

[‡] Corresponding author; Technical University Berlin, Germany; Potsdam Institute for Climate Impact Research – member of the Leibniz Association, Germany and University of Oxford, UK; Email: *linus.mattauch@tu-berlin.de.*

1 Introduction

Introducing a price on carbon is the efficient way to reduce greenhouse gas (GHG) emissions. Most countries, however, do not have substantial carbon pricing instruments (Stiglitz et al., 2017). Even where carbon pricing exists, price levels usually fall far short of those required to meet international climate targets. One potential reason for the insufficient use of pricing instruments is the concern that they might increase inequality. Rising costs of carbon-intensive energy and essential goods can burden low-income households more than high-income households. For example, evidence shows that low-income households spend a higher share of their income on energy and other carbon-intensive goods like food, at least in high-income countries (Flues and Thomas, 2015; Grainger and Kolstad, 2010).

Non-pricing instruments, such as fuel economy standards and technology mandates, have been more popular on a global scale, although they are not efficient (US Environmental Protection Agency, 2011; National Research Council, 2002).[1] They may be preferred by politicians and the public because the price effects of these policies are less visible, and citizens are perhaps not as aware of their equity implications (Finon, 2019; Fischer and Pizer, 2019). Yet, a distributional motive for choosing non-pricing regulation, however, has not been clearly identified in prior research (see Heutel (2020)).

This study examines whether society's preference for non-pricing instruments can be justified on equity grounds. Specifically, under which conditions are non-pricing alternatives more equitable than pricing instruments? We develop two models to examine two policy-relevant cases: efficiency standards for household energy technologies and intensity standards for carbon-intensive goods.[2] We ask under which conditions these instruments have better distributional consequences than pricing. The models represent key consumer behaviours determining the carbon-intensity of consumption, which hold equity implications for climate policy.[3]

First, we show that a preference for high-carbon technology attributes can make effi-

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[1] Hereafter, we use "pricing instruments" to refer to both ordinary carbon taxes and cap-and-trade programmes as both of them put a price on carbon. Non-pricing instruments refer to emissions-restricting regulatory policies including, for example, standards, mandates and labelling.

[2] Efficiency standards regulate how much output is produced by an energy technology for a unit of energy input, for example, miles per gallon for automobiles or BTUs per kWh for heating and cooling technologies. BTU is the British Thermal Unit—a unit of heat. kWh stands for kilowatt-hour—a unit of electricity. Intensity standards regulate the quantity of emissions produced per unit of output, e.g., emissions per kWh of generated electricity or emissions per ton of steel produced.

[3] While there are more types of non-pricing instruments additional to standards, we choose standards as the focus of this study since they are widely used in important carbon-emitting sectors such as transport, power, home appliance and heating. Transport, power and heat production, and buildings jointly account for 45% of global emissions based on the 2010 data (Intergovernmental Panel on Climate Change, 2014). Also transport emissions tend to increase as countries become wealthier (Timilsina and Shrestha, 2009; Wei et al., 2020).

ciency standards more progressive than carbon pricing in energy-services consumption.[4] The intuition is simple. We assume households prefer more energy services. For very simple energy services such as lighting, two mechanisms exist: either consuming more energy or buying more efficiency. Energy services are merely the product of energy and efficiency. In cases such as lighting, therefore, richer households spend more on efficient technologies, for example, on LED lighting. However, if energy services have attributes that lead to inefficient energy usage—acceleration, comfort and roominess in the case of cars—this simple intuition is not accurate. Since such "high-carbon" attributes decrease efficiency, richer households might not use more efficient technologies after all. They might buy inefficient cars because achieving efficiency is costly when they also prefer bigger and more powerful vehicles. We design a formal model to examine this hypothesis by generalising Levinson's (2019) set-up for simple energy services. We show that when households have a marked propensity to spend on high-carbon attributes, efficiency standards are more progressive than carbon pricing. We test the theoretical results with US data and find that such a preference exists and that standards could be more favourable for low-income groups, unless recycling of the proceeds from pricing is strongly progressive.

Second, we analyse how non-homothetic preferences may change the equity ranking between intensity standards and carbon pricing, by generalising Klenert and Mattauch (2016). Prior work had neither examined regulatory standards nor carbon-intensive "luxury goods" under such preferences. We show that consumption patterns and the carbon intensity of goods interact to determine which policy instrument is more favourable. When luxury goods are more carbon intensive than subsistence goods, intensity standards are better for the poor. Once again, this result holds as long as the revenue from carbon pricing is not very progressively redistributed to households. We calibrate the analytical model to the Chinese vehicle market and confirm by simulation that standards can be an equitable alternative to pricing instruments. We also show that this equity advantage may justify majority support for standards when aversion to inequality is accounted for.

Taken together, our two models illustrate how households' preferences for both technology attributes and carbon-intensive goods play a role in determining distributional consequences of standards. Focusing on transport, for example, the models explain why richer households drive more and use bigger cars, take more flights and use less public transport. Our first model suggests that one reason is a preference for high-carbon travel attributes such as acceleration, space and comfort. Our second model represents richer households as not only driving more "gas-guzzlers" but also owning more cars and driving

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[4] When writing that households prefer something or there is a preference for something, we mean that households buy more of them as they get richer. This indicates that such goods are normal goods. Here, in particular, we assume that high-carbon technology attributes are normal goods.

longer distance, while lower-income households choose public transport. Preferences for high-carbon attributes of cars, and the effect of income on propensity for car use, both shape the distributional impact of transport policy.

Our contribution builds on three strands of prior work: The first is the few studies directly discussing the incidence of regulatory standards (Fullerton and Muehlegger, 2019; Heutel, 2020; Metcalf, 2019; Rausch and Mowers, 2014). These studies reach no clear consensus. Efficiency standards are described as both regressive and progressive (Levinson, 2019; Davis and Knittel, 2019; Jacobsen, 2013). Nevertheless, several studies make a strong case against regulatory standards: Levinson (2019) develops a theoretical model showing that richer households consume more efficient technologies and more energy. Therefore, efficiency standards favour rich households more than carbon taxes do. Similarly, Metcalf (2019) argues that most regulatory energy policies in the US are regressive. A carbon tax can replace these policies and ensure a progressive outcome. Finally, a comprehensive study by Jacobsen (2013) employs a sophisticated general equilibrium model that incorporates heterogeneous households and car manufacturers. Its results show that the US fuel economy standard is regressive when the used car market is considered. If these arguments are correct, non-pricing instruments should perform worse than pricing instruments in terms of both efficiency and equity.

These empirical studies do not, however, analyse which mechanisms drive the consumption patterns observed in data. Our study identifies two theoretical mechanisms that do: high-carbon technology attributes and non-homothetic preferences. Compared to Levinson (2019), which describes households as only interested in the quantity of energy services, our theory treats households as also liking the qualitative aspects of energy services—and better quality may require more energy. This more nuanced representation of consumer behaviours helps identify the conditions required for standards to be either more or less progressive than taxes. Our conclusion therefore differs from the unambiguous conclusion reached by Levinson (2019). Furthermore, our methodological choice differs from sophisticated equilibrium simulations such as Jacobsen (2013), which covers complex labour- and product-market interactions. We choose to maintain theoretical simplicity instead, which helps uncover new mechanisms affecting consumption patterns and distributional consequences.

As our study compares the incidence of standards with that of taxes, studies on the incidence of environmental taxation are a further relevant body of literature. Those contributions distinguish uses-side and sources-side incidence, namely, the expenditure and the income sides. The uses-side effect is regressive in high-income countries, although this is not generally true in low- and middle-income countries (Sterner, 2012; West and Williams, 2004; Goulder et al., 2019; Liang and Wei, 2012; Dorband et al., 2019). The sources-side can be progressive, particularly when the pricing revenue is progressively redistributed (Rausch et al., 2011; Dissou and Siddiqui, 2014; Goulder and Hafstead, 2017; Williams III et al., 2015). Those effects can potentially offset the uses-side effect, making the overall result progressive (Rausch et al., 2010; Klenert and Mattauch, 2016; Klenert et al., 2018b). Our work uses insights from the tax incidence literature, but has a different focus: comparing the incidence of standards and taxes.

Efficiency analysis of climate policy instruments is the third related strand of literature. Prior research has compared the cost-effectiveness of standards with that of pricing instruments (Fischer, 2001). These studies show that Pigouvian taxes are more cost-effective (see for example Landis et al. (2019)), except in special cases: Goulder et al. (2016) present a case in which pre-existing factor market distortions make clean energy standards more cost-effective than pricing, due to the smaller price effect of standards. Fischer and Springborn (2011) use a dynamic model showing that intensity standards generate higher economic output than pricing instruments, when macroeconomic fluctuations are considered. This study follows their approach in formalising emissions taxes and standards, but is motivated with the other increasingly pertinent concern—equity.

The broader significance of our work flows from the fact that most countries are currently not on track to meet global climate targets, whether they regulate carbon emissions by pricing or non-pricing. While the theoretical case for pricing being the most efficient way to decrease emissions is beyond doubt, and revenue redistribution can in theory resolve inequality, citizens have further concerns about carbon pricing: they often care about the immediate regulatory impacts on their budgets and do not appreciate, support or trust the possibility of a complex tax-plus-redistribution scheme (Hammar et al., 2004; Kallbekken et al., 2011; Douenne and Fabre, 2022; Sommer et al., 2022). Once the objective of climate mitigation policy becomes to do "whatever works" to reduce emissions (Goulder, 2020), standards could be desirable, second-best instruments in given governance circumstances. Our contribution is thus related to Stiglitz (2019) and Heutel (2020), who also examine when standards might be preferable from an equity perspective.

The remainder of the article is organised as follows. In Section 2, we present an analytical model for household energy technologies, and show theoretical results on efficiency standards and carbon pricing. The findings are tested with data from the US vehicle market. In Section 3, we describe a model for subsistence and luxury carbon-intensive consumption, and compare intensity standards to carbon pricing with different revenue-redistribution schemes. Section 4 presents further equity dimensions and discusses how those reveal limitations of our results, but also indicate directions for future work. Section 5 concludes.

2 Distributional impacts of efficiency standards for household energy technologies

This section investigates distributional effects of carbon taxes on fuels and efficiency standards for energy technologies. We focus on household-owned energy technologies, e.g. automobiles, air conditioners, heaters and household appliances. To analyse both taxes and standards in one model, we follow Levinson's (2019) approach in conceptualising consumption of energy technologies as consuming energy services. Households make two decisions when consuming energy services. They purchase energy technology such as automobiles. Then they buy energy fuels such as gasoline, natural gas and electricity to power energy technologies. Carbon taxes target fuel consumption, while efficiency standards target energy technologies.

We introduce the additional assumption that households value both the quantity and quality of energy services. In Levinson (2019), energy services are defined as the functional services households consume, e.g. miles driven or hours of TV watching. Energy services are delivered by consuming energy and technology efficiency, i.e. equal to the product of energy and efficiency consumption. Efficiency is the quantity of services delivered per unit of energy input, and is the only attribute defining an energy technology. While being attractively simple, this model neglects the fact that households do not simply consume functional services delivered by energy technologies but also the quality of these services. Driving a sport utility vehicle (SUV) should provide a different utility gain to households than what driving a compact car gives, for the same number of miles driven. The utility gain from watching TV for a given number of hours on a 30-inch TV should be different from that of watching on a 50-inch TV.[5] To address this issue, we generalise Levinson's (2019) model by differentiating energy technologies not only by technical efficiency but also by other attributes such as power, size and weight. We show that these attributes have an impact on household choices of efficiency. Specifically, we demonstrate that efficiency consumption may decrease with income, contrary to Levinson's (2019) conclusion, and prove that whether standards or taxes are more equitable is conditional on preferences for high-carbon attributes.

The rest of this section is organised as follows. In Section 2.1, we introduce the model for energy-services consumption, and show analytical results on consumption patterns of efficiency. In Section 2.2, we derive conditions for an efficiency standard to be more progressive than a carbon tax. We then discuss multiple alternative standard designs

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[5] To be clear, Levinson (2019) recognises from his data that richer households tend to buy bigger and more cars. But his model differentiates household consumption of automobiles only on energy efficiency without the inclusion of these attributes.

including attribute-adjusted standards in Section 2.3. Finally, Section 2.4 presents an empirical analysis of the US automobile market.

2.1 The model

We assume that households derive utility from two goods, a numeraire good X and an energy service S:

$$U = U(X, S). \tag{1}$$

Energy service is a function of energy fuel E, technology efficiency R, and technology attributes J_i:

$$S = S(ER, J_1, J_2..., J_n) = S(P, J_1, J_2..., J_n), \tag{2}$$

$$P = ER. \tag{3}$$

n is the total number of attribute types. Technology attributes may include size, performance, appearance, quantity etc. To simplify the expression, we only include one attribute represented by J, but the derivation should not be very different when multiple attributes are considered. The product of energy fuel E and efficiency R is the consumed functional service P, such as miles driven for automobiles. Efficiency R can be for example miles per gallon for automobiles or BTUs per kilowatt-hour for heating technologies.

Equation (3) generalises Levinson's (2019) specification in considering technology attributes additional to efficiency as factors defining energy services and contributing to the utility. This specification is reminiscent of Lancaster (1966), which develops a consumer theory based on utility gains from attributes of goods instead of goods themselves. It seems relevant for the automobile market for example, in which cars vary by attributes, and new cars are designed with new combinations of attributes.

Households have the budget constraint:

$$Y = X + p_E E + p_R(J)R + p_J J. \tag{4}$$

p_E, p_R and p_J are the prices of energy, efficiency and the technology attribute respectively. Y is household income. The prices of efficiency and technology attributes can be interpreted as the amortised cost of purchasing an energy technology, since households usually make one-time expenses in energy technologies like automobiles. The efficiency and the attribute expenditure constitute the total expense for purchasing energy technologies. Alternatively, one can imagine households renting energy technologies instead of paying the amortised cost. Here we assume that households face constant prices, i.e. individual households are price takers.[6]

The key assumption of our model is that the price of efficiency $p_R(J)$ is a function of technology attributes. Examples to justify this specification include the following: In the automobile industry, cars vary by their size, appearance, engine power, weight and more. These attributes affect the difficulty of achieving technology efficiency. For instance, to realise a certain level of efficiency, a heavier car requires a better-designed engine and a more fluent transmission system than what a lighter car requires. The better-designed engine and the more fluent transmission system need higher-standard materials, more intellectual input and higher-precision manufacturing techniques. These requirements could result in a higher cost compared to the cost of achieving the same efficiency by a lighter car. Therefore, technology attributes affect the costs of achieving efficiency, i.e. efficiency prices.[7]

By maximising the utility function (1) under the budget constraint (4), we can use the first-order conditions of the problem to obtain:[8]

$$p_E E = p_R(J)R. \tag{5}$$

Differentiating (5) with respect to income Y and rearranging gives:

$$\frac{dR}{dY} = (p_E \frac{dE}{dY} - R \frac{dp_R(J)}{dY})/p_R(J). \tag{6}$$

Based on Equation (6), the following result on consumption behaviours of efficiency is established:

Proposition 1. *Assume that energy and the technology attribute are normal goods. If the technology attribute is high-carbon, i.e. increasing efficiency price or* $\frac{\partial p_R(J)}{\partial J} > 0$, *then the*

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[6] By holding prices fixed, we assume that subsequent price increases resulting from both carbon taxes and efficiency standards fully fall on consumers. In reality, producers would certainly bear a share of the policy cost, too. Producers would share more of that burden if consumers are responsive to price changes. Therefore, our estimates of policy incidence on households are likely to be upper bound, particularly for lower income households who tend to be price responsive.

[7] Admittedly, this assumption may seem *ad-hoc* at first. However, one could think that the production of efficiency requires inputs such as capital and labour. Production technologies associating factor inputs and efficiency output are affected by attributes of energy technologies. Therefore, production costs of efficiency are influenced by technology attributes. This could be founded in a general equilibrium extension of the approach taken here, but is beyond the scope of this article.

[8] See Appendix A.1 for a detailed proof.

relationship between efficiency consumption and income can be characterised as follows:

$$\frac{dR}{dY} < 0 \text{ if and only if } p_E \frac{dE}{dY} < R \frac{\partial p_R(J)}{\partial J} \frac{dJ}{dY}. \tag{7}$$

Further, the second inequality is equivalent to:

$$\frac{\partial p_R(J)/p_R(J)}{\partial J/J} \frac{dJ/J}{dY/Y} - \frac{dE/E}{dY/Y} > 0. \tag{8}$$

Proof. See Appendix A.1. □

The assumption of normal goods in the proposition is plausible for energy consumption such as gasoline and electricity (Espey and Espey, 2004; Alberini et al., 2011), and for attributes such as engine and house sizes and vehicle weight (Wilson and Boehland, 2008; West, 2004).[9]

The interpretation of Proposition 1 is intuitive. According to Equation (8), the relationship between income and efficiency is governed by three elasticities: the income elasticities of energy and attribute, and the attribute's elasticity of efficiency price. First, a higher income elasticity of energy signals a marked preference for functional energy services, which leads households to consume more efficiency and energy, i.e. pushing up dR/dY (see Equation (5) for the relation between efficiency and energy consumption). Second, in contrast, a high income elasticity of attribute and a positive relationship between attribute and efficiency price—this measures how much the high-carbon attribute makes achieving efficiency difficult—will make households demand less efficiency, i.e. pushing down dR/dY (again, see Equation (5) where $p_R(J)$ affects R if we take the expenditure on efficiency as given). Therefore, the income effect on efficiency consumption depends on the relative significance of these two channels, as Inequality (8) reveals.[10]

We can use personal vehicles to illustrate this intuition. If we assume households prefer bigger vehicles while vehicle size makes efficiency costly, households face a trade-off between buying more efficient cars and buying a car that is heavier, i.e. a high-carbon attribute. Given that the efficiency-price rises with the vehicle size, richer households might purchase less efficient cars despite the desire to spend more on efficiency.

For comparison, Levinson (2019) reaches the definitive conclusion that dR/dY is

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[9] The data used in West (2004) and Levinson (2019) both show that wealthier US households own larger cars for example. Wilson and Boehland (2008) indicates that richer households own bigger houses and consume much more energy. Also see Section 2.4 for additional evidence from the US automobile market where the data indicate a preference for roominess and engine power.

[10] Based on this result, we show in Appendix C that we can use simple data of income elasticities on energy and travel demand to understand consumption patterns of efficiency, and how they affect distributional results.

positive because his model does not include the second term at the right-hand side of Equation (6). In Levinson's (2019) model, Equation (6) becomes:

$$p_R \frac{dR}{dY} = p_E \frac{dE}{dY}. \tag{9}$$

This indicates that the marginal efficiency consumption should increase as the marginal energy consumption rises. This is true for simple energy services such as lighting, the service being solely defined by lightness. In this simple case, consumers demand only energy and efficiency to obtain the service. When services are defined also by high-carbon quality attributes, however, Proposition 1 and its proof show that efficiency consumption can decrease with income.

Note that our model does not assume that the income effect on efficiency consumption is always negative. dR/dY turns positive when the condition in Proposition 1 is violated. In particular, the signs of the income elasticity of attribute $\frac{dJ/J}{dY/Y}$ and the attribute's impact on efficiency price $\frac{\partial p_R(J)/p_R(J)}{\partial J/J}$ can both be reversed against our assumptions. For instance, consumers usually prefer personal computers to be lighter and more compact. This preference has incentivised manufacturers to produce high-efficiency computing chips, eliminate excessive accessories, and use thinner screens that require smaller batteries. In this case, the preference for lightness and compactness, i.e. quality attributes, makes computers more efficient.

Proposition 1 does not treat the relative regressivity of a carbon tax and an efficiency standard. This is modelled next.

2.2 Comparing distributional impacts of efficiency standards and carbon taxes

We model a carbon tax and an efficiency standard as follows: The impact of a carbon tax on households is $\tau_E E$, with τ_E being the tax levied on the carbon content of that energy. Following Fischer (2001), Goulder et al. (2016) and Davis and Knittel (2019), we represent the effect of an efficiency standard as a tax on inefficiency relative to a benchmark efficiency standard R_0, expressed as $\tau_R(R_0 - R)$. It becomes a subsidy when $R_0 < R$ (see Appendix D).

Note that efficiency standards must be tradable for the whole regulated industry to face the same τ_R (see Appendix D). It is also a common regulatory practice: in China and the US, for example, fuel economy standards allow companies to trade their "permits" with other automakers. As the focus of this specific section is a marginal analysis, the following result still holds when standards are not tradable.

Furthermore, efficiency standards can take a variety of forms, including single-benchmark standards, attribute-adjusted standards, taxes on inefficient technologies, subsidies to efficient technologies, and "feebates" schemes. We complete the theoretical analysis first for single-benchmark standards, and then discuss how the results could inform our understanding of other types of standards (see Section 2.3).

A policy intervention is regressive when its relative impact on income is higher among lower-income households. Dividing the absolute impact by total income gives the relative impact, i.e. $\tau_E E/Y$ and $\tau_R(R_0 - R)/Y$ in our case. We ignore how the revenue from carbon taxes is used here as we focus on impacts on the expenditure side.[11] The tax revenue may of course be used for rebating households, while there is no revenue from standards. We consider options of revenue recycling in Section 2.4 that follows.

Differentiating the relative impact with respect to income Y gives:

$$RG_E = \frac{\tau_E E}{Y^2}\left(\frac{Y}{E}\frac{dE}{dY} - 1\right), \tag{10}$$

$$RG_R = -\frac{\tau_R R}{Y^2}\left(\frac{Y}{R}\frac{dR}{dY} + \frac{R_0}{R} - 1\right). \tag{11}$$

RG_E and RG_R represent the regressivity of a carbon tax and an efficiency standard respectively. RG_E and RG_R are the local slopes of policy incidence at a certain income level Y. If RG_E is positive, it means the incidence increases as income rises, suggesting the policy is progressive at the margin. If negative, the incidence declines as income grows, suggesting the policy is regressive at the margin. The same logic works for RG_R. While being regressive or progressive at the margin does not conclude a policy's regressivity across the income spectrum, it signals how the incidence changes at the local income area.[12]

From Equations (10) and (11), we establish the following results on the distributional impacts of standards and taxes.

Lemma 2. *A carbon tax is progressive at the margin when:*

$$\frac{dE/E}{dY/Y} > 1. \tag{12}$$

It becomes regressive when Inequality (12) is reversed.

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[11] Note that this omission may be realistic as many citizens do not trust the government to rebate them in their preferred ways, and households are more concerned with the direct expenditure impact (see Section 4). Also, policymakers may not want to generate new tax revenue whose existence creates rent-seeking opportunities and could delay progress on addressing climate change (Cullenward and Victor, 2020).

[12] See also Appendix B where we apply a Cobb-Douglas utility to illustrate how this marginal analysis extends to the full income-spectrum.

An efficiency standard is progressive at the margin when:

$$\frac{dR/R}{dY/Y} + \frac{R_0}{R} < 1. \tag{13}$$

It becomes regressive when Inequality (13) is reversed.

Proof. Lemma 2 directly follows from Equations (10) and (11). If RG_E is larger than zero, the relative impact increases with income, i.e. the carbon tax is progressive. The carbon tax is regressive when RG_E is negative. The same logic applies to RG_R. □

In Lemma 2, the left-hand side of Inequality (12) is the income elasticity of energy demand. If the income elasticity of energy demand is equal to one, households spend constant shares on energy. Therefore, a carbon tax would be distribution-neutral, i.e. all households experience equal impacts. If it is larger than one, richer households suffer a bigger impact from a carbon tax.

Other than the income elasticity of efficiency demand, Inequality (13) has one more term, R_0/R, at the left-hand side. As R_0/R is positive, it makes achieving Inequality (13) more difficult. This is because the price effect of standards, i.e. $\tau_R(R_0 - R)$, can be interpreted as a subsidy on efficiency $-\tau_R R$ and a lump-sum charge on households $\tau_R R_0$. The term R_0/R is the result of that lump-sum charge on households. The charge burdens low-income households relatively more than high-income households, making an efficiency standard less progressive.

Following Davis and Knittel (2019), we contrast the distributional impacts of two policies by comparing the local slopes of the relative impacts at a certain income level. Therefore, the relative regressivity between a carbon tax and an efficiency standard can be derived through subtracting (11) from (10):

$$RG_R - RG_E = -\frac{\tau_R R}{Y^2}(\frac{Y}{R}\frac{dR}{dY} + \frac{R_0}{R} - 1) - \frac{\tau_E E}{Y^2}(\frac{Y}{E}\frac{dE}{dY} - 1). \tag{14}$$

Mathematically speaking, if (14) is less than zero, it means the local slope of the tax's incidence is larger than that of the standard's incidence, which implies that the incidence of the carbon tax increases faster than that of the standard as income grows. The carbon tax is therefore more progressive (or say less regressive) than the efficiency standard at the margin.

From Equation (14), we establish the following result:

Proposition 3. *An efficiency standard is more equitable at the margin at income level Y when:*

$$1 - \frac{dE/E}{dY/Y} + \eta(\frac{\partial p_R(J)/p_R(J)}{\partial J/J} \frac{dJ/J}{dY/Y} - \frac{R_0}{R}) > 0, \tag{15}$$

$$\eta = \frac{\tau_R R}{\tau_R R + \tau_E E} \qquad \eta \in [0, 1]. \tag{16}$$

A carbon tax is more equitable at the margin at income level Y when Inequality (15) is reversed.

Proof. See Appendix A.2. ☐

The policy stringency of the carbon tax and the efficiency standard determines η. It is larger when the stringency of the efficiency standard is increased relative to the tax, i.e. when τ_R grows higher to induce more uses of efficient technologies.

Proposition 3 suggests that the relative regressivity of an efficiency standard and a carbon tax is dependent on five factors, i.e., the income elasticity of energy demand $\frac{dE/E}{dY/Y}$, the attribute's elasticity of efficiency price $\frac{\partial p_R(J)/p_R(J)}{\partial J/J}$, the income elasticity of attribute $\frac{dJ/J}{dY/Y}$, the ratio of the efficiency benchmark and the consumed efficiency R_0/R, and η.

An efficiency standard thus tends to be more equitable than a carbon tax at the margin when the income elasticity of attribute and the attribute's elasticity of efficiency price are positive and relatively high, the income elasticity of energy demand is relatively low and the efficiency ratio R_0/R is relatively small. In this situation, with a marginal income increase, households demand more of the technology attribute. This additional attribute consumption results in a substantial increase in the efficiency price $p_R(J)$ because $\frac{\partial p_R(J)/p_R(J)}{\partial J/J}$ is high. As the income elasticity of energy demand is relatively low, meaning that the demand for the functional energy service is low, the increased expenditure on both energy and efficiency will be small—recalling that the demand for energy and efficiency is interrelated (see Equations (5) and (3)).[13] Since $p_R(J)$ rises substantially but the expenditure on efficiency $p_R(J)R$ increases little, households will reduce marginal efficiency consumption or even consume less efficiency R as income rises. Meanwhile, a small $\frac{dE/E}{dY/Y}$ also suggests that the carbon tax would tend to be regressive or less progressive.

Further, a small efficiency ratio R_0/R suggests that households already consume high levels of efficiency relative to the standard benchmark. Therefore, as the efficiency price increases due to the attribute's effect, achieving this high level of efficiency becomes particularly difficult and unappealing. These factors, adding together, can discourage efficiency consumption to the degree that makes the standard more equitable than the

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[13] We assume again that energy is a normal good. The income elasticity of energy demand is positive.

tax.[14]

A carbon tax would be more equitable than an efficiency standard at the margin when the inequality condition in Proposition 3 is reversed. In this case, the income elasticity of attribute and the attribute's impact on efficiency price are not strong enough, compared to other factors, to reduce efficiency consumption and make the standard more equitable.

2.3 Distributional impact of alternative standard designs

Here we discuss how alternative standard designs modify the analysis of Section 2.2. Four variations of standards are discussed: subsidies on efficient technologies, taxes on inefficient technologies, attribute-adjusted standards, and feebates programmes.

First, we model a simple subsidy on efficiency by setting R_0 to zero in Equation (15). In this special case, governments give monetary rewards to households using efficient technologies. Similar real-world policies include tax credits or subsidies for energy-saving cars and appliances. Equation (15) reveals that such subsidies tend to be more progressive than single-benchmark standards if households with increasing income desire some high-carbon attributes detrimental to efficiency. Governments can also apply a subsidy only when efficiency reaches a certain level. Again, such a subsidy can be progressive when households prefer high-carbon attributes, particularly to the extent that richer households use less efficient technologies. This aligns with our general conclusion in Section 2.2.

Second, a simple tax on inefficiency can be modelled by setting R_0 in Equation (15) at the highest achievable efficiency in the market. In such a case, everyone pays a fee and no one receives a subsidy. Equations (15) and (13) show that such a tax tends to be more regressive than single-benchmark standards because all households must pay a certain amount of taxes. For such a tax to be progressive, richer households must pay much more given their income is higher. This rapid rise of tax payment is difficult to be met even when richer households use inefficient technologies. This explains why West (2004) and Levinson (2019) find that a tax on miles per gallon or engine size is regressive.

Third, some countries like the US and China have enacted attribute-adjusted standards in their vehicle markets. For example, the US Corporate Average Fuel Economy standard adjusts fuel economy targets according to vehicle footprint. Vehicles with larger footprint face a less stringent standard. From a distributional perspective, compared to

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[14] The role of η is less clear. It increases as the stringency of the standard rises relative to the tax. Increasing the stringency of the standard also reduces the value of the bracket in Inequality (15) through R_0. In the end, the effect of η depends on the sign and size of the bracket, which is also controlled by the policy stringency of standard. We expect that there can be a turning point for the policy stringency, after which the standard becomes more regressive than the tax, since increasing R_0 could make the bracket negative. Also see the numerical analysis in Section 2.4, which indicates that standards become more regressive as stringency rises.

a single-benchmark standard, this approach increases the requirement for efficient technologies and reduces the benchmark for inefficient technologies. Therefore, if poorer households use more efficient technologies, attribute-adjusted standards will be more regressive than single-benchmark standards.

Fourth, feebates schemes are popular in some European countries. Durrmeyer and Samano (2018) and Roth (2015) have compared fuel economy standards with "feebates", i.e. a mix of taxes and subsidies based on vehicle efficiency, and showed the theoretical equivalence of them in terms of economic efficiency. This is easy to understand: Feebates are schemes that taxes inefficiency and subsidises efficiency. If properly designed, they can be equivalent to single-benchmark standards or even multiple-benchmark standards because standards are effectively implicit taxes and subsidies (see Appendix D). Therefore, the results in Section 2.2 apply to feebates too.

2.4 Application: Evidence from the US Vehicle Market

We use the data of US household vehicle ownership to analyse an empirical case supporting our theoretical findings: preferences for efficiency-decreasing attributes reduce households' demand for efficiency, and might make a fuel economy standard more equitable than a carbon tax. We also evaluate the distributional consequences of alternative standard designs, as discussed in Section 2.3.

We use the 2009 US National Household Travel Survey (NHTS), produced by the US Department of Transportation, which includes vehicle and demographic information of over 110,000 households. The survey data is coupled with vehicle specifications obtained from CarQuery. We then drop households with more than five vehicles and those entries with missing data points such as income and fuel economy, following Levinson (2019). The cleaned data consist of 102,404 households and 148,114 vehicles. Table 1 shows the descriptive statistics.[15]

The last two columns of Table 1 show that richer households drive less efficient vehicles, which our model suggests might be caused by high-carbon attributes. Table 2 presents attribute characteristics of vehicles owned by each income group. We observe that richer households do buy larger, heavier and more powerful vehicles. These attributes affect the difficulty of achieving fuel economy, and consequently the cost of efficiency, as assumed in the model of Section 2.1.

We regress efficiency consumption against household income and vehicle characteristics to further verify the implied relation among household income, efficiency consumption

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[15] Note that in Table 1, numbers in miles per gallon do not equal to 100 times the inverse of numbers in gallons per hundred miles. This is because numbers in Table 1 are arithmetically averaged across households.

Table 1: Descriptive statistics of household and vehicle information.

(1) Household Income (2009 $)	(2) Number of Households	(3) Number of Vehicles	(4) Gasoline Usage (Gallons)	(5) Miles Driven	(6) Gallons per Hundred Miles	(7) Miles per Gallon
<$10,000	4,845	0.60	251	5,287	3.88	26.96
$10,000–$19,999	9,194	0.91	373	7,894	3.87	27.06
$20,000–$29,999	10,583	1.15	510	10,763	3.91	26.90
$30,000–$39,999	10,283	1.27	616	12,960	3.96	26.56
$40,000–$49,999	9,817	1.34	683	14,429	3.97	26.58
$50,000–$59,999	9,122	1.42	758	16,065	3.98	26.55
$60,000–$69,999	7,640	1.48	820	17,370	4.00	26.48
$70,000–$79,999	7,599	1.52	871	18,429	4.01	26.48
$80,000–$99,999	10,351	1.58	924	19,590	4.01	26.43
>=$100,000	22,970	1.65	995	21,013	4.03	26.57
Total	102,404	1.37	735	15,544	3.98	26.60

Note: Data are from the US National Household Travel Survey and CarQuery, as compiled by Levinson (2019). Columns 3 to 5 are averaged across all households including those without vehicles. Columns 6 and 7 are averaged across vehicles owned by each income group.

Table 2: Household consumption of efficiency-decreasing attributes of vehicles.

(1) Household Income (2009 $)	(2) Number of Households	(3) Weight (kg)	(4) Engine Power (horsepower)	(5) Height (mm)	(6) Width (mm)	(7) Wheelbase (mm)
<$10,000	4,845	1,411	164	1,490	1,794	2,661
$10,000–$19,999	9,194	1,439	167	1,494	1,800	2,652
$20,000–$29,999	10,583	1,482	174	1,524	1,814	2,697
$30,000–$39,999	10,283	1,503	179	1,546	1,822	2,727
$40,000–$49,999	9,817	1,515	182	1,560	1,824	2,740
$50,000–$59,999	9,122	1,522	183	1,572	1,829	2,757
$60,000–$69,999	7,640	1,543	186	1,586	1,832	2,768
$70,000–$79,999	7,599	1,543	188	1,588	1,833	2,766
$80,000–$99,999	10,351	1,551	189	1,601	1,838	2,782
>$100,000	22,970	1,569	197	1,603	1,840	2,780
Total	102,404	1,528	185	1,572	1,829	2,750

Note: Data are from the US National Household Travel Survey and CarQuery, as compiled by Levinson (2019). Columns 3 to 7 are averaged across vehicles owned by each income group.

and high-carbon attributes, as predicted by our theoretical model. The results are shown in Table 3. We allow attributes to take logarithmic forms and original values to remain agnostic towards the functional form of the equation system defined in Section 2.1. The regression suggests that the overall effect of income on fuel economy is negative. Only after blocking the importance of attributes, the income effect becomes positive. This result is consistent with our theoretical prediction: richer households want more fuel economy, but they nevertheless drive gas-guzzlers due to preferences for high-carbon attributes. These preferences offer the necessary condition for the standard to be more progressive than carbon taxes.

Using the data of fuel consumption and fuel economy, we first estimate the incidence of carbon taxes and several single-benchmark efficiency standards. Following the definition in the theoretical model, we use miles per gallon as the measurement of efficiency. For the standard, we assume three levels of increasing stringency, i.e. 60%, 65%, and 70% quantiles of fuel economy of all vehicles. The three stringency levels correspond to 27, 27.8 and 28.6 miles per gallon respectively. The US Corporate Average Fuel Economy (CAFE) standard was set at 27.5 miles per gallon before it moved to an attribute-adjusted scheme after 2010 (US Congress, 2021). Therefore, as the data was collected near 2010, the 65-quantile standard is most similar to the by-then US CAFE standard. The 60-quantile is less stringent than CAFE and the 70-quantile is more stringent. For estimating the incidence on each income group, we calculate the average gap between the standard benchmark and household-owned vehicles and divide it by mean income using the formula $\tau_R(R_0 - R)/Y$, as we do in Section 2.2.[16]

We additionally model two special fuel economy standards: the attribute-adjusted US CAFE standard after 2010 and a simple tax on fuel economy with the revenue proportionally redistributed to households based on income. Governments sometimes design attribute-adjusted standards which give more leniency to vehicles with larger footprint. Gas-guzzlers therefore face less stringent fuel economy requirement than economy cars. It is worthwhile to investigate how this move affects the distributional consequence. We

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[16] Note that in the simulations that follow, we have not distinguished between the new and used car markets, which Jacobsen (2013) shows are important for equity implications. We assume that the burden of meeting fuel economy standards falls on all vehicles equally. In reality, often only new car sales are covered by fuel economy standards, and the impact would reach the used-car market over time. The price impact on used cars should be smaller due to capital depreciation. Therefore, we may overestimate the burden received by those who drive used cars in this study. According to Jacobsen (2013), poorer households tend to buy more used cars in the US. Thus, the incidence could be smaller for low-income households relative to our current result if the distinction between new and used cars is made, i.e. standards might be more progressive than we describe here. At first look, this contradicts Jacobsen's (2013) result showing that adding the used-car market makes standards more regressive. In fact, no contradiction exists because Jacobsen (2013) compares a case of new cars only with including a used car market. We instead consider all cars but have the shortcoming that the impact of a standard is exaggerated on used cars.

Table 3: Fuel economy regressed by household income and vehicle attributes.

	Dependent variable:			
	Log(miles per gallon)		Miles per gallon	
	(1)	(2)	(3)	(4)
Log(income) ($)	-0.014^{***}	0.017^{***}	-0.218^{***}	0.619^{***}
	(0.001)	(0.001)	(0.029)	(0.022)
Weight (kg)		-0.254^{***}		-0.004^{***}
		(0.004)		(0.0001)
Width (mm)		-0.345^{***}		-0.010^{***}
		(0.015)		(0.0003)
Height (mm)		-0.620^{***}		-0.009^{***}
		(0.005)		(0.0001)
Wheelbase (mm)		-0.158^{***}		0.0002^{**}
		(0.008)		(0.0001)
Engine power (horsepower)		-0.176^{***}		-0.029^{***}
		(0.002)		(0.0004)
Constant	3.387^{***}	14.265^{***}	28.656^{***}	62.930^{***}
	(0.010)	(0.084)	(0.299)	(0.434)
All variables logged	Yes	Yes	No	No
Observations	128,569	128,569	128,569	128,569

Note: Standard errors in parentheses
*p<0.1; **p<0.05; ***p<0.01

simulate this attribute-adjusted CAFE by setting R_0 (measured in miles per gallon) according to a relationship with vehicle footprint (measured in squared feet), as defined in the 2012 US CAFE standard. The relationship is given as follows:

$$R_0 = \begin{cases} -0.533 * \text{footprint} + 57.817, & \text{if } 41 \leq \text{footprint} \leq 56 \\ 35.95, & \text{if footprint} < 41 \\ 27.95, & \text{if footprint} > 56 \end{cases} \tag{17}$$

For the tax, the incidence on each group is calculated by dividing average fuel consumption by mean income, i.e. $\tau_E E/Y$. Revenue redistribution is not considered in this first carbon-tax case. We then model a second carbon-tax scheme with the revenue redistributed to households in proportion to income levels, similar to a broad income-tax cut (Goulder and Hafstead, 2017; Williams III et al., 2015). We consider these two tax cases to reflect two views on revenue recycling: First, governments fail to, or they are not trusted to, redistribute the tax revenue, or governments put the revenue into unproductive uses. Therefore, how the tax revenue is used means little for the incidence perceived by households.[17] The second scenario considers that governments actually redistribute the revenue to households by an income tax cut.

To ensure comparability, we maintain revenue equivalence among these instruments. The carbon tax is set to raise per gallon gasoline price by \$0.5, i.e. roughly \$50 per ton of carbon emissions based on the carbon content of gasoline. The implicit tax on efficiency τ_R, resulted by the standard, is set to raise the same amount of revenue to subsidise efficient technologies.[18] Figure 1 illustrates the results.

Efficiency standards can be more progressive than carbon taxes in the US vehicle market. However, incidence of standards is sensitive to stringency levels, as Figure 1 reveals. Standards setting the benchmark at 60% and 65% quantiles create smaller impacts on the lower three income groups compared to both tax schemes. The 60-quantile standard is mostly progressive while all other instruments are regressive. When the benchmark

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[17] Evidence also shows that citizens focus more on expenditure impacts (Douenne and Fabre, 2022; Kallbekken et al., 2011).

[18] For example, if we set the efficiency benchmark at 27 miles per gallon, the implicit price τ_R will subsidise those people who drive cars with miles-per-gallon higher than 27. In the estimation, we require the total amount of subsidies is equal to the carbon-tax revenue. Those who drive inefficient cars with fuel economy lower than 27 miles per gallon will therefore implicitly pay for these subsidies, as proved in Appendix D. If we set a higher efficiency benchmark, there would be fewer cars being subsidised. The implicit price must be raised higher to maintain the revenue equivalence with the tax. This is consistent with the fact that a higher efficiency benchmark needs a larger price adjustment to change households' purchasing behaviours. The same logic works for the US CAFE standard although it set varied benchmarks according to car sizes. For the fuel-economy tax, we require that it raises the same amount of revenue as the carbon tax.

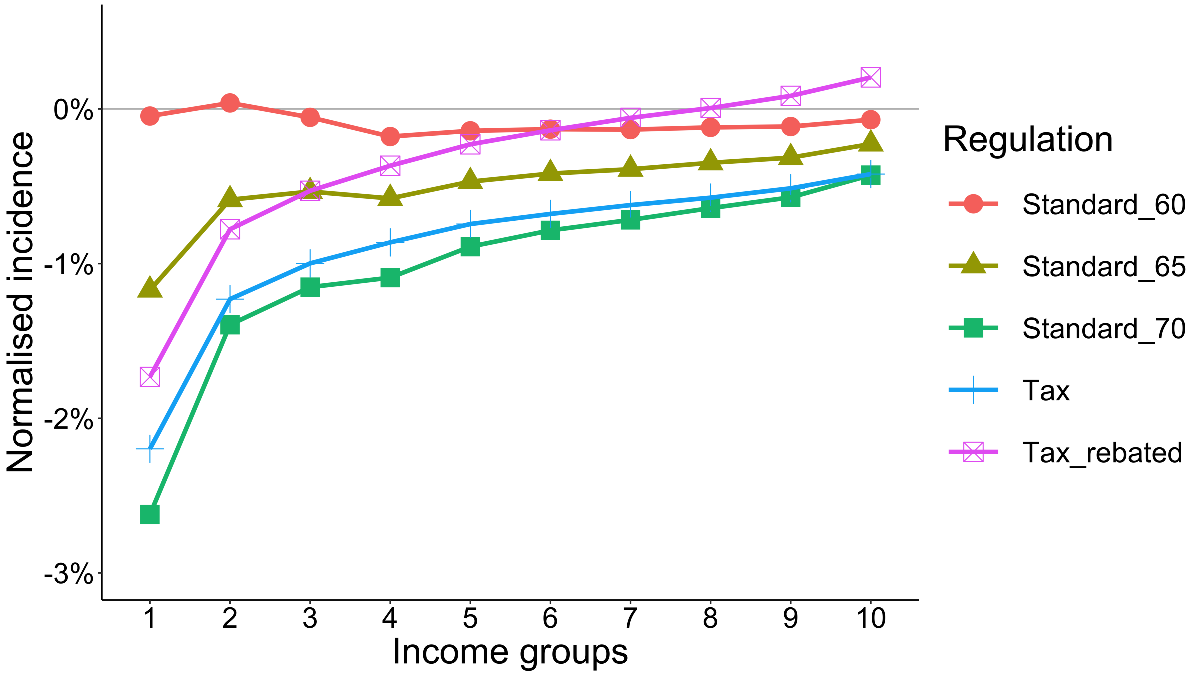

Figure 1: The incidence of carbon taxes and different levels of efficiency standards for the US vehicle market.

Note: Household income of each income group is defined in Table 1. $Standard\_60$, $Standard\_65$, and $Standard\_70$ represent efficiency standards with the benchmark efficiency set at 60%, 65%, and 70% quantiles of fuel economy of all vehicles; that is, from $Standard\_60$ to $Standard\_70$ policy stringency increases. The efficiency measurement is miles per gallon. Tax represents a carbon tax on fuels excluding revenue recycling. *Tax_rebated* denotes a tax where revenue is recycled to households by proportional income-tax cuts. Positive values indicate income gains and negative values indicate income losses.

increases to 70% quantile, the distributional effect of standards becomes similar to that of a carbon tax. The theoretical model predicts this regressive tendency since Inequality (13) in Proposition 2 tends to be violated when R_0 increases. Despite that, a more stringent standard in the US vehicle market is almost as progressive as a fuel tax.[19]

Figure 1 shows that revenue-recycling by income-tax cuts does not improve progressivity of carbon taxes. Many earlier studies noted that proportional income-tax rebates are distribution-preserving (Goulder and Hafstead, 2017; Williams III et al., 2015; Klenert et al., 2018b). There are, of course, well-known ways to progressively recycle the revenue, such as lump-sum rebates or transfers targeted only to low-income households.

Figure 2 compares a carbon tax of proportionate recycling with the other two special cases of efficiency standards: the US CAFE standard and a simple tax on fuel economy with revenue proportionally returned to households. Both standards show high regressivity with the CAFE standard being highly regressive, consistent with the prediction made in Section 2.3. The US CAFE standard particularly affects lower-income households, and creates larger impacts to all households. This is because the CAFE standard, being a footprint-adjusted standard, affects people's efficiency choices through only one channel: technical improvement. However, single-benchmark standards, as modelled before, have two channels: technological improvement and downsizing. Since the incidence of technical improvement falls on all households but downsizing falls more on richer households, CAFE standards are more regressive than single-benchmark standards. Also, as CAFE standards solely act on technical improvement, they can cause larger economic losses to households when equivalence is required—either revenue equivalence or emissions-reduction equivalence.

Our empirical conclusion contrasts with Levinson (2019), although we use the same data source, i.e. 2009 NHTS. It should be noted again that our theory differs from Levinson's (2019) model in making quality of energy services matter for households' choices, but this alone should not make us reach a different empirical conclusion. The reason for our empirical difference is instead that we model the incidence of standards differently. Levinson (2019) uses a simple tax on inefficiency (see Figure 2) to approximate an efficiency standard, however, we use the established theoretical representation of a standard, i.e. implicit subsidies and taxes relative to the efficiency benchmark (see how the incidence is measured earlier in this Section and also in Section 2.2). Figures 1 and 2 show that an inefficiency tax is indeed slightly more regressive than an unrebated carbon tax, as Levinson (2019) finds, but also that an efficiency standard could be more

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[19] Note that Figure 1 is not a statistical statement showing that the incidence difference among income groups is significant. It instead reflects the average trend across the income spectrum. It might of course be that variations within income groups are large as well, as Fischer and Pizer (2019) have shown. We focus on vertical equity and therefore do not engage with horizontal variations within income groups.

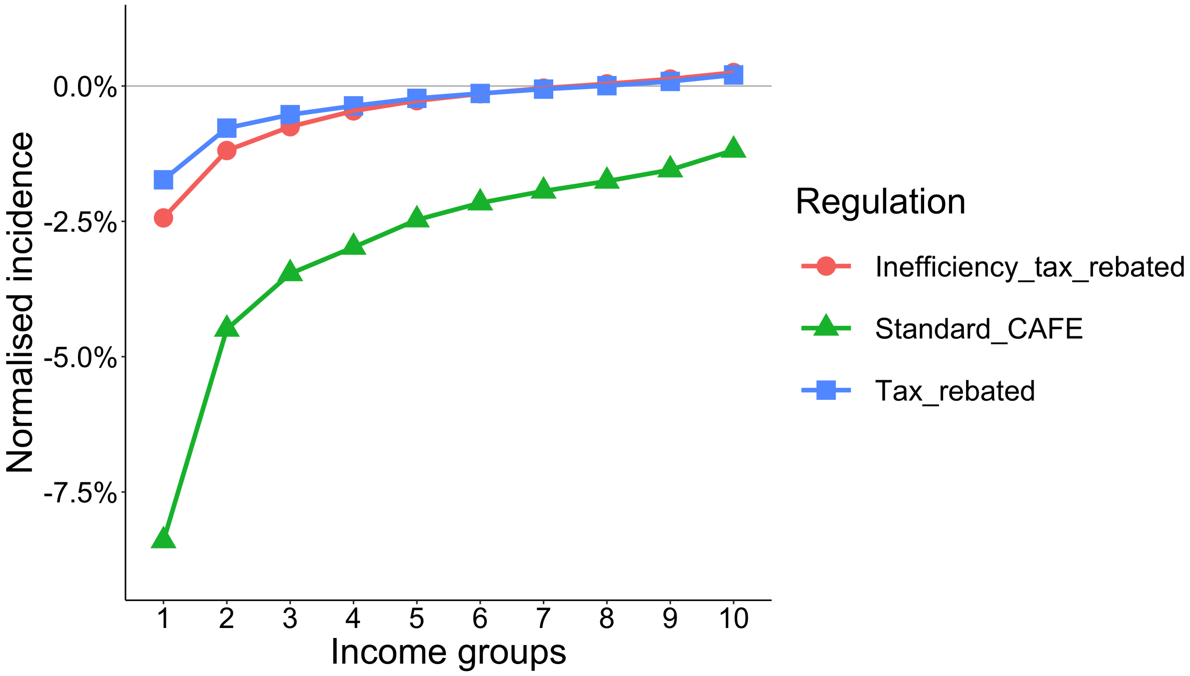

Figure 2: The incidence of an inefficiency tax, the US CAFE standard, and a carbon tax.

Note: Household income of each income group is defined in Table 1. *Tax_rebated* represents a carbon tax on fuels with proportionate recycling. *Inefficiency_tax_rebated* refers to a simple tax on fuel economy where inefficient vehicles are charged more. The tax revenue is returned to households proportional to their income, same as the *Tax_rebated* scenario. The efficiency, or fuel economy, measurement is miles per gallon. *Standard_CAFE* models the 2012 US CAFE standard. Positive values indicate income gains and negative values indicate income losses.

progressive than the carbon tax when it is not too stringent.

We also note that this empirical analysis has not considered how the increasing adoption of electric vehicles (EV) and hybrids (HEV) will modify our results. Some early studies show that rich households tend to buy more EV and HEV, and existing EV policies such as subsidies and tax credits are regressive in the US (Metcalf, 2022; Ku and Graham, 2022; Muehlegger et al., 2018). The EV adoption affects the incidence of carbon taxes, too, as EVs are less carbon-intensive to drive. Additionally, early adopters of EV, despite likely being rich, will drive down EV costs, making it affordable for less wealthy people later (as was the case with solar panels). The impact of EV on the relative regressivity between standards and pricing is therefore not straightforward. Nevertheless, our theoretical work suggests factors to consider for an analysis including EV and HEV: whether attributes of EV and HEV are liked or disliked by households and how they are related to fuel economy.

In sum, the empirical evidence from the US vehicle market supports our theoretical findings: Preferences for high-carbon attributes reduce richer households' tendency to consume more efficiency, and might cause them to use less efficient technologies. When such an efficiency-decreasing preference is strong enough, single-benchmark efficiency standards can be more equitable than a carbon tax, absent progressive revenue redistribution. We also demonstrate that attribute-adjusted standards could be the most regressive instrument.

3 Distributional impacts of intensity standards for subsistence and luxury goods

The analysis of the previous section assumed that expenditure shares on goods do not change with income, i.e. we assumed homothetic preferences. This is often not true in reality. For example, lower-income households spend higher income shares on energy fuels and essential goods like food and clothing (Grainger and Kolstad, 2010). Some of these goods are carbon-intensive. Meanwhile, there are some carbon-intensive goods disproportionately consumed by the rich, such as air travel and cars. Intuitively, policies reducing emissions from luxury goods burden low-income households less, while policies on subsistence goods burden them more. However, whether intensity standards or carbon pricing are more equitable under non-constant expenditure shares remains unclear.

To discuss how such consumption patterns may affect distributional impacts of policy instruments, this section develops a static, partial-equilibrium model with non-homothetic preferences for two carbon-intensive goods and one numeraire good. One carbon-intensive good is cleaner than the other. One good is a “luxury” good, i.e. richer households spend a higher share of income on it. The other is a “subsistence” good, i.e. poorer households spend a higher share of income on it.

There are two ways to interpret luxury and subsistence consumption from a regulatory perspective. First, luxury and subsistence goods might be thought of as goods in the same sector, but have different consumption patterns and levels of emissions, i.e. products in that sector are differentiable. For example, passenger transport includes private and public transport. Private transport is more often used by the rich than public transport does, and has generally higher carbon intensity. Additionally, private transport may be further segregated into higher-carbon transport like SUVs and lower-carbon transport like compact cars. Consumption patterns of types of cars, and correspondingly transport services, are different for rich and poor households. Therefore, modes of transport are often regulated differently to achieve cost-effectiveness and distributional goals.

The second way of approaching the distinction between luxury and subsistence goods is to take a multi-sector perspective.[20] As stated, households spend varied income shares on goods such as food, aviation and electricity. Policy instruments may be designed to target these sectors differently. In this case, intensity standards across multiple sectors could be designed as an output-based emissions trading system, also called tradable performance standards. Emissions quotas to each sector are not fixed caps but adjustable output-based allocations, i.e. the quotas a firm received is the firm’s production output multiplied by the government-set intensity level.[21] Different sectors can be regulated with different intensity levels to balance between cost-effectiveness and equity.

We develop a simple analytical model to elucidate the distributional implications of regulations in this setting with non-homothetic preferences (Section 3.1). We show how different consumption patterns affect the regressivity of intensity standards and carbon taxes, and contrast them. Our main result is that, absent progressive revenue recycling, intensity standards are generally more equitable than carbon taxes when luxury goods are more carbon-intensive than subsistence goods (Section 3.2). We apply the model to the Chinese vehicle market in Section 3.3, and illustrate that standards can be preferable

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[20] An additional regulatory interpretation of luxury and subsistence goods is regulating one sector with a non-differentiable good. The good may be of luxury or subsistence characteristics. A classic case is electricity. Although electricity is non-differentiable, we can use different technologies to produce it. Therefore, climate policy can motivate companies to substitute dirty technologies with clean technologies, and encourage less electricity consumption. We do not discuss this scenario here as it has been analysed before. See Rausch and Mowers (2014) for example.

[21] For example, if an electricity company generates one-million kWhs and the company faces an intensity standard of 500 gram-CO_2e per kWh, the emissions quotas the company receives are 500 multiplied by one million. Companies can trade with others to comply with these quotas. See Goulder et al. (2022) for a discussion of such a programme in the Chinese power sector. Also see Fischer (2001) for an analytical discussion of output-based instruments.

on progressivity. In Section 3.4, we use the simulation results and a fairness metric to evaluate the political feasibility of policies when considering both efficiency and equity.

3.1 The model

We follow Ballard et al. (2005), Klenert et al. (2018b), Aubert and Chiroleu-Assouline (2019), and Jacobs and van der Ploeg (2019) in modelling households with non-homothetic preferences by introducing a Stone-Geary utility function:

$$U_i = X_i^{\theta}(S_{1,i} - S_1^0)^{\alpha}(S_{2,i} + S_2^0)^{\beta} l_i^{\gamma}. \tag{18}$$

We assume, without loss of generality, that the sum of θ, α, β, and γ is equal to one for tractability. There are N households, indexed by i. l_i is the share of time consumed by household i as leisure. Correspondingly, $1 - l_i$ is the share of time households sell as labour. Every household has the same time endowment. X is a numeraire good. S_1 and S_2 represent the subsistence good and the luxury good respectively. S_1^0 controls the minimum level of subsistence consumption, i.e. all households must consume a minimal amount of S_1^0. The interpretation of S_2^0 is less intuitive but Appendix E.1 shows that it effectively controls the minimal income for households to start consuming S_2. If S_1^0 and S_2^0 are set to zero, Equation (18) becomes a homothetic utility function. S_1^0 and S_2^0 in effect control the significance of the subsistence and luxury properties of consumption. A greater S_1^0 suggests that more of the good is needed for subsistence.

We consider two policy instruments: carbon taxes and intensity standards.[22] Carbon taxes charge the embodied emissions of goods. Intensity standards set an emissions intensity benchmark for the regulated goods, with the high-emissions ones being discouraged and the low-emissions ones being encouraged. In Appendix D, we show that in effect intensity standards have two components: an implicit tax on high-emissions goods and an implicit subsidy on low-emissions goods.

Intensity standards do not generate government revenue. Implicit taxes on high-emissions goods are set equal to implicit subsidies to low-emissions goods. By contrast, carbon taxes generate government revenue. We consider three cases: the revenue is not returned to households, it is returned to households through lump-sum rebates, and briefly the implication of returning the revenue to households through proportionate income tax cuts. The case of no redistribution is important for two reasons: First, it

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[22] We use "intensity standards" instead of "efficiency standards" for easier comparison with carbon taxes in this section. The unit of intensity is emissions per unit output. The unit of efficiency is output per unit emissions input, i.e. the inverse of intensity.

is representative of government consumption not affecting households directly, ranging from infrastructure investment to corruption. Second, households may not trust the government to the extent that they do not believe governments will put the tax revenue into effective uses (Klenert et al., 2018a; Douenne and Fabre, 2020). Therefore, when households evaluate policy options *ex-ante*, they consider how rising commodity prices would affect them, ignoring redistribution.

We assume that households have heterogeneous earning abilities. Households' income is given by:

$$I_i = \phi_i \omega (1 - l_i)(1 - \tau_w), \tag{19}$$

where I_i is the household income and ϕ_i is the earning ability of household i. We normalise household earning abilities so that $\sum_{i=1}^{N} \phi_i = 1$. The wage faced by all households is ω. The labour tax rate is τ_w, which can be calibrated to tax levels in relevant cases.

The budget constraint of households is given by:

$$X_i + S_{1,i}(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)) + S_{2,i}(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0)) = I_i + L_i. \tag{20}$$

The emissions intensity of the subsistence good, the luxury good and the standard are denoted by e_1, e_2 and e_0 with $e_1 < e_0 < e_2$ or $e_2 < e_0 < e_1$. The standard must be set between e_1 and e_2. L_i is the uniform lump-sum rebate from the carbon tax revenue and may be zero. p_1 and p_2 are the prices of S_1 and S_2 respectively. The carbon tax rate is τ_e. $\tau_r(e_1 - e_0)$ and $\tau_r(e_2 - e_0)$ are the price effects of the intensity standard. It is a tax on goods that have emissions intensity higher than the standard e_0 and a subsidy on goods that have emissions intensity lower than the standard e_0. The implicit tax rate of the intensity standard is τ_r. Regulators set the standard benchmark e_0 instead of the tax rate τ_r, as τ_r is endogenously determined. This implicit tax rate affects demand of goods, and consequently ensures that the standard benchmark e_0 is met by the average of all consumed goods.[23]

As the standard binds and does not generate revenue, the following equation holds:

$$\sum_{i=1}^{N} S_{1,i}(e_1 - e_0) + \sum_{i=1}^{N} S_{2,i}(e_2 - e_0) = 0. \tag{21}$$

Equation (21) is met by endogenously adjusting τ_r which affects the demand of S_1 and S_2. We assume that only one regulation exists, i.e. either τ_e or τ_r is zero.

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[23] Note that the intensity standards must be tradable for τ_r to be constant across companies. If one company fails to comply, it can buy extra "credits" or "quotas" from those companies complying better than they should. See Appendix D for details.

We obtain the below expressions of X_i, $S_{1,i}$, $S_{2,i}$ and l_i by transforming the first-order conditions for maximising utility (18) subject to the budget constraint (20):

$$\begin{aligned}
X_i &= \theta(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1+\tau_e e_1+\tau_r(e_1-e_0)) \\
&\quad +S_2^0(p_2+\tau_e e_2+\tau_r(e_2-e_0))), \qquad (22)\\
S_{1,i} &= \frac{\alpha}{p_1+\tau_e e_1+\tau_r(e_1-e_0)}(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1+\tau_e e_1+\tau_r(e_1-e_0)) \\
&\quad +S_2^0(p_2+\tau_e e_2+\tau_r(e_2-e_0))) + S_1^0, \qquad (23)\\
S_{2,i} &= \frac{\beta}{p_2+\tau_e e_2+\tau_r(e_2-e_0)}(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1+\tau_e e_1+\tau_r(e_1-e_0)) \\
&\quad +S_2^0(p_2+\tau_e e_2+\tau_r(e_2-e_0))) - S_2^0, \qquad (24)\\
l_i &= \frac{\gamma}{\phi_i\omega(1-\tau_w)}(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1+\tau_e e_1+\tau_r(e_1-e_0)) \\
&\quad +S_2^0(p_2+\tau_e e_2+\tau_r(e_2-e_0))). \qquad (25)
\end{aligned}$$

We use the utility ratio of two households as a measure of the distributional impact. The two households i and j have discrete earning abilities, and therefore one is richer than the other. Using Equations (22), (23), (24) and (25), we obtain the ratio of the indirect utilities of the two households:

$$\begin{aligned}
\frac{U_i}{U_j} &= \frac{X_i^\theta (S_{1,i}-S_1^0)^\alpha (S_{2,i}+S_2^0)^\beta l_i^\gamma}{X_j^\theta (S_{1,j}-S_1^0)^\alpha (S_{2,j}+S_2^0)^\beta l_j^\gamma} \\
&= \left(\frac{\phi_j}{\phi_i}\right)^\gamma \left(\frac{\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1+\tau_e e_1+\tau_r(e_1-e_0))}{\phi_j\omega(1-\tau_w) + L_j - S_1^0(p_1+\tau_e e_1+\tau_r(e_1-e_0))}\right. \\
&\quad \left.\frac{+S_2^0(p_2+\tau_e e_2+\tau_r(e_2-e_0))}{+S_2^0(p_2+\tau_e e_2+\tau_r(e_2-e_0))}\right). \qquad (26)
\end{aligned}$$

We define the utility ratio before regulations as $\left(\frac{U_i}{U_j}\right)^{\text{BR}}$, the utility ratio after implementing an intensity standard as $\left(\frac{U_i}{U_j}\right)^{\text{AS}}$, the utility ratio after implementing a carbon tax with lump-sum rebates as $\left(\frac{U_i}{U_j}\right)^{\text{AT-L}}$, and the utility ratio after implementing a carbon tax with no redistribution as $\left(\frac{U_i}{U_j}\right)^{\text{AT-N}}$. The respective equations are:

$$\left(\frac{U_i}{U_j}\right)^{\text{BR}} = \left(\frac{\phi_j}{\phi_i}\right)^{\gamma}\left(\frac{\phi_i\omega(1-\tau_w) - S_1^0 p_1 + S_2^0 p_2}{\phi_j\omega(1-\tau_w) - S_1^0 p_1 + S_2^0 p_2}\right), \tag{27}$$

$$\begin{aligned}\left(\frac{U_i}{U_j}\right)^{\text{AS}} = \left(\frac{\phi_j}{\phi_i}\right)^{\gamma}\Bigg(&\frac{\phi_i\omega(1-\tau_w) - S_1^0(p_1 + \tau_r(e_1 - e_0))}{\phi_j\omega(1-\tau_w) - S_1^0(p_1 + \tau_r(e_1 - e_0))}\\ &\frac{+S_2^0(p_2 + \tau_r(e_2 - e_0))}{+S_2^0(p_2 + \tau_r(e_2 - e_0))}\Bigg),\end{aligned} \tag{28}$$

$$\begin{aligned}\left(\frac{U_i}{U_j}\right)^{\text{AT-L}} = \left(\frac{\phi_j}{\phi_i}\right)^{\gamma}\Bigg(&\frac{\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1)}{\phi_j\omega(1-\tau_w) + L_j - S_1^0(p_1 + \tau_e e_1)}\\ &\frac{+S_2^0(p_2 + \tau_e e_2)}{+S_2^0(p_2 + \tau_e e_2)}\Bigg),\end{aligned} \tag{29}$$

$$\begin{aligned}\left(\frac{U_j}{U_i}\right)^{\text{AT-N}} = \left(\frac{\phi_i}{\phi_j}\right)^{\gamma}\Bigg(&\frac{\phi_i\omega(1-\tau_w) - S_1^0(p_1 + \tau_e e_1)}{\phi_j\omega(1-\tau_w) - S_1^0(p_1 + \tau_e e_1)}\\ &\frac{+S_2^0(p_2 + \tau_e e_2)}{+S_2^0(p_2 + \tau_e e_2)}\Bigg).\end{aligned} \tag{30}$$

For $\left(\frac{U_i}{U_j}\right)^{\text{AT-L}}$, the following equation must be satisfied to ensure revenue neutrality:

$$\sum_{i=1}^{N} L_i = \tau_e e_1 \sum_{i=1}^{N} S_{1,i} + \tau_e e_2 \sum_{i=1}^{N} S_{2,i}. \tag{31}$$

3.2 Comparing distributional impacts of intensity standards and carbon taxes

From Equations (27), (28), (29) and (30), we can derive several propositions. Taken together, these indicate that the incidence of both standards and taxes depends on carbon intensities and the degree of subsistence and luxury consumption (S_1^0 and S_2^0). A tax with lump-sum rebates will, however, be progressive under all circumstances.

Lemma 4. *An intensity standard regulating carbon-intensive goods with luxury and subsistence properties is*
(a) progressive if the luxury good has a higher carbon emissions intensity, i.e. $e_1 < e_2$*;*
(b) regressive if the subsistence good has a higher carbon emissions intensity, i.e. $e_1 > e_2$.

Lemma 5. *A carbon tax with lump-sum rebates levied on carbon-intensive goods with luxury and subsistence properties is always progressive.*

A carbon tax with no redistribution is
(a) progressive when $S_1^0 e_1 < S_2^0 e_2$*;*

(b) regressive when $S_1^0 e_1 > S_2^0 e_2$.

Proof. For the proofs of Lemmas 4 and 5, see Appendix E.2. ☐

An intuitive understanding of Lemmas 4 and 5 emerges from the fact that a tax (or a subsidy) on luxury goods is progressive (or regressive) since richer households spend higher shares of income on them. The converse is true for a tax or a subsidy on subsistence goods. When goods of luxury and subsistence properties both exist, the regressivity of a carbon tax therefore depends on the relative magnitude of the burden on these two types of consumption, which in turn is determined by these goods' carbon intensities and the degree of their luxury and subsistence properties. Lemma 5 demonstrates this intuition. Different from the carbon tax, regressivity of standards depends only on emissions intensities, as demonstrated in Lemma 4. This is because a standard is an implicit subsidy on low-emissions goods and an implicit tax on high-emissions goods. When the luxury good is more carbon-intensive for example, i.e. $e_1 < e_2$, the implicit tax on the luxury good is progressive and the implicit subsidy on the low-emissions subsistence good is also progressive. Combining two progressive instruments is surely progressive no matter the magnitude of each.

We now contrast the incidence of taxes and standards, especially for equivalent emissions reductions. The following proposition is obtained:

Proposition 6. *When the subsistence good has a higher carbon intensity, a necessary condition for an intensity standard to be more equitable than a carbon tax with no redistribution is:*

$$\frac{e_0}{e_1} > (1 - \frac{\tau_e}{\tau_r}). \tag{32}$$

If Inequality (32) is satisfied, the sufficient condition is:

$$\frac{S_1^0}{S_2^0} > \frac{\left(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\right)}{\left((1 - \frac{\tau_e}{\tau_r})\frac{e_1}{e_2} - \frac{e_0}{e_2}\right)}. \tag{33}$$

Proof. See Appendix E.3. ☐

Inequality (32) is implausible when an equivalent abatement is required for the two instruments. This is first because $1 - \frac{\tau_e}{\tau_r}$ is close to one when an equivalent emissions reduction is sought: The implicit tax τ_r should be much greater than τ_e to achieve an equivalent abatement (see, for example, Goulder et al. (2022), Goulder et al. (2016)

and Landis et al. (2019) and also the numerical Section 3.3). The reason for this is that a carbon tax reduces emissions through two channels, i.e. demand reduction and the substitution between high-emissions goods and low-emissions goods. An intensity standard, however, reduces emissions primarily through the substitution between the two goods (see Appendix D). This single abatement channel requires the intensity standard to establish a much larger price difference between the two goods by the implicit tax and subsidy. Therefore, τ_r is much larger than τ_e, making $1 - \frac{\tau_e}{\tau_r}$ close to one. Second, a sizeable difference should exist between e_0, e_1 and e_2, as otherwise a technology mandate or no regulation would be enough instead of going through the effort of implementing an intensity standard.[24] This difference should make e_1 reasonably greater than e_0. Thus, $\frac{e_0}{e_1}$ is unlikely to be larger than $1 - \frac{\tau_e}{\tau_r}$. Inequality (32) is implausible.

The intuition of Proposition 6 is first that the necessary condition (32) requires a less stringent standard, i.e. a higher e_0 and consequently a lower τ_r. Under the assumptions of Proposition 6, lower stringency reduces the tax on high-emissions subsistence goods and the subsidy on low-emissions luxury goods, making the standard less regressive. Second, the sufficient condition requires a more pronounced subsistence property relative to the luxury property, i.e. a higher $\frac{S_1^0}{S_2^0}$. As the incidence of carbon taxes is more influenced by consumption quantities than that of standards, more consumption of high-emissions goods by lower-income groups exacerbates the regressivity of a carbon tax more than that of an intensity standard.[25] Meeting the two conditions therefore is beneficial for making the standard more equitable than the tax, as Proposition 6 indicates. However, when an equivalent emissions reduction is needed, the stringency of the standard cannot be very low, making the necessary condition hard to be met. Proposition 6 thus implies that under the equivalence requirement, a carbon tax with no revenue redistribution is more equitable than an intensity standard when subsistence goods are more carbon-intensive.

Similarly, we have:

Proposition 7. *A necessary condition for a carbon tax with no redistribution to be more equitable than an intensity standard when the luxury good has a higher emissions intensity is:*

$$\frac{e_0}{e_2} > (1 - \frac{\tau_e}{\tau_r}). \tag{34}$$

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[24] For example, if the intensity difference between the standard and the high-emissions good is small, implementing a standard would be meaningless in terms of reducing emissions. If the difference between the standard and the low-emissions good is small, regulators might simply mandate the use of the cleaner good.

[25] This is because an intensity standard is essentially a tax on emissions plus an output subsidy, which generates a smaller price impact than a similarly stringent carbon tax. For details, see Appendix D.

If Inequality (34) is satisfied, the sufficient condition is:

$$\frac{S_1^0}{S_2^0} < \frac{\left(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\right)}{\left((1 - \frac{\tau_e}{\tau_r})\frac{e_1}{e_2} - \frac{e_0}{e_2}\right)}. \tag{35}$$

Proof. See Appendix E.3. □

Similar to Propostion 6, Inequality (34) is implausible when an equivalent abatement is achieved. The rationale is, again, Equation (34) is unlikely to be satisfied since $1 - \frac{\tau_e}{\tau_r}$ is close to 1 and $\frac{e_0}{e_2}$ should be reasonably smaller than one as discussed above. Therefore, a standard is generally more progressive than a tax without revenue recycling when the luxury good is more carbon-intensive and an equivalent abatement is needed.

A similar interpretation can also be given of Proposition 7. The necessary condition requires a less stringent standard. Lower stringency makes the standard less progressive under the setting of Proposition 7. Reducing $\frac{S_1^0}{S_2^0}$ increases the progressivity of the carbon tax more than the standard. Therefore, meeting Inequalities (34) and (35) makes the tax more equitable than the standard. However, an equivalent abatement makes the necessary condition, i.e. lower standard stringency, hard to be met.

What happens when we instead consider revenue recycling? Lemmas 4 and 5 jointly demonstrate that carbon taxes with lump-sum rebates are strictly preferred on equity grounds if subsistence goods have a higher carbon footprint than luxury goods. The relative incidence is ambiguous when luxury goods have a higher carbon intensity. However, it is anticipated that under most parameter choices, a carbon tax with lump-sum rebates would still be more equitable since lump-sum transfers are highly progressive (see Landis et al. (2019) and Rausch and Mowers (2014)).

Finally, we expect that proportionate income tax cuts are mostly utility-ratio-preserving according to earlier studies (see e.g. Klenert and Mattauch (2016)), implying that they do not change the incidence of carbon taxes much. In other words, implications from Lemma 5, and Propositions 6 and 7 for taxes with no redistribution should still hold for taxes with proportionate redistribution. We next explore this numerically.

3.3 A numerical application to the Chinese transport sector

In this section, we illustrate the theoretical results with data on automobile ownership in China. The data are provided by the *China Household Finance Survey (CHFS)* published by Southern University of Finance and Economics (2019). Note that we do not consider the incidence on households with no car. If it were considered, all regulations would be more progressive since low-income households often do not own a car. We separate privately-owned cars into two groups according to their engine sizes, i.e. a group of high-emissions cars and a group of low-emissions cars. The low-emissions group includes cars with an engine size smaller than 2.5 litres. The high-emissions group has cars with an engine size bigger than 2.5 litres.

For parameterisation, we specify five households to represent five income quintiles. The earning abilities of the five households are given by the normalised average income of each group in the CHFS. The normalised earning abilities from low to high are 0.065, 0.106, 0.147, 0.207 and 0.475.

We consider driving high-emissions cars as the luxury good and driving low-emissions cars as the subsistence good; so we focus on energy-services consumption instead of car ownership to illustrate our model.[26] Expenditure shares in these two goods are approximated by the expenditure shares in gasoline for driving the two types of cars. The expenditure shares of driving high-emissions cars by income group from low to high are 0.003, 0.003, 0.005, 0.008 and 0.011. The expenditure shares of driving low-emissions cars by income group from low to high are 0.108, 0.093, 0.083, 0.065, and 0.033.

Share parameters of goods and leisure θ, α, β and γ are set to 0.96, 0.03, 0.01 and 0.1 according to the expenditure shares of the highest income group.[27] S_1^0 and S_2^0 are set to 1 and 0.13 so that the expenditure shares for the luxury and subsistence goods of the lowest income group are the same as in the data. Wage w is normalised to 1000. The income tax rate τ_w is set to 0.15.[28] Prices of the numeraire good, the subsistence good and the luxury good are 1, 1 and 2 respectively. The price of driving high-emissions cars is double than the price of driving low-emissions cars to match the average fuel efficiency of the two groups of cars. Accordingly, the emissions rates e_1 and e_2 are set to 0.5 and 1.

We model four regulations with the same amount of emissions reduction relative to a no-regulation scenario, i.e. each achieving approximately a 12% reduction in carbon emissions. The four regulations are (i) an intensity standard, (ii) a carbon tax with a lump-sum redistribution, (iii) a carbon tax with proportionate rebates according to each household's productivity, (iv) a carbon tax with no redistribution. A carbon tax with proportionate rebates is similar to returning the revenue through proportionate income tax cuts since both redistribution schemes are largely determined by households' earning

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[26] The design of intensity standards here is similar to the "feebate" scheme used in France. Like the feebate, the intensity standard implicitly taxes or subsidises vehicles based on their emissions intensity (see Gillingham (2013) and Durrmeyer and Samano (2018) for a comparison between these two instruments). A difference is that the intensity standard as defined in our model regulates transport services, i.e. driving cars, and the feebate scheme regulates vehicles, i.e. cars themselves. However, a feebate could be made equivalent to an intensity standard if it takes people's average driving distance into account.

[27] For a Stone-Geary utility function, expenditure shares approximate the share parameters when income is high enough.

[28] The average income tax rate in China is not officially published. Modifying the income tax rate does not change the results.

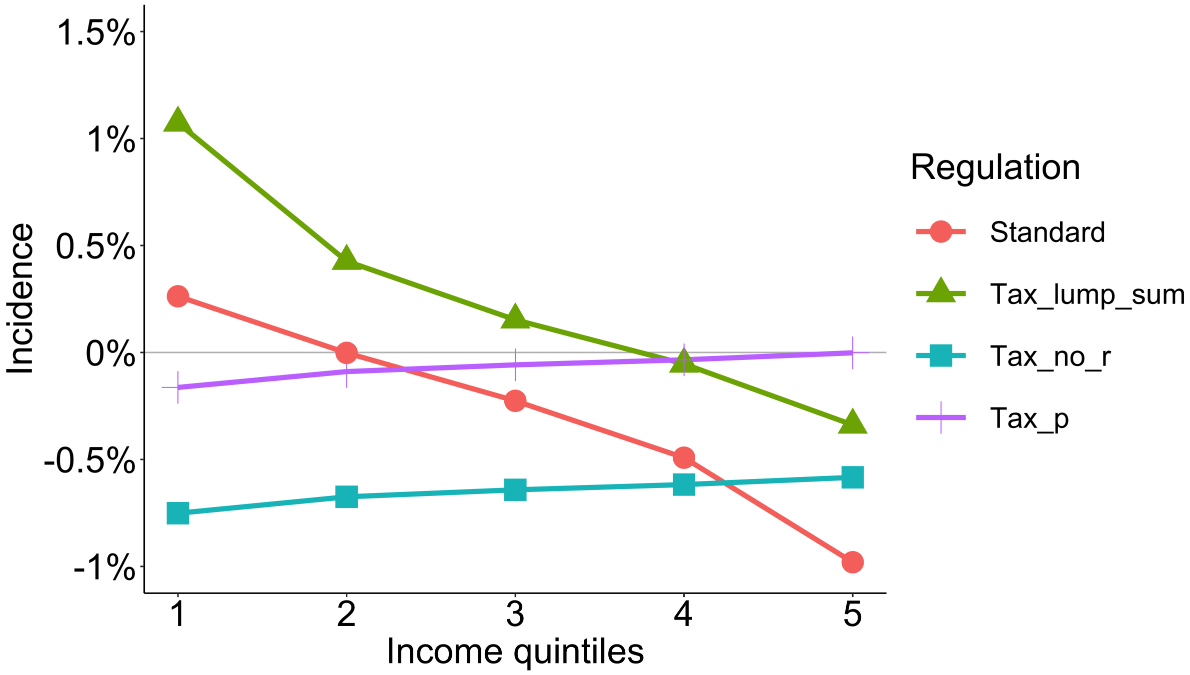

Figure 3: Comparison of the incidence of an intensity standard, a carbon tax with lump-sum rebates, and a carbon tax with proportionate redistribution.

Note: *Standard*, *Tax_lump_sum* and *Tax_no_r* represent the standard, the carbon tax with lump-sum rebates, and the carbon tax with proportionate rebates according to households' productivity respectively. Parameters are calibrated to the Chinese automobile sector. Positive values indicate utility gains and negative values indicate utility losses for each quintile. Incidence is expressed as the percentage of utility changes.

ability. For the non-redistributing tax, we assume that the government uses the revenue to purchase commodities according to households' expenditure shares. The emissions tax τ_e and the standard e_0 are endogenously determined at 0.3 and 0.504 to achieve the equivalent emissions reduction. The implicit tax τ_r entailed by the standard is determined endogenously as 15, which supports the conclusion made in Section 3.2 that τ_r should be much larger than τ_e for equivalent emissions reduction. Programming language *R* is used to simulate the model and R package *DEoptimR* is used for optimisation.

Results are given by Figure 3. It indicates that carbon taxes with no redistribution and proportionate returns are slightly regressive, and the carbon tax with lump-sum rebates and the intensity standard are sharply progressive. The simulation can be used to illustrates Lemmas 4, 5 and Proposition 7. Since $e_1 < e_2$, the intensity standard should be progressive. The carbon tax with no redistribution is regressive as $S_1^0 e_1 > S_2^0 e_2$. The outcome supports the finding that the intensity standard can be more equitable than carbon taxes, absent progressive redistribution, when luxury goods embody more carbon emissions. The result also supports the argument that proportionate rebates do not change the distributional consequences of taxes much.

3.4 The role of efficiency and equity in political feasibility

A further question, after analysing results on equity of policy instruments, is how much they matter for public support of standards and taxes. Besides equity, efficiency also influences a policy's political feasibility. While a general analysis of which matters more is beyond the scope (but see for example Sommer et al. (2022) for carbon prices), we close this section by outlining one potential approach to quantifying their respective importance, and apply it to the above analysis.

Concerning efficiency, Figure 3 shows that the carbon tax with lump-sum rebates, compared to the intensity standard, creates larger utility gains to low-income households and smaller utility losses to high-income households. This confirms the cost-effectiveness of carbon taxes. Similarly, the carbon tax with proportionate returns causes a smaller total welfare loss (if simple addition is used) than the standard: by aggregating individual utilities, we obtain a social welfare loss of the standard of -0.06% and a loss of the tax with proportionate returns of -0.04%.

Nevertheless, focusing on efficiency cannot explain observed public support for environmental policy instruments: carbon taxes are often disliked. It remains open whether including an equity dimension into an analysis of political feasibility better explains the observed public support for mitigation instruments. To resolve this, we must understand how efficiency and equity matter in public choices. Efficiency is immediately relevant because individuals are personally affected by policy changes. For equity, despite being more complex, people care about how they compare to others. Indeed, such a tendency to compare is supported by both classical theories of justice and behavioural economics. Therefore, we examine how people's experience of policy impacts can be assessed by both "consumption-driven" utility changes and what they consider a fair burden of distribution, i.e. "fairness-driven" utility changes.

In fact, recent developments in optimal taxation and environmental policy have built on the classical concept of equal sacrifices (Weinzierl, 2014; Fischer and Pizer, 2019), popularized by Mill (1871), Marshall and Sidgwick. They argue that people should experience an equal sacrifice for supporting the functioning of the government (if the current distribution is seen as just). Some scholars provide survey evidence and theoretical work supporting that this might be how people think (Weinzierl, 2014; Jessen et al., 2018). Furthermore, fairness can be integrated into utility functions by calculating the deviations of impacts between what is considered fair and what people actually experience

(Fehr and Schmidt, 1999; Bolton and Ockenfels, 2000). These studies show that fairness-inclusive utility functions better explain observed behaviours in experimental settings. Behavioural economics also offers experimental results and theoretical work suggesting that people value gains or losses against a reference point, such as the Prospect theory (Tversky and Kahneman, 1992). Where this reference point lies might be determined by people's expectation of a fair impact.

A universal feature of equal sacrifice, fairness, and Prospect theories is that people's perception of a just burden matters. Therefore, equity alongside efficiency might jointly explain the public support we observe. While efficiency can be quantified by personal impacts experienced—which we define as "consumption-driven" utility changes, equity less straightforward. Here we assume that people experience welfare gains or losses when their personal impact deviates from a reference point, and we call these welfare impacts "fairness-driven" utility changes (Bolton and Ockenfels, 2000; Weinzierl, 2014; Fischer and Pizer, 2019). The reference point is people's expectation about a fair burden, and is defined as equal percentage changes of utility across income groups, following the equal sacrifice principle.

Therefore, we calculate the consumption-driven utility change, expressed in percentage, as follows:

$$\Delta u_{C,i} = \frac{\Delta U_{C,i}}{U_{C,i}} \tag{36}$$

Here ΔU_C and Δu_C are absolute and relative utility changes caused by the policy reform. Δu_C is calculated by dividing ΔU_C by the initial utility U_C and is expressed in percentage, which is the same as in Figure 3.

We next define the fairness-driven utility change $\Delta u_{F,i}$ which measures the deviation between the impact $\Delta U_{C,i}$ received by household i and the fair burden $U_{C,i} \sum_{i=1}^{N} \Delta U_{C,i} / \sum_{i=1}^{N} U_{C,i}$. This fair burden is an equal percentage change in individual utility as averaged from the total impact. $\Delta u_{F,i}$ is also expressed in percentage and is calculated as:

$$\Delta u_{F,i} = (\Delta U_{C,i} - U_{C,i} \frac{\sum_{i=1}^{N} \Delta U_{C,i}}{\sum_{i=1}^{N} U_{C,i}})^{\alpha} / U_{C,i} \tag{37}$$

People's aversion to unfairness is defined by α. It may differ for gains and losses as shown in the Prospect theory (Tversky and Kahneman, 1992). The total change in individual welfare, driven by both consumption and fairness, is defined by the value function $v(\Delta u_{C,i}, \Delta u_{F,i})$:

$$v_i(\Delta u_{C,i}, \Delta u_{F,i}) = \Delta u_{C,i} + \lambda \Delta u_{F,i} \tag{38}$$

The weight given to fairness relative to consumption is represented by λ.

Assuming $\alpha = 1$ and using the results in Section 3.3, we compute two types of utility changes for every income group under each policy scenario. Table 4 shows the results. On average, both carbon tax schemes fare better than the standard when only consumption-driven utility is involved. This again confirms the efficiency advantage of carbon pricing.[29]

Table 4: Consumption-driven and fairness-driven utility changes under three policy scenarios.

	Tax_p		*Tax_lump_sum*		*Standard*	
Quintile	Δu_C	Δu_F	Δu_C	Δu_F	Δu_C	Δu_F
1	-0.16%	-0.13%	1.07%	1.10%	0.26%	0.85%
2	-0.09%	-0.05%	0.43%	0.46%	-0.00%	0.58%
3	-0.06%	-0.02%	0.15%	0.19%	-0.23%	0.36%
4	-0.03%	0.00%	-0.05%	-0.02%	-0.49%	0.09%
5	-0.00%	0.03%	-0.34%	-0.30%	-0.98%	-0.40%
Mean	-0.07%	-0.03%	0.25%	0.29%	-0.29%	0.30%

Note: Δu_C and Δu_F are consumption-driven and fairness-driven utility changes. *Tax_p*, *Tax_lump_sum* and *Standard* represent a carbon tax with proportionate returns, a carbon tax with lump-sum rebates, and a fuel economy standard respectively. Quintiles 1 to 5 are from the lowest income to the highest income. Negative values indicate utility losses.

However, when we consider how people *perceive* unfairness (gains and losses) in policy burdens, results become mixed. The standard and the lump-sum tax make lower-income households much better off on fairness, due to their progressivity. On average, their fairness metrics are much better than the outcome for the tax with proportionate rebates (see the *Mean* row in Table 4). Therefore, depending on how much weights we give to consumption-driven and fairness-driven changes, citizens might prefer the standard over the proportionate tax. For example, if assuming the consumption- and fairness-driven changes having equal weights, i.e. $\lambda = 1$, we find that the standard, compared to the proportionate tax, makes the lower three income groups experience larger positive gains,

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[29] We neglect specifying social welfare functions here and only compare policies by a simple utilitarian approach. There are of course multiple social welfare conceptions, such as the Rawlsian one, that can be used to evaluate inequality-aversion as part of social welfare. But it is unlikely that they are relevant for determining individual support for a policy.

i.e. winning majority support. This advantage of standards extends to the case in which households do not trust their government to put the tax revenue into effective uses.

Finally, the results in this subsection provide support to Stiglitz's (2019) observation that differential treatments to goods disproportionately consumed by the rich and the poor may create a larger social welfare gain than a single carbon tax applied to all goods. The numerical case reveals that this observation can be potentially true for the comparison between intensity standards and carbon taxes without progressive redistribution. In Figure 3, the standard generates utility gains to lower-income households, despite causing bigger losses to higher-income households than the tax with proportionate recycling. If the utility gain in lower-income households provides a much larger marginal increase in social welfare, the standard, which causes different price effects to luxury and subsistence goods, may be preferable over carbon taxes even from a social welfare perspective, not only a distributional one.

4 Discussion

We have shown that regulatory standards can be more equitable than pricing instruments at least on the expenditure side, that is, ignoring revenue recycling and general-equilibrium sources-side effects. We now review three additional equity aspects not modelled above but which are relevant for instrument choice between pricing and non-pricing. These indicate the limitations of our study.

First, we focus this study on analysing incidence across income groups, i.e. vertical equity. However, several studies have shown and argued that horizontal equity, i.e. policy impacts within income groups, are relevant to environmental policy interventions (Pizer and Sexton, 2019; Burtraw et al., 2005; Rausch et al., 2011; Douenne, 2020). It might be unfair for policy interventions to burden households of similar income differently (Elkins, 2006). Some studies show that it is difficult or even infeasible to mitigate this variation of impacts within income groups, while the compensation across income groups is comparatively easy to do (Sallee, 2019). This difficulty stems from household heterogeneities in energy consumption which cannot be accurately targeted by government rebates. Importantly, Fischer and Pizer (2019) demonstrate that carbon taxes with lump-sum redistribution are less favourable than similarly stringent intensity standards in the US power sector when the welfare loss of perceived unfairness in horizontal equity is included. How horizontal equity may affect distributional consequences, and total welfare, in other political, geographical and sectoral settings needs more research. It also needs to be clarified how exactly efficiency and equity considerations affect political feasibility across these different settings in future work (see a recent attempt by Vandyck et al. (2022)), as both genuinely matter for policy approval by the public (Maestre-Andrés et al., 2019; Sommer et al., 2022).

Second, policy debates around equity issues are often dominated by political-economy factors. Interests of specific industries and household groups can be influential in determining policy success. Carbon-intensive industries whose shareholders and workers have already made long-term investments in capital and labour skills may suffer severely in the short term (Fullerton and Muehlegger, 2019; Castellanos and Heutel, 2019). Household interests also play a role in climate policymaking: some households may be particularly impacted if they involuntarily live a high-carbon lifestyle. Examples include peri-urban workers who have poor access to public transport and must drive a long distance to work, and low-income households living in private, rental housing with inefficient heating systems (Landis and Rausch, 2019; Bourgeois et al., 2019). If these affected industry and household groups are politically mobile, a carbon tax reform may be blocked.[30]

Third, another caveat is that we do not consider the distribution of environmental benefits, and how these benefits (and policy costs) may be shared intergenerationally. Studies have shown that vulnerable groups in developed and developing economies may be disproportionately impacted by environmental damages and pollutions (Holland et al., 2019; Zhang et al., 2018; Mideksa, 2010). Reducing emissions mitigates these damages. Various policy designs also share policy burdens among generations differently (Rausch and Yonezawa, 2018). We recognise that this (intergenerational) distribution of benefits and costs is relevant for optimal policy responses to climate change. However, policy-induced burdens on the current generation are the primary obstacle preventing policies being enacted now.

Our analysis is an initial step to understanding the incidence of standards and has not delved into many nuanced impacts on specific groups. Recognising this leads us to indicate the limitations of this study. For understanding the detailed impacts on agents in the economy, a general equilibrium (GE) is useful to reveal the full incidence from both the expenditure side and the income side. For example, Rausch and Mowers (2014) employs such an approach to studying US Federal Clean Energy Standards (CES) and Renewable Energy Standards (RES), and reveal that the distributional impact of CES and RES is less regressive than an emissions cap on the power sector. We instead take the partial equilibrium approach mainly because the complexity of the GE approach will constrain our analysis into numerical studies of specific industry and country without obtaining theoretical clarity and intuitive results. Also, we intentionally focus on the incidence on the expenditure side because the impacts from rising commodity prices are

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[30] For example, Holland et al. (2015) argue that the more skewed cost distribution of regulatory standards among US counties and districts means that standards, compared to pricing, give a small group large gains and give others dispersed costs.

more visible to citizens, the incidence of revenue recycling is uncertain due to potential government failures, and the price increase is the dominant subject of political debates on environmental taxation. Future work can complement our analysis by providing more detailed views on the impacts on real income and specific groups, including sources-side and product-market effects not discussed here.

A final limitation is that we frame our analysis around sectoral contexts instead of economy-wide policies. A uniform, economy-wide carbon tax is the efficient way to reduce emissions, and governments can address undesirable equity consequences by using the tax-and-transfer system. The political economy prospect of achieving a high enough universal carbon tax and simultaneously reforming the tax-and-transfer system is nevertheless low in many governance situations. Cullenward and Victor (2020) thus argue that it is necessary to look into industry-specific instruments and understand their equity implications given the higher probability of a successful implementation.

5 Conclusion

Rich societies enjoy better and more energy services. Yet, a carbon tax often penalises the poor more than the rich in those societies—unless the revenue is returned back to the former. This makes it difficult to follow the advice of Pigou (1920) for delivering on global climate targets. Could regulatory standards have better distributional effects? We answer this question by comparing regulatory standards and carbon pricing, building on recent studies of the distributional impacts of pricing and non-pricing instruments (Jacobsen, 2013; Rausch and Mowers, 2014; Levinson, 2019; Davis and Knittel, 2019). We develop two analytical models which show that regulatory standards can be progressive. In fact, some types of standards can address inequality better than carbon pricing, when revenue is not recycled progressively.

Specifically, we first generalise Levinson's (2019) model by introducing the assumption that consumers exhibit a preference for high-carbon attributes, such as the acceleration and roominess of automobiles. We prove that efficiency standards can be more equitable than carbon pricing on the expenditure side under that assumption. Evidence from the US automobile sector supports our findings: A single-benchmark efficiency standard can be at least as equitable as a carbon tax. We also show how attribute-adjusted standards like the US Corporate Average Fuel Economy standards could be much more regressive than single-benchmark standards.

Second, we use a model generalising Klenert and Mattauch (2016) to analyse the equity effects of intensity standards and carbon pricing for carbon-intensive goods. We demonstrate that the relative carbon intensity of luxury and subsistence goods is critical for distributional impacts. When luxury goods are more carbon-intensive than subsistence goods, intensity standards are generally more progressive than carbon pricing (ignoring the option of strongly progressive revenue recycling). A numerical application to the Chinese transport sector, in which wealthier households drive more polluting cars, confirms that standards can be more progressive than a fuel tax, when the revenue is not rebated or only proportionally rebated. We also demonstrate that in the above example standards can receive majority support when citizens value fairness as least as much as personal financial consequences.

Complying with the Paris Agreement and achieving carbon neutrality globally by mid-century are ambitious endeavours, especially if one is concerned with implementing concrete policy instruments. Compromising on equity may create political impediments for the implementation of such instruments, particularly when one acknowledges how citizens think about the equity of taxes. Impacts on own income matter, but so do general fairness conceptions, the salience of the incidence of taxation (as opposed to direct regulation), and distrust in government implying disbelief in any revenue recycling (Hammar et al., 2004; Douenne and Fabre, 2022; Sommer et al., 2022). The distributional effects of carbon pricing have thus been a great concern for a wide variety of political actors. Since the prospect of getting high carbon prices implemented remains uncertain, different forms of regulatory standards at the industry level play a role in delivering on climate targets. Understanding the equity implications of these standards is therefore important for policymakers who want to advance for decarbonisation.

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Appendix for online publication

A Proofs for Section 2

A.1 Proof for Proposition 1

The Lagrangian equation of the problem is:

$$\mathcal{L} = U(X,S) - \lambda(X + p_E E + p_R(J)R + p_J J - Y). \tag{39}$$

The first order conditions of (39) are:

$$U_X = \lambda, \tag{40}$$

$$RU_S S_P = \lambda p_E, \tag{41}$$

$$EU_S S_P = \lambda p_R(J), \tag{42}$$

$$U_S S_J = \lambda(p_J + p'_R(J)R). \tag{43}$$

We first prove the first part (7). Substituting (41) into (42) gives Equation (5). It means that the expenditure on energy and efficiency should be equal. This is a natural result of (3) in which E and R have a Cobb-Douglas relation. Differentiating (5) with respect to income Y gives:

$$p_E \frac{dE}{dY} = p_R(J)\frac{dR}{dY} + R\frac{dp_R(J)}{dY}. \tag{44}$$

Define the marginal expenditure increase in energy as:

$$ME_E = p_E \frac{dE}{dY}, \tag{45}$$

and the marginal expenditure increase in efficiency as:

$$ME_R = ME_{R,R} + ME_{R,p_R} = p_R(J)\frac{dR}{dY} + R\frac{dp_R(J)}{dY}, \tag{46}$$

$$ME_{R,R} = p_R(J)\frac{dR}{dY}, \tag{47}$$

$$ME_{R,p_R} = R\frac{dp_R(J)}{dY}. \tag{48}$$

In (46), the marginal expenditure on efficiency ME_R has two parts, i.e. the marginal expenditure resulted from the income effect on efficiency consumption $ME_{R,R}$ and the marginal expenditure resulted from the income effect on efficiency price ME_{R,p_R}.

Thus, (44) becomes:

$$ME_E = ME_R = ME_{R,R} + ME_{R,p_R}. \tag{49}$$

Equation (49) implies that the marginal expenditure on energy is equal to the marginal expenditure on efficiency, which is a natural result of (5).

Rearranging (44) gives:

$$\frac{dR}{dY} = (p_E \frac{dE}{dY} - R\frac{dp_R(J)}{dY})/p_R(J), \tag{50}$$

$$= (p_E \frac{dE}{dY} - R\frac{\partial p_R(J)}{\partial J}\frac{dJ}{dY})/p_R(J). \tag{51}$$

The above expression can be expressed also by marginal expenditures:

$$\frac{dR}{dY} = (ME_E - ME_{R,p_R})/p_R(J). \tag{52}$$

ME_E and ME_{R,p_R} are both positive since dE/dY, dJ/dY and $\partial p_R(J)/\partial J$ in (51) are assumed to be positive. Therefore, from Equation (52), if the marginal expenditure on energy ME_E is smaller than the marginal expenditure on efficiency caused by the income effect on efficiency price ME_{R,p_R}, the income effect on efficiency consumption dR/dY would be negative. The condition in (7) enables this. This proves the first part.

Second, it remains to prove that (7) is equivalent to (8). We multiply both sides of (7) by Y/E and use (5) to replace E at the right hand side:

$$p_E \frac{dE/E}{dY/Y} < R(\frac{p_E}{p_R(J)R})\frac{dp_R(J)}{dY/Y}. \tag{53}$$

Rearranging (53) gives (8).

A.2 Proof for Proposition 3

Substituting (6) into (14) and rearranging gives:

$$Y^2(RG_R - RG_E) = -\tau_R R(\frac{p_E Y}{p_R(J)R}\frac{dE}{dY} - \frac{Y}{p_R(J)}\frac{dp_R(J)}{dY} + \frac{R_0}{R} - 1)$$
$$-\tau_E E(\frac{Y}{E}\frac{dE}{dY} - 1). \tag{54}$$

Using (5) to replace $p_R R$ with $p_E E$ in (54) and rearranging, we obtain:

$$\frac{Y^2}{\tau_R R + \tau_E E}(RG_R - RG_E) = 1 - \frac{dE/E}{dY/Y} + \frac{\tau_R R}{\tau_R R + \tau_E E}\frac{dp_R(J)/p_R(J)}{dY/Y} - \frac{\tau_R R_0}{\tau_R R + \tau_E E}. \tag{55}$$

Using η, we can rewrite (55) as:

$$\frac{Y^2}{\tau_R R + \tau_E E}(RG_R - RG_E) = 1 - \frac{dE/E}{dY/Y} + \eta(\frac{dp_R(J)/p_R(J)}{dY/Y} - \frac{R_0}{R}). \tag{56}$$

Equation (56) naturally gives Proposition 3.

B Distributional impacts of efficiency standards across the income distribution for a specific utility function

This section compares the impact on two households with distinct income levels and thereby illustrates the distributional impact across the income distribution. In order to carry out this analysis, we need to work with specific functional forms.

Here we assume that the technology attribute augments the utility gain from consuming functional energy services. The utility function takes a Cobb-Douglas form:

$$U(X, E, R, J) = X^\alpha J^\theta (ER)^\beta. \tag{57}$$

α, θ, and β are share parameters.

The relationship between efficiency price and the technology attribute is represented by:

$$\begin{aligned} p_R(J) &= (J/J_0)^\epsilon p_R^0 && \text{when } J \geq J_0, && (58)\\ &= p_R^0 && \text{when } J < J_0, && (59)\\ \epsilon &> 0. && && (60) \end{aligned}$$

The scale factor ϵ governs the curvature of the relation between the technology attribute and efficiency price. By making $\epsilon > 0$, we ensure that the technology attribute has a positive impact on efficiency price, i.e. the assumption made in Proposition 1. J_0 is the reference efficiency and p_R^0 is the reference price of efficiency. It is designed that when attribute consumption is below the reference level, efficiency price is not affected by the attribute.[31]

From the household problem defined by Equations (57) to (59), we can establish:

Corollary 8. *With Cobb-Douglas-type utility and functional forms as given by Equation (58), Proposition 1 implies the following:*

$$\frac{dR}{dY} < 0 \text{ if and only if } \epsilon > 1. \tag{61}$$

Proposition 3 implies that:

$$\epsilon > \frac{R_0}{R}. \tag{62}$$

Proof. Our aim is to derive an explicit form of the inequalities in Propositions 1 and 3.

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[31] The reference attribute consumption can be interpreted as the minimum level of attribute consumption for it to have an impact on achieving efficiency. This specification is necessary to ensure that efficiency price does not drop to an unrealistic low level.

First, we get partial derivatives of the utility function:

$$\frac{\partial U}{\partial X} = \alpha X^{\alpha-1} J^{\theta} (ER)^{\beta}, \tag{63}$$
$$\frac{\partial U}{\partial J} = \theta X^{\alpha} J^{\theta-1} (ER)^{\beta}, \tag{64}$$
$$\frac{\partial U}{\partial E} = \beta X^{\alpha} J^{\theta} E^{\beta-1} R^{\beta}, \tag{65}$$
$$\frac{\partial U}{\partial R} = \beta X^{\alpha} J^{\theta} E^{\beta} R^{\beta-1}. \tag{66}$$

The derivative of efficiency price (58) with respect to J is:[32]

$$p'_R(J) = \frac{\epsilon}{J_0} (J/J_0)^{\epsilon-1} p_R^0. \tag{67}$$

First order conditions under a budget constraint are:

$$\left(\frac{\partial U}{\partial E}\right) / \left(\frac{\partial U}{\partial X}\right) = p_E, \tag{68}$$
$$\left(\frac{\partial U}{\partial R}\right) / \left(\frac{\partial U}{\partial X}\right) = p_R(J), \tag{69}$$
$$\left(\frac{\partial U}{\partial J}\right) / \left(\frac{\partial U}{\partial X}\right) = p_J + p'_R(J)R. \tag{70}$$

Substituting partial derivatives of the utility function into first order conditions (68), (69) and (70), and rearranging gives:

$$X = \frac{\alpha p_E E}{\beta}, \tag{71}$$
$$R = \frac{p_E E}{p_R(J)}, \tag{72}$$
$$J = \frac{\theta p_E E}{\beta (p_J + p'_R R)}. \tag{73}$$

Substituting (58), (67) and (72) into (73) and rearranging gives:

$$J(\beta p_J J + (\epsilon\beta - \theta) p_E E) = 0. \tag{74}$$

As J should not be zero, (74) implies:

$$J = \frac{(\theta - \epsilon\beta) p_E E}{\beta p_J}. \tag{75}$$

---

[32] We consider the situation that attribute consumption is above the minimum level to have an impact on efficiency price, i.e. (58). The situation of (59) is the case where attribute consumption does not have an impact on efficiency price. In this case, Levinson's (2019) conclusion applies.

(75) implies that $\theta - \epsilon\beta$ should be greater than zero, i.e.

$$\theta - \epsilon\beta > 0. \tag{76}$$

Otherwise, attribute consumption will be negative, which is unrealistic. The reason is that θ and β indicate households' preference for the attribute and the energy service, therefore, indirectly for efficiency. ϵ measures the attribute's impact on efficiency price. As a result, (76) suggests that if the preference for the attribute is not strong enough to mitigate the negative effect of attribute consumption on getting utility from efficiency, households would not demand attribute. The specification in (58) and (59) ensure that this situation would not take place as it sets a minimum level for the attribute to have an impact on efficiency price—Below the minimum level, *epsilon* is effectively zero.

Substituting (71), (72) and (75) into the budget constraint (4) gives:

$$Y = (2 + \frac{\alpha}{\beta} + \frac{(\theta - \epsilon\beta)}{\beta p_J})p_E E. \tag{77}$$

Equation (77) suggests that there is a linear relationship between income and energy consumption. This is because the utility function implies that households will spend a constant share of their income on energy. As energy price is constant, the relation between income and energy consumption should be linear. It also indicates that income elasticity of energy demand $\frac{dE/E}{dY/Y}$ is equal to one, which implies that the incidence of a carbon tax is neutral across the income spectrum. This result suggests that for an efficiency standard to be more equitable than a carbon tax, the standard must at least be progressive.

The next step is to derive income effect on efficiency price $dp_R(J)/dY$ and the income elasticity of efficiency price $\frac{dp_R(J)/p_R(J)}{dY/Y}$.

According to (77) and (75), we define linear relationships between E, J and Y as:

$$E = k_2 Y, \tag{78}$$
$$J = k_1 E = k_1 k_2 Y, \tag{79}$$
$$k_1 = \frac{(\theta - \epsilon\beta)p_E}{\beta p_J}, \tag{80}$$
$$\frac{1}{k_2} = (2 + \frac{\alpha}{\beta} + \frac{(\theta - \epsilon\beta)}{\beta p_J})p_E. \tag{81}$$

The linear relation between J and Y indicates that the income elasticity of attribute consumption is equal to one.

Substituting (79) into (58), and then differentiating it with respect to Y, we obtain the relation between $p_R(J)$ and Y:

$$p_R(J) = (k_1 k_2 Y/J_0)^{\epsilon} p_R^0, \tag{82}$$
$$\frac{dp_R(J)}{dY} = \frac{\epsilon k_1 k_2}{J_0}(k_1 k_2 Y/J_0)^{\epsilon-1} p_R^0. \tag{83}$$

Using (82) and (83), we get the income elasticity of efficiency price:

$$\frac{dp_R(J)/p_R(J)}{dY/Y} = \epsilon. \tag{84}$$

Equation (84) looks surprisingly simple. It can be better understood by the equation:

$$\frac{dp_R(J)/p_R(J)}{dY/Y} = \frac{\partial p_R(J)/p_R(J)}{\partial J/J}\frac{dJ/J}{dY/Y}. \tag{85}$$

This means that the income elasticity of efficiency price is the product of the income elasticity of attribute consumption and the attribute's elasticity of efficiency price. As the income elasticity of attribute consumption is equal to one according to (79), the value of $\frac{dp_R(J)/p_R(J)}{dY/Y}$ is controlled by $\frac{\partial p_R(J)/p_R(J)}{\partial J/J}$. The attribute's elasticity of efficiency price is ϵ, which has been defined by Equation (58).

Substituting (72), (82), (83) into Inequality (7) of Proposition 1, and using the knowledge that dE/dY is equal to k_2 according to (78), we could obtain (61).

For Proposition 3, we substitute (84) into Inequality (15), use the knowledge that income elasticity of energy consumption is equal to one, and obtain (62). ☐

Equation (61) means that, for efficiency consumption to decrease with income, ϵ should be greater than one. In this case, attribute consumption has an exponential impact on efficiency price according to Equation (58). The interpretation is that if efficiency price is not affected by the technology attribute and is constant, the income elasticity of efficiency demand would be one under the utility function (57). Households will consume more efficiency proportionate to an income increase. To offset this effect and make households consume less efficiency as income increases, the income elasticity of efficiency price ϵ must be greater than one.

Equation (62) indicates that, for an efficiency standard to be more equitable than a carbon tax at the margin, ϵ should be greater than R_0/R. It does not require efficiency consumption to decrease with income because Equation (62) can be less stringent than Equation (61) when R is greater than R_0. This is because when R is greater than R_0, an efficiency standard is equivalent to a subsidy on the extra efficiency greater than the standard benchmark R_0. In this case, richer households should consume much more efficiency to ensure that the subsidy they receive grows fast enough to match the speed of their income growth, so that their relative utility gain from the subsidy does not decrease.

We now extend the analysis to two households with discrete income, and then show how the incidence of efficiency standards could look like across the income spectrum.

We define two households of income Y_a and Y_b, with:

$$Y_a > Y_b. \tag{86}$$

We use subscripts a and b to represent households a and b subsequently. We define that the income Y_0 is the income level making households consume exactly the standard benchmark of efficiency R_0. The following results can be proved:

Proposition 9. *The static impact on household a is greater than that on household b when:*

$$\epsilon > 1, \tag{87}$$

$$Y_b < Y_a < \epsilon^{1/(\epsilon-1)} Y_0, \tag{88}$$

or

$$\epsilon > 1, \tag{89}$$

$$Y_b < Y_0 < \epsilon^{1/(\epsilon-1)} Y_0 < Y_a, \tag{90}$$

or

$$\epsilon < 1, \tag{91}$$

$$\epsilon^{1/(\epsilon-1)} Y_0 < Y_b < Y_a. \tag{92}$$

Household b experiences an greater impact when the above conditions are met except that the inequalities of ϵ, i.e., Inequalities (87), (89) and (91), are reversed. Irrespective of the value of ϵ, the relation between the two impacts is ambiguous when:

$$Y_0 < Y_b < \epsilon^{1/(\epsilon-1)} Y_0 < Y_a. \tag{93}$$

Proof. The static impact of a standard on household a and household b is $\tau_R(R_0 - R_a)/Y_a$ and $\tau_R(R_0 - R_b)/Y_b$. We can compare the impact on two households by:

$$RI = \frac{\tau_R(R_0 - R_a)}{Y_a} - \frac{\tau_R(R_0 - R_b)}{Y_b}. \tag{94}$$

RI is the relative impact between two households. R_a and R_b are the efficiency consumption of households a and b at their income levels. The impact on household a is greater if RI is positive.

Substituting (78) and (82) into (5) gives:

$$R = \frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon} Y^{1-\epsilon}. \tag{95}$$

Substituting (95) into (94) and rearranging, we get:

$$\frac{RI}{\tau_R} = (\frac{R_0}{Y_a} - \frac{R_0}{Y_b}) - (\frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon} \frac{1}{Y_a^\epsilon} - \frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon} \frac{1}{Y_b^\epsilon}). \tag{96}$$

We first consider the situation that RI is greater than zero, i.e.

$$(\frac{R_0}{Y_1} - \frac{R_0}{Y_2}) - (\frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon} \frac{1}{Y_1^\epsilon} - \frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon} \frac{1}{Y_2^\epsilon}) > 0. \tag{97}$$

We define:

$$x = \frac{1}{Y}, \tag{98}$$

$$y = x^{\epsilon} = \frac{1}{Y^{\epsilon}}, \tag{99}$$

$$k_3 = \frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^{\epsilon}}. \tag{100}$$

Equations (97) and (95) can be rewritten as:

$$R_0(x_a - x_b) - k_3(y_a - y_b) > 0, \tag{101}$$

$$R = k_3 Y^{1-\epsilon}. \tag{102}$$

Rearranging (101) gives:

$$\frac{y_a - y_b}{x_a - x_b} > \frac{R_0}{k_3}. \tag{103}$$

To obtain Equation (103), we exploit the fact that Y_a is greater than Y_b. Therefore, x_a is smaller than x_b.

Using Equation (102), we can get:

$$k_3 = \frac{R_0}{Y_0^{1-\epsilon}}. \tag{104}$$

Substituting (104), (99) and (100) into (103) gives:

$$\frac{y_a - y_b}{x_a - x_b} > \frac{y_0}{x_0}, \tag{105}$$

$$x_0 = \frac{1}{Y_0}, \tag{106}$$

$$y_0 = x_0^{\epsilon}. \tag{107}$$

For household a to experience a greater impact than household b, Inequality (105) must be met.

Proposition 9 follows from a "geometric" argument on Inequality (105). It can be interpreted from geometry that the left hand side of Inequality (105) is the slope of the line connecting (x_a, y_a) and (x_b, y_b). The right hand side is the slope of the line connecting (x_0, y_0) and the origin.

We only prove the case for household a to experience a greater impact. The case for household b to have a greater impact can be proved with a similar procedural. We illustrate two graphs in Figure 4 for function $y = x^{\epsilon}$. The top one is for situations when $\epsilon > 1$. The bottom one is for situations when $\epsilon < 1$.

We assume that y_0/x_0 is the green line in Figure 4. The left hand side of (105) is the slope of the line connecting point (x_a, y_a) and (x_b, y_b). We draw multiple lines in Figure 4 to represent different scenarios mentioned in Proposition 9. The point $(1/\epsilon^{1/(\epsilon-1)} x_0, y(x))$ is where the first-order derivative of $y(x)$ is equal to y_0/x_0, i.e. the slope of the green line.

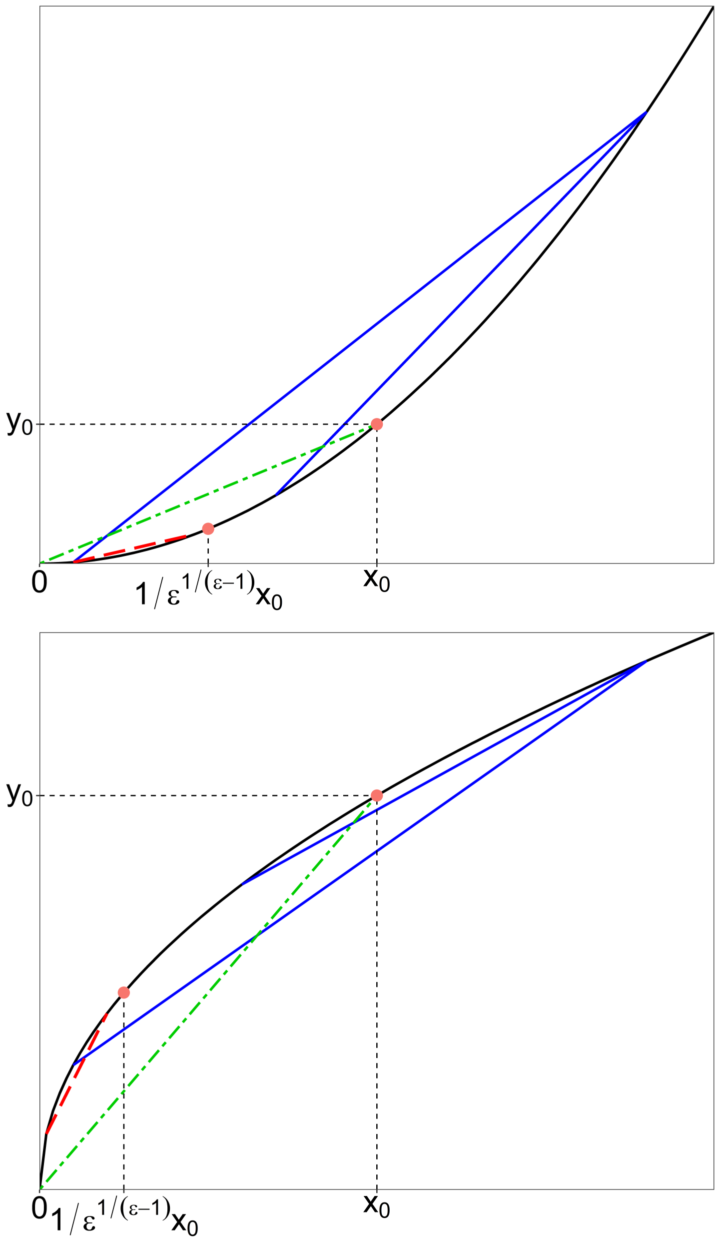

Figure 4: A representative illustration of function $y = x^{\epsilon}$ when $\epsilon > 1$ (top) and $\epsilon < 1$ (bottom).

Note: The green lines represent y_0/x_0. The blue lines represent $\frac{y_a - y_b}{x_a - x_b}$ when the conditions (88) and (90) are met. The red lines represent $\frac{y_a - y_b}{x_a - x_b}$ when (92) is met. The highlighted red points represent $(x_0,\, y_0)$ and $(1/\epsilon^{1/(\epsilon-1)}x_0,\, y(x))$. $(1/\epsilon^{1/(\epsilon-1)}x_0,\, y(x))$ is the point at which the first-order derivative of $y(x)$ is equal to y_0/x_0.

According to (99), the point $(1/\epsilon^{1/(\epsilon-1)}x_0, y(x))$ is corresponding to an income of $\epsilon^{1/(\epsilon-1)}Y_0$. Therefore, when $\epsilon > 1$ and $x_b > x_a > 1/\epsilon^{1/(\epsilon-1)}x_0$ or $x_b > x_0 > 1/\epsilon^{1/(\epsilon-1)}x_0 > x_a$, i.e. when (88) and (90) are satisfied, it can be shown by using the properties of convex functions that Inequality (105) is met.[33] These two scenarios are represented by the blue solid lines in the top graph of Figure 4. The slope of the two blue solid lines must be greater than the green line. If $\epsilon < 1$ and $x_a < x_b < 1/\epsilon^{1/(\epsilon-1)}x_0$, i.e. when (92) is satisfied, it can be certain that Inequality (105) is met again by using the properties of concave functions. This scenario is shown by the red dashed line in the bottom graph of Figure 4. The relation between the static impacts of households a and b is ambiguous when their income satisfies the condition (93). In this scenario, the specific values of Y_a and Y_b must be known.

The same analysis can be applied for household b to experience a greater impact. Therefore, Proposition 9 is proved. □

For the incidence across the income spectrum, we can derive an explicit function of $\tau_R(R_0 - R)/Y$ by using the relation $R = R_0 Y_0^{\epsilon-1} Y^{1-\epsilon}$ as proved before:[34]

$$IN_R = \frac{\tau_R(R_0 - R)}{Y} = \tau_R R_0 (Y^{-1} - Y_0^{\epsilon-1} Y^{-\epsilon}). \tag{108}$$

IN_R is the incidence of an efficiency standard. Figure 5 (top) shows a representative curve of Equation (108) when ϵ is greater than one, i.e., richer households consume less efficiency. It can be seen that when household income is below $\epsilon^{1/(\epsilon-1)}Y_0$, the incidence of an efficiency standard decreases with income, i.e. a smaller positive impact or a bigger negative impact. After $\epsilon^{1/(\epsilon-1)}Y_0$, the incidence increases with income. Income $\epsilon^{1/(\epsilon-1)}Y_0$ is a critical point because when income increases over $\epsilon^{1/(\epsilon-1)}Y_0$ and consequently efficiency consumption decreases, the Inequality (62) is violated. Y_0 is the income level marks the transition from a subsidy on households who consume more efficiency than the standard to a tax on households who consume efficiency less than the standard. A representative curve of Equation (108) when ϵ is smaller than one is shown in Figure 5 (bottom). It can be explained similarly as for the top graph in Figure 5.

Policy stringency also impacts the outcome displayed in Figure 5. When $\epsilon > 1$, increasing policy stringency R_0 lowers Y_0 and therefore moves the red points in the figure to the left.[35] This does not change the shape of the curve, but lowers the income level at which the distribution changes from progressive to regressive. Conversely, when $\epsilon < 1$, increasing policy stringency moves the red points to the right. The two graphs are consistent with what is concluded in Corollary 8 and Proposition 9.

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[33] Here we use the relation (99), i.e. $x = Y^{-1}$.

[34] We can establish this by using Equations (102) and (104) in Appendix B

[35] This is because Y_0 is the income level for households to consume R_0. When $\epsilon > 1$, according to Corollary 8, lower-income households consume more efficiency. Therefore, a rise in R_0 decreases Y_0.

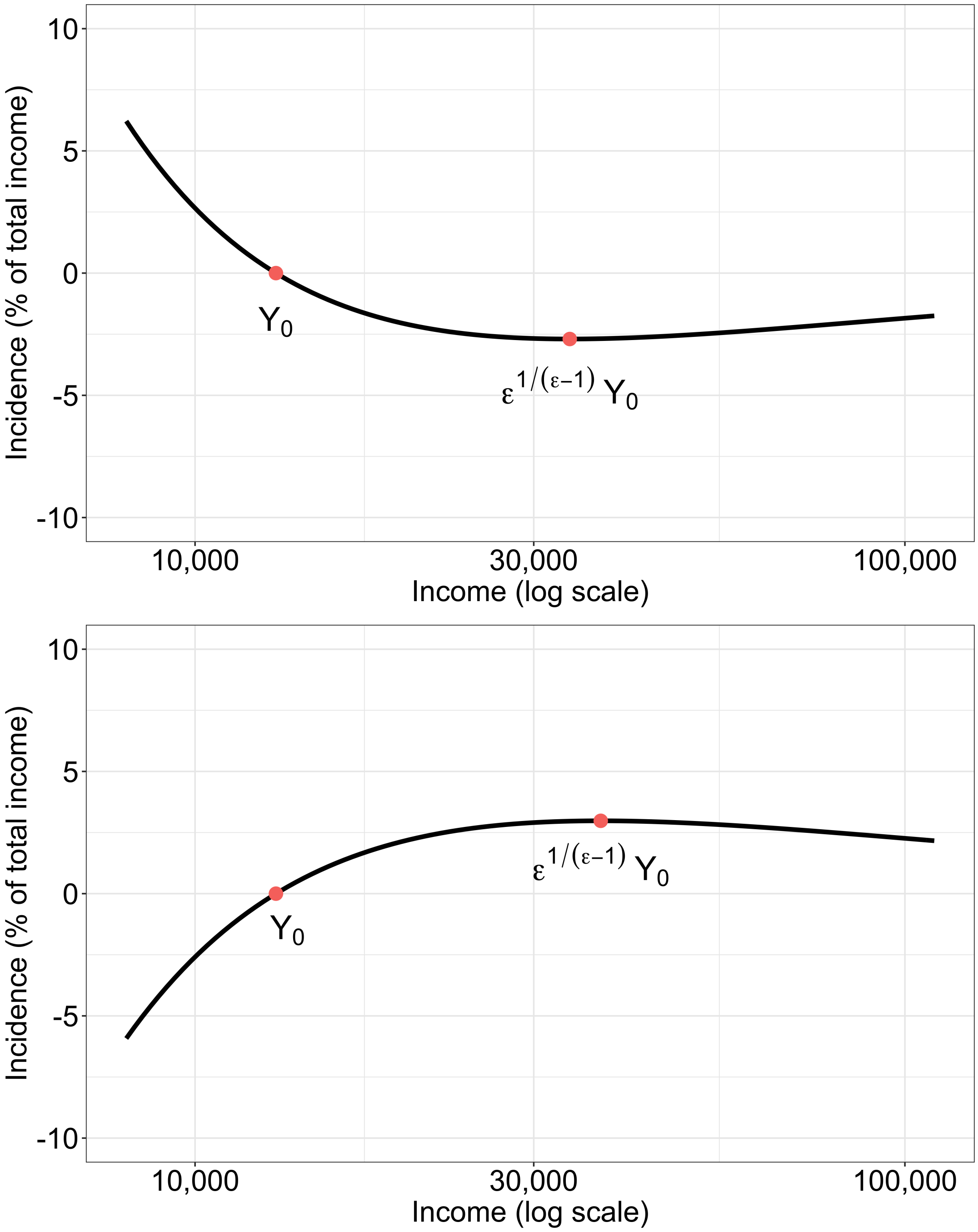

Figure 5: Incidence of an efficiency standard according to Equation (108) when $\epsilon > 1$ (top); and when $\epsilon < 1$ (bottom).

Note: Positive values indicate income gains and negative values indicate income losses. For the top graph, the parameters in Equation (108) are set as follows: ϵ is set to 1.1. Y_0 is set to 13,000. $\tau_R R_0$ is set to 77. Note that the figure is only a representative graph to show the properties of Equation (108). It does not reflect any economies or sectors. For the bottom graph, all parameters are the same with those used in the top graph, except that ϵ is set to 0.9.

C Estimating the incidence by elasticities

We use the data of the automobile sector to test Propositions 1 and 3. We focus on the automobile sector because its income elasticities have been extensively studied. As this analysis investigates the static incidence of regulations, we use long-run elasticities to capture household consumption behaviours under long-term equilibria.

As $P = ER$, the relation among income elasticities of the functional energy service, energy and efficiency is:

$$e_P = e_E + e_R. \tag{109}$$

e_P, e_E and e_R are the income elasticity of the functional energy service, energy and efficiency respectively. The income elasticity of fuel consumption has a large range of estimates. We adopt a value of one and complete a sensitivity test later.[36] We choose 0.8 for the income elasticity of car-travel demand. Fouquet (2012), Dargay (2007) and Goodwin et al. (2004) review estimates from the UK and similar countries, and their reported mean values are 0.8, 1.1 and 0.73.

Therefore, e_R is equal to e_P minus e_E, i.e. -0.2. A negative e_R suggests that efficiency consumption decreases with income. This is confirmed by the literature summarised by Johansson and Schipper (1997) and Bonilla and Foxon (2009). Both conclude that the income elasticity of fuel economy is negative, at least in the short run when regulatory change and technology progress are not in effect.

According to Equation (5), the relation among income elasticities of energy, efficiency and efficiency price is:

$$e_E = e_R + e_{p_R}. \tag{110}$$

e_{p_R} is the income elasticity of efficiency price. We obtain e_{p_R} by subtracting e_E by e_R, which is 1.2. As a result, Proposition 1 is fulfilled, i.e. Inequality (8) holds.

With $\frac{dE/E}{dY/Y} = 1$ and $\frac{dp_R/p_R}{dY/Y} = 1.2$, Inequality (15) in Proposition 3 can be calculated as below:

$$1.2 - \frac{R_0}{R} > 0. \tag{111}$$

Equation (111) suggests that an efficiency standard would be more equitable than a carbon tax at the margin when R_0/R is less than 1.2, i.e. when R is greater than $\frac{1}{1.2}R_0$. Since efficiency consumption decreases with income, it suggests that, for households who earn less than the income level of consuming $\frac{1}{1.2}R_0$, an efficiency standard is progressive

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[36] Johansson and Schipper (1997) report a range from 0.05 to 1.6 with the mean at 1.2 in their review for OECD countries. Sterner and Dahl (1992) show the majority of estimates are close to and above one. Similarly, Goodwin et al. (2004) and Graham and Glaister (2002) review studies from the UK and similar countries and suggest a mean value of 1.08 and 1.17 respectively. In contrast, Espey (1998) provides a lower estimate at 0.81 in her global review. Dahl (2012) further shows that, if corrected for publication bias, the estimate is even lower, at 0.23. In addition, Dahl (2012) shows that fuel elasticities decrease as countries get rich. Goodwin et al. (2004) and Fouquet (2012) also observe a downward trend for fuel elasticities in the UK and OECD countries. Elasticities for developing nations may be different from those for developed nations. Litman (2012) suggest that using elasticities from high-income nations can be a good approximation if data are not available.

and more equitable than a carbon tax. For households earning more than the income of consuming $\frac{1}{1.2}R_0$, an efficiency standard is regressive and less equitable than a carbon tax.[37] This result confirms the U-shape relation found in Section B.

Table 5: A sensivity analysis of income elasticities in the automobile sector for Propositions 1 and 3.

e_E	e_P	Test of (8) in Proposition 1	Condition for Proposition 3
1	0.8	True	$\frac{R_0}{R} < 1.2$
0.8	0.8	False	$\frac{R_0}{R} < 0.8 + \frac{0.2}{\eta}$
0.6	0.8	False	$\frac{R_0}{R} < 0.4 + \frac{0.4}{\eta}$
1.2	0.8	True	$\frac{R_0}{R} < 1.6 - \frac{0.2}{\eta}$

Note: e_E is the income elasticity of energy demand, i.e. gasoline consumption; e_P is the income elasticity of functional energy service, i.e. miles driven.

Table 5 completes a sensitivity analysis on e_E and e_P. It suggests that the relative regressivity between an efficiency standard and a carbon tax is also dependent on the policy stringency of the two regulations. Policy stringency determines R_0 and η in the last column of Table 5. If the policy stringency of efficiency standard increases relatively, R_0 and η will both rise. We do not complete a sensitivity analysis on e_P because the logic is similar and the existing research suggests a narrower range of it, i.e. between 0.5 to 1 (Goodwin et al., 2004; Burt and Hoover, 2006; Sheng and Sharp, 2019; Dargay, 2007).

Table 5 also shows efficiency consumption will decrease with income and an efficiency standard will tend to be more equitable than a carbon tax in the lower-income region when e_E is greater than e_P. This is because e_R is less than zero when $e_E > e_P$ according to Equation (109). Additionally, if $e_E > e_P$, the Inequality (15) of Proposition 3 is met when R is high. As the efficiency consumption decreases with income, a high R signals a relatively low income. Therefore, efficiency standards tend to be more favourable when income is low. Conversely, when e_E is less than e_P, efficiency consumption will increase with income and a carbon tax will be preferable in the lower-income region.

D A model for the price effects of regulatory standards

Largely following Davis and Knittel (2019), we illustrate the formalisation of standards by using two examples: fuel economy standards and clean energy standards.

On fuel economy standards, we assume a perfectly competitive vehicle market. An automaker chooses the quantity to maximise its profits. The profit maximisation function

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[37] We know the standard is progressive or regressive because a carbon tax is distribution-neutral at the fuel elasticity of one. If the standard is more equitable than the carbon tax, that also means that the standard is progressive.

for each automaker is:

$$\max_{q_1,q_2\cdots,q_j} \sum_{j=1}^{J} \Big(q_j p_j - c_j(q_j)\Big), \tag{112}$$

where q_j and p_j are the quantity and price of vehicle model j respectively. $c_j(q_j)$ is the cost function of model j. With a fuel economy standard, an automaker maximises its profits subject to the condition:

$$\sum_{j=1}^{J} \Big((r_0 - r_j)q_j\Big) + Q = 0, \tag{113}$$

where r_j and r_0 are the miles per gallon for model j and the efficiency standard set by the government. Automakers need to comply with the standard by themselves or by trading with other automakers if the standard is tradable. When it is tradeable, Q denotes the number of permits purchased by the firm to comply with the standard, else $Q = 0$.

The Lagrangian equation for this constrained maximisation problem can be written as:

$$\mathcal{L} = \sum_{j=1}^{J} \Big(q_j p_j - c_j(q_j)\Big) - \lambda \sum_{j=1}^{J} \Big((r_0 - r_j)q_j + Q\Big). \tag{114}$$

The first-order conditions can be obtained by differentiating Equation (114) by q_j:

$$p_j = c'_j(q_j) + \lambda(r_0 - r_j). \tag{115}$$

λ represents the shadow price of compliance permits. The shadow price is equal across firms if the standard is tradable. Equation (115) suggests that the price set by automakers for model j should equal to the marginal cost of production plus the additional cost incurred from the efficiency standard. For vehicles that perform better than the standard, the regulation serves as an implicit subsidy on the final price. For vehicles that perform worse than the standard, the regulation serves as an implicit tax.

By analogy, for clean energy standards in the power sector, we may simply drop the subscript j of p since electricity is not differentiable no matter its source of generation. We also need to change the order of r_0 and r_j since emissions intensity is the lower the better and efficiency is the higher the better. Therefore, we get:

$$p = c'_j(q_j) + \lambda(r_j - r_0). \tag{116}$$

Here j does not represent vehicle models but generation technologies such as wind, solar, nuclear, and coal power. r_0 is the intensity standard, i.e. grams of carbon emissions per kWh. r_j is the emissions intensity of technology j. Similarly, the intensity standard becomes an implicit subsidy on low-emissions generation technologies and an implicit tax on high-emissions generation technologies.

Moving λr_0 from the right-hand side to the left-hand side, one obtains:

$$p + \lambda r_0 = c'_j(q_j) + \lambda r_j. \tag{117}$$

Equation (117) provides the second interpretation of intensity standards. λr_j is a tax on emissions and λr_0 is a lump-sum subsidy on output. This interpretation reveals a key feature of intensity standards: Standards have a smaller price effect than carbon taxes due to the output subsidy and therefore provide less incentive to reduce emissions through demand reduction.

This simple analytical model suggests that the equity effect of an efficiency standard depends on the composition of energy technologies such as passenger vehicles and appliances among households. The incidence of an intensity standard is dependent on consumption patterns of regulated goods such as electricity, petrochemical products, and transport services like aviation and rail among income groups.

E Proofs for Section 3

E.1 Proof for the effect of the luxury component

Equation (24) can be used to prove that there exists a minimal income for starting consuming S_2. Supposing that there are no climate policies, we can simplify (24) as:

$$S_{2,i} = \frac{\beta}{p_2}(\phi_i \omega (1-\tau_w) - S_1^0 p_1 + S_2^0 p_2) - S_2^0. \tag{118}$$

Since $S_{2,i}$ must be non-negative, we could get:

$$\phi_i \geq \frac{S_2^0 p_2 + \beta S_1^0 p_1 - \beta S_2^0 p_2}{\beta \omega (1-\tau_w)} \tag{119}$$

Therefore, for households have earning abilities lower than what the condition (119) requires, they consume no S_2, i.e. the luxury good.

E.2 Proofs for Lemmas 4 and 5

Proof for Lemma 4

We first prove part (a) of Proposition 4. Relative to (27), (28) adds the term $-S_1^0\tau_r(e_1 - e_0) + S_2^0\tau_r(e_1 - e_0)$ to both the numerator and the denominator. As e_0 is between e_1 and e_2, $e_1 < e_2$ implies that $e_1 - e_0$ is negative and $e_2 - e_0$ is positive. Therefore, it can be certain that the added term is positive.

For the proof that an intensity standard is progressive, it is sufficient to demonstrate that $\left(\frac{U_i}{U_j}\right)^{\mathrm{AS}} > \left(\frac{U_i}{U_j}\right)^{\mathrm{BR}}$ for $\phi_j > \phi_i$. It implies that the introduction of an intensity standard narrows the relative utility difference between richer and poorer households. $\left(\frac{U_i}{U_j}\right)^{\mathrm{BR}}$ must be smaller than 1 since $\phi_j > \phi_i$. The proof of Proposition 4 is completed by using the below relation:

$$\text{If } \frac{a}{b} < 1, \text{ then } \frac{a}{b} < \frac{a+c}{b+c} \text{ for } c > 0 \text{ and } \frac{a}{b} > \frac{a+c}{b+c} \text{ for } c < 0. \tag{120}$$

The added term $-S_1^0\tau_r(e_1 - e_0) + S_2^0\tau_r(e_1 - e_0)$ can be thought as c in (120). It has been shown that the second fraction at the right hand side of (27) is smaller than one, i.e. the condition $\frac{a}{b} < 1$ is met. Therefore, Proposition 4 is proved.

Part (b) of Proposition 4 can be proved with a similar process.

Proof for Lemma 5

Klenert and Mattauch (2016) contains a proof for the tax with lump-sum rebates in Proposition 5, when there is only a subsistence good. A pure tax on subsistence goods is regressive. The tax becomes progressive when lump-sum rebates are included since a lump-sum rebate scheme is highly progressive. Except for a subsistence good, Equation (18) adds a luxury good. It can be proved by symmetry that, absent redistribution, a tax on luxury goods is progressive. Lump-sum rebates will further increase the progressivity of such a tax. As a result, a carbon tax with lump-sum rebates on luxury and subsistence goods is surely progressive.

The tax with no redistribution in Proposition 5 can be proved by using the relation (120). Relative to (27), Equation (30) adds the term $S_2^0\tau_e e_2 - S_1^0\tau_e e_1$ to both the numerator and the denominator. According to (120), a carbon tax is regressive when $S_2^0\tau_e e_2 - S_1^0\tau_e e_1 < 0$. The condition in Proposition 5 can be obtained by rearranging $S_2^0\tau_e e_2 - S_1^0\tau_e e_1 < 0$. Similarly, a carbon tax is progressive when $S_2^0\tau_e e_2 - S_1^0\tau_e e_1 > 0$.

E.3 Proofs for Propositions 6 and 7

Again, we use the relation (120) to prove Propositions 6 and 7. For Proposition 6, it is sufficient to prove that $\left(\frac{U_i}{U_j}\right)^{\text{AS}}$ is bigger than $\left(\frac{U_i}{U_j}\right)^{\text{AT-N}}$ when $\phi_j > \phi_i$. Compared to $\left(\frac{U_i}{U_j}\right)^{\text{AT-N}}$, $\left(\frac{U_i}{U_j}\right)^{\text{AS}}$ adds $-S_1^0\tau_r(e_1 - e_0) + S_2^0\tau_r(e_2 - e_0) + S_1^0\tau_e e_1 - S_2^0\tau_e e_2$ to both the numerator and the denominator. According to the relation (120), it suffices to prove:[38]

$$-S_1^0\tau_r(e_1 - e_0) + S_2^0\tau_r(e_2 - e_0) + S_1^0\tau_e e_1 - S_2^0\tau_e e_2 > 0. \tag{121}$$

Dividing (121) by $S_2^0\tau_r e_2$ and Rearranging, we obtain:

$$\frac{S_1^0}{S_2^0}\Big(\frac{e_1}{e_2}(\frac{\tau_e}{\tau_r} - 1) + \frac{e_0}{e_2}\Big) + \Big(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\Big) > 0. \tag{122}$$

As it is assumed in Proposition 6 that $e_1 > e_0 > e_2$, we could know that the second bracketed term of (122) is surely negative. For (122) to be positive, the first bracketed term must at least be positive. This gives the necessary condition in Proposition 6. On the condition that it has been met, we can rearrange (122) to get the sufficient condition in Proposition 6.

Similarly, for Proposition 7, it suffices to prove:

$$\frac{S_1^0}{S_2^0}\Big(\frac{e_1}{e_2}(\frac{\tau_e}{\tau_r} - 1) + \frac{e_0}{e_2}\Big) + \Big(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\Big) < 0. \tag{123}$$

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[38] Note that for the relation (120) to apply, we have also assumed that both policies do not change the utility ranking between households, i.e. $U_i < U_j$ under both policy scenarios.

As Proposition 7 assumes $e_1 < e_0 < e_2$, the first bracketed term in (123) is surely bigger than zero. Therefore, the second bracketed term must at least be negative for (123) to work. This gives the necessary condition in Proposition 7. If the necessary condition is satisfied, rearranging (123) gives the sufficient condition.