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Abstract

Carbon pricing is the efficient instrument to reduce emissions. However, the geographical and sectoral coverage of substantial carbon pricing is low, often due to concerns that pricing may increase economic inequality. Regulatory standards such as fuel economy standards are more popular. But do they have an equity advantage over carbon pricing? We develop two new formal models to identify economic situations, in which standards could be preferred over carbon pricing. First, we prove that an efficiency standard can be more equitable than carbon pricing when consumers exhibit a preference for high-carbon technology attributes. Evidence from the US vehicle market confirms this finding. Second, we show theoretically, and by means of a numerical application to the Chinese transport sector, that intensity standards are preferable when richer households consume more goods with higher carbon intensity. Our results hold when the revenue from carbon pricing is not very progressively redistributed. These insights can help advance decarbonisation when pricing remains unpopular.

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

JEL codes: H22, H23, Q52, Q54

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1 Introduction

Introducing a price on carbon is the economically efficient way to induce emissions reduction. Most countries, however, do not have a substantial carbon pricing regime.[1] Where pricing mechanisms have been established, the price level usually falls far short of the levels required to meet international climate targets such as those laid out in the 2015 Paris Agreement.

One commonly cited reason for the unpopularity of pricing instruments is the concern that they might increase inequality. Rising costs of energy and essential goods can burden low-income households more than high-income households. Evidence shows that low-income households tend to spend higher income shares on energy and some further carbon-intensive goods like food and clothing, at least in high-income countries (Sterner, 2012; Flues and Thomas, 2015; Levinson and O'Brien, 2019).

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; Fowlie et al., 2014). These non-pricing instruments 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).[2]

But can the preference for non-pricing instruments be justified on equity grounds? Specifically, are non-pricing alternatives more equitable than pricing instruments? If yes, under which conditions? We use two new models to examine two policy-relevant cases: efficiency standards for household energy technologies and intensity standards for carbon-intensive goods.[3] We ask under which conditions these instruments may have better distributional consequences than pricing instruments.[4]

First, we show that efficiency standards address inequality better than pricing when

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[1] The Carbon Pricing Leadership Coalition's *Report of the High-Level Commission on Carbon Prices* states that to be consistent with the Paris Agreement, carbon prices must reach at least US$40-80/tCO2 by 2020 and US$50-100/tCO2 by 2030 (Stiglitz et al., 2017).

[2] Hereafter, we use 'pricing instruments' to refer to both ordinary carbon taxes and cap-and-trade programmes because these policies put a price on carbon. Non-pricing instruments refer to emissions-restricting regulatory policies including, for example, standards, mandates and labellings.

[3] 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 or 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.

[4] While there are more non-pricing instruments than 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, there is an increasing trend for transport emissions to grow as countries accrue wealth (Timilsina and Shrestha, 2009; Wei et al., 2020).

consumers exhibit a significant preference for technology attributes that cause inefficiency. The intuition is that consumers choose technology attributes when they purchase energy technologies. Some attributes such as the size and the engine power of automobiles have a negative effect on efficiency. When the preference for these efficiency-decreasing attributes is significant enough, it causes richer households purchasing less efficient technologies to the degree that makes efficiency standards more favourable than pricing to low-income households. We present a formal model that generalises a simple set-up conceived by Levinson (2019) and derive general conditions under which this equity advantage of standards exists. We test the theoretical findings by calibration to transport elasticities, and by empirical evidence from the US vehicle market. Importantly, both tests confirm that efficiency standards could be more equitable, especially for lowest-income households. We also show that the incidence of standards may take a U-shape across the income spectrum.

Second, we examine how subsistence and luxury consumption patterns of carbon-intensive goods affect the incidence of intensity standards and carbon pricing. We prove that intensity standards are generally more progressive than pricing when luxury goods are more carbon-intensive than subsistence goods. This result is conditional on that the pricing revenue is not very progressively redistributed. Conversely, when subsistence goods are more carbon-intensive, intensity standards are less favourable to the low-income under most revenue redistribution schemes. We calibrate the analytical model to the British transport sector and confirm, by means of a simple simulation, that standards can be an equitable alternative to pricing instruments.

Our two approaches interact in illustrating how households' preference for high-carbon technology attributes and carbon-intensive luxury goods can both at play in determining distributional consequences of standards. A model of technology attributes can provide an explanation for the assumption of non-constant expenditure shares in the second model. For example, why do richer households drive more, take more flights and use less public transport? Our first model suggests that it is because of the preference for efficiency-decreasing attributes such as speed, space and comfort. Furthermore, the two models can work together to explain sectoral consumption patterns. Richer households may not only drive more gas-guzzlers but also purchase disproportionately more cars. Lower-income households may not own a car at all. The preference for efficiency-decreasing attributes and the luxury characteristic of cars may both play a role in shaping the distributional impact of policy instruments.

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. For example, efficiency standards are described as both regressive and progressive (Levinson, 2019; Davis and Knittel, 2019; Jacobsen, 2013). Nevertheless, several studies appear to 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 have a greater propensity than carbon taxes to favour rich households. Similarly, Metcalf (2019) argues that most regulatory energy policies in the US are regressive. A carbon tax can replace these policies and ensure a more progressive equity outcome. If these arguments are correct, non-pricing instruments will perform worse than pricing instruments on both efficiency and equity dimensions.

In relation to these contributions, our approach develops insights that have not been reported in previous studies. First, compared to Levinson (2019), we introduce more realistic assumptions about consumer behaviours in purchasing energy technologies—they value technology attributes besides efficiency. Therefore, our results are more nuanced than Levinson (2019), which argues that standards are more regressive than taxes. Second, our theoretical approach generalises distributional analyses of standards and pricing to broader geographical and sectoral contexts: The current geographical coverage is concentrated on the United States and Western Europe (Fullerton and Muehlegger, 2019; Landis et al., 2019). Sectors so far discussed are largely the automobile and power sector (Heutel, 2020), perhaps due to the overwhelmingly used pure numerical approach in estimating the incidence of non-pricing instruments. Our theoretical work has direct implications for developing countries where the preference for high-carbon technology attributes and carbon-intensive luxury goods is emerging and evolving.

The second related stream is the literature on the incidence of environmental taxation, as this study contrasts the incidence of standards and taxes. The literature distinguishes 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., 2019a; Liang and Wei, 2012; Dorband et al., 2019). The sources-side effect 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). The sources-side effect 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 much different focus, i.e. how the incidence of tax is relative to the incidence of standards. Additionally, we incorporate luxury and subsistence consumption into the incidence analysis by generalising Klenert and Mattauch (2016).

The efficiency analysis of climate policy instruments is the third related stream. The efficiency literature has compared the cost-effectiveness of standards and pricing instruments (Fischer, 2001). These studies show that Pigouvian taxes are generally more cost-effective.[5] However, standards could be effective in special cases. Goulder et al. (2016) present a case that 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 can sustain higher levels of economic output compared to pricing instruments.

This study takes a similar approach of the efficiency literature in formalising emissions taxes and standards. But we motivate our research with another increasingly pertinent concern—equity effects of policy instruments. The results of this study, therefore, contribute to instrument choice for mitigation policy, additional to responses from the efficiency literature.

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 the carbon emissions of their economies by pricing or by 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' broader fairness concerns are real (Hammar et al., 2004; Kallbekken et al., 2011; Douenne and Fabre, 2019). The point is reinforced by differences across world regions. For global decarbonisation to succeed, a crucial question is whether citizens in low- and middle-income countries will develop tastes for high-carbon attributes and carbon-intensive goods similar to those high-income societies as their economies grow. How these tastes will develop holds significant—but, we believe, underappreciated—distributional implications when policymakers choose mitigation instruments for their countries. Once the objective of climate mitigation policy becomes to do 'whatever works' to reduce emissions (Goulder, 2020), standards could also be highly effective instruments in given governance circumstances. We contribute to a growing number of studies in economics exploring when regulation by standards might be helpful from that perspective, such as Stiglitz (2019) and Heutel (2020).

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. 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 the connection between the models and their relevance to developing countries, and discusses limitations and directions for future work. Section 5 concludes.

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[5] See for example Landis et al. (2019).

2 Distributional impacts of efficiency standards for household energy technologies

This section investigates distributional effects of carbon taxes on energy 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 households buy energy fuels like gasoline, natural gas and electricity to power energy technologies. Carbon taxes target fuel consumption. 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. energy services are equal to the product of energy and efficiency consumption. Efficiency is the quantity of services delivered per unit of energy consumption, 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, while the miles driven could be the same. The utility gain from watching certain hours of a 30-inch TV should be different from the utility of watching a 50-inch TV.[6]

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. We prove that the relative incidence of standards and taxes is not conclusive but conditional. Evidence from the automobile sector further supports these findings.

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 prove conditions for an efficiency standard to be progressive,

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[6] 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 efficiency without the inclusion of other attributes

and to be more equitable than a carbon tax at the margin. Section 2.3 uses a Cobb-Douglas-type utility function to test the propositions obtained in Sections 2.1 and 2.2, and demonstrates the distributional impact of standards across the income spectrum. Section 2.4 shows how the model can be parameterised by using elasticities. Section 2.5 presents empirical support from 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:

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

The 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 and so on. 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 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. This theory is indeed relevant to, for example, the automobile market 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. 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 expenditure for purchasing energy technologies. Alternatively, one can think that households rent energy technologies instead of pay the amortised cost. Here we assume that households face constant prices, i.e., individual households are price takers. Y is household income.

The key assumption of our model is that the price of efficiency $p_R(J)$ is a function of technology attributes. Examples can be given to justify this specification. 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 probably 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 probably need higher-standard materials, more intellectual input and higher-precision manufacturing techniques, resulting in a higher cost compared to the cost of achieving the same efficiency by a lighter car. This reasoning suggests that technology attributes affect the costs of achieving efficiency, i.e. efficiency prices.

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.

Given the budget constraint (4) and the utility function (1), the Lagrangian equation can be written as:

$$\mathcal{L} = U(X, S) - \lambda(X + p_E E + p_R(J)R + p_J J - Y). \tag{5}$$

We can use the first-order conditions of Equation (5) to get:[7]

$$p_E E = p_R(J)R. \tag{6}$$

Differentiating (6) with respect to income Y and rearranging gives:

$$\frac{\partial R}{\partial Y} = (p_E \frac{\partial E}{\partial Y} - R\frac{\partial p_R(J)}{\partial Y})/p_R(J),. \tag{7}$$

Based on Equation (7), the following result on consumption behaviours of efficiency can be established:

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[7] See Appendix B.1 for a detailed proof.

Proposition 1. *If energy and technology attribute are normal goods and the technology attribute has a positive impact on efficiency price, i.e.* $\frac{\partial p_R(J)}{\partial J} > 0$*, then the relationship between efficiency consumption and income can be characterised as follows:*

$$\frac{\partial R}{\partial Y} < 0 \textit{ if and only if } p_E \frac{\partial E}{\partial Y} < R \frac{\partial p_R(J)}{\partial J} \frac{\partial J}{\partial Y}. \tag{8}$$

Further, the second inequality is equivalent to:

$$\frac{\partial E/E}{\partial Y/Y} < \frac{\partial p_R(J)/p_R(J)}{\partial Y/Y}. \tag{9}$$

Proof. See Appendix B.1 □

The assumption of normal goods in the proposition is generally true for fuel consumption such as gasoline and electricity (Espey and Espey, 2004; Alberini et al., 2011), and for attributes such as engine size and vehicle weight (Wilson and Boehland, 2008; West, 2004), though not necessarily hold for all attributes.[8] Equation (9) establishes that efficiency consumption decreases with income when the income elasticity of energy is smaller than the income elasticity of efficiency price.[9]

The condition in (8) establishes that efficiency consumption tends to be negatively related to income when the income effect on energy consumption $\partial E/\partial Y$ is low, and the income effect on attribution consumption $\partial J/\partial Y$ and the effect of the attribute on efficiency price $\partial p_R(J)/\partial J$ are high. The income effect on energy consumption is governed by the household preference for the functional energy service as specified in Equations (1) and (3). The household preference for the attribute determines the income effect on attribute consumption. The nature of the attribute governs the effect of the attribute on efficiency price. Therefore, Proposition 1 indicates that a strong preference for "high-carbon" attributes, i.e. attributes that have a substantial effect on raising efficiency price, combining with a low preference for functional energy services as households get rich, tends to make the relation between income and efficiency consumption negative. An example could be that richer households tend to drive bigger cars like SUVs and lower-income households drive compact cars. The preference for a bigger car makes efficiency price high, and as a result, richer households may drive less fuel-efficient SUVs.

Initial efficiency consumption R is also relevant in (8). A high initial R tends to make households decrease their efficiency consumption at the margin as they get rich.

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[8] Also see Section 2.5 for additional evidence from the US automobile market.

[9] It might seem strange to have an income elasticity of a price. It may help to disentangle $\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y}$ into $\frac{\partial p_R(J)/p_R(J)}{\partial J/J} \frac{\partial J/J}{\partial Y/Y}$, which reveals that the income elasticity of efficiency price is controlled by the income elasticity of efficiency consumption and the efficiency's effect on efficiency price.

The intuition is that the marginal cost of attribute consumption is determined by the marginal change in efficiency price and the initial consumption of efficiency R. A high R results in a bigger budgetary burden on households as efficiency price rises, and therefore households may decrease their efficiency consumption.

For comparison, Levinson (2019) reaches the definitive conclusion that $\partial R/\partial Y$ is positive because his model does not include the second term at the right-hand side of Equation (7). In Levinson's (2019) model, Equation (7) becomes:

$$p_R \frac{\partial R}{\partial Y} = p_E \frac{\partial E}{\partial Y}. \tag{10}$$

This indicates the marginal efficiency consumption should increase as the marginal energy consumption rises. Instead, Proposition 1 and its proof show that efficiency consumption can decrease with income if there is a preference for efficiency-decreasing technology attributes, contradicting Levinson's (2019) main conclusion. We do not claim that the income effect on efficiency consumption is always negative. $\partial R/\partial Y$ can also be positive when the condition in Proposition 1 is violated. What we show is that the income effect on efficiency consumption is conditional on the household preference for attributes and the effect of attributes on efficiency price, and it can be negative.[10]

Proposition 1 only discusses the consumption behaviours of efficiency but gives no result on the relative regressivity between 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 static impact of a carbon tax on households is $\tau_E E$, and τ_E is the tax levied on the carbon content of that energy. Following Fischer (2001), Goulder et al. (2016) and Davis and Knittel (2019), we express the effect of an efficiency standard as a tax on lower efficiency and a subsidy on

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[10] As in Levinson (2019), richer households have a preference for more efficient energy technology, other things equal. But we prove that the positive effect of this preference for efficiency can be completely offset and reversed when attribute consumption makes achieving efficiency particularly expensive.

higher efficiency relative to the benchmark efficiency standard R_0.[11] Therefore, the static impact of an efficiency standard can be expressed as $\tau_R(R_0 - R)$. It is positive when R is lower than R_0 and negative when R is higher than R_0.[12]

A policy intervention is regressive when its relative impact on income is higher among lower-income households. Dividing the static impact by total income gives the relative impact, i.e. $\tau_E E/Y$ and $\tau_R(R_0 - R)/Y$.[13]

Differentiating the relative impact with respect to income Y gives:

$$RG_E = \frac{\tau_E E}{Y^2}\left(\frac{Y}{E}\frac{\partial E}{\partial Y} - 1\right), \tag{11}$$

$$RG_R = -\frac{\tau_R R}{Y^2}\left(\frac{Y}{R}\frac{\partial R}{\partial Y} + \frac{R_0}{R} - 1\right). \tag{12}$$

RG_E and RG_R is the regressivity of a carbon tax and an efficiency standard respectively.

From Equations (11) and (12), we establish the following results on the distributional impacts of standards and taxes.

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

$$\frac{\partial E/E}{\partial Y/Y} > 1. \tag{13}$$

It becomes regressive when Inequality (13) is reversed.

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[11] See Appendix A for a mathematical derivation of this equivalence. In fact, 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. Note that Levinson (2019) models efficiency standards as a simple tax on efficiency, which is an important difference leading to our dissimilar theoretical and empirical findings. Note also that efficiency standards can be defined in many ways. Here we use a common definition—a benchmark standard on the quantity of delivered functional service per unit of energy consumption, such as miles driven per gallon. Alternative definitions such as footprint-based fuel economy standards can change the results and have important policy implications. See Section 4 for further discussion, and Gillingham (2013) for how footprint-based standards provide a perverse incentive to upsize vehicles.

[12] It should be emphasised that efficiency standards must be tradable for the whole regulated industry to face the same τ_R (see Appendix A). We therefore generally assume that efficiency standards are tradable to simplify the analysis throughout the paper. It is, moreover, common practices to have tradable standards. In China and the US, fuel economy standards allow companies to trade their "permits" with other automakers. However, since the focus of this specific section is merely a marginal analysis, the following result still holds when standards are not tradable.

[13] We ignore how the revenue from carbon taxes is used in the analysis that follows as we focus on marginal impacts on the expenditure side. The tax revenue may of course be used for rebating households, while there is no revenue from standards. Note that this may be policy-relevant, as many citizens may 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, climate policy-makers may not want to generate new tax revenue whose uses can be contested and therefore delay the progress for emissions reduction (Cullenward and Victor, 2020).

An efficiency standard is progressive at the margin when:

$$\frac{\partial R/R}{\partial Y/Y} + \frac{R_0}{R} < 1. \tag{14}$$

It becomes regressive when Inequality (14) is reversed.

Proof. Lemma 2 is a natural result of Equations (11) and (12). 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 (13) is the income elasticity of energy demand. If the income elasticity of energy demand is equal to one, households spend equal shares on energy. Therefore, a carbon tax would be distribution-neural, 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 (14) has one more term R_0/R at the left-hand side. As R_0/R is positive, it makes achieving Inequality (14) 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 uniform charge on households $\tau_R R_0$. The term R_0/R is the result of that uniform charge on households. The charge burdens low-income households more than high-income households, making an efficiency standard less equitable.

Following Davis and Knittel (2019), we contrast the distributional impacts of two policies by comparing the slopes of the relative impact with respect to income. The relative regressivity between a carbon tax and an efficiency standard can be derived through subtracting (12) from (11). We obtain:

$$RG_R - RG_E = -\frac{\tau_R R}{Y^2}\left(\frac{Y}{R}\frac{\partial R}{\partial Y} + \frac{R_0}{R} - 1\right) - \frac{\tau_E E}{Y^2}\left(\frac{Y}{E}\frac{\partial E}{\partial Y} - 1\right). \tag{15}$$

If (15) is less than zero, the carbon tax is less regressive or more progressive than the efficiency standard at the margin, i.e. it is more equitable.

From Equation (15), we establish the following result.

Proposition 3. *An efficiency standard is more equitable when:*

$$1 - \frac{\partial E/E}{\partial Y/Y} + \eta\left(\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y} - \frac{R_0}{R}\right) > 0, \tag{16}$$

$$\eta = \frac{\tau_R R}{\tau_R R + \tau_E E} \qquad \eta \in [0,1]. \tag{17}$$

A carbon tax is more equitable when Inequality (16) is reversed.

Proof. See Appendix B.2. ☐

The policy stringency of the carbon tax and the efficiency standard controls η. It is larger when the efficiency standard increases its stringency 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 at the margin is dependent on four factors, i.e., the income elasticity of energy demand $\frac{\partial E/E}{\partial Y/Y}$, the income elasticity of efficiency price $\frac{\partial p_R/p_R}{\partial Y/Y}$, the ratio of the efficiency benchmark and the consumed efficiency R_0/R, and η.

An efficiency standard tends to be more equitable than a carbon tax at the margin when the income elasticity of efficiency price is 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 $p_R(J)$ as $\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y}$ is high. As the income elasticity of energy demand is relatively low, the increased expenditure on both energy and efficiency will be small according to Equation (6).[14] Since $p_R(J)$ rises substantially but the expenditure on efficiency $p_R(J)R$ increases little, households tend to reduce the marginal efficiency consumption or even consume less efficiency R as they get rich. A small efficiency ratio R_0/R also suggests that households already consume high efficiency relative to the standard benchmark. As the efficiency price increases due to the effect of the technology attribute, achieving this high efficiency becomes particularly difficult and unappealing. This tendency to discourage efficiency consumption is more significant than the tendency to increase energy consumption as income increases, which makes the efficiency standard, targeting efficiency, more equitable than the carbon tax, targeting energy.[15]

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 efficiency price $\frac{\partial p_R(J)/p_R(J)}{Y/Y}$ is not strong enough, when compared to other factors, to discourage efficiency consumption to the degree that makes the efficiency standard more equitable.

Proposition 3 demonstrates that the relative regressivity between a carbon tax and an efficiency standard is conditional. To guide policy practices, the inequality conditions in Propositions 1 and 3 are next explored with an explicit utility function (Section 2.3)

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

[15] The role of η is less clear. η 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 (16). In the end, the effect of η depends on the sign and size of the bracket, which is also controlled by the policy stringency. It is expected that there can be a turning point of the policy stringency after which the standard becomes more regressive than the tax.

and data from the transport sector (Section 2.4).

2.3 Distributional impacts across the income distribution for a specific utility function

This section compares the impact on two households with distinct income levels and thereby elucidates 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 and the utility function takes a Cobb-Douglas form:

$$U(X, E, R, J) = X^{\alpha} J^{\theta} (ER)^{\beta}. \tag{18}$$

α, θ, and β are share parameters.

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

$$\begin{aligned} p_R(J) &= (J/J_0)^{\epsilon} p_R^0 \qquad \text{when } J \geq J_0, && (19) \\ &= p_R^0 \qquad\qquad\quad \text{when } J < J_0, && (20) \\ \epsilon &> 0. && (21) \end{aligned}$$

The scale factor ϵ governs the curvature of the relation between the technology attribute and efficiency price. $\epsilon > 0$ ensures 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.[16]

From the household problem defined from Equations (18) to (20), we can establish:

Corollary 4. *With Cobb-Douglas-type utility and functional forms as given by Equation* (19)*, Proposition 1 implies the following:*

$$\frac{\partial R}{\partial Y} < 0 \text{ if and only if } \epsilon > 1. \tag{22}$$

---

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

Proposition 3 implies that:

$$\epsilon > \frac{R_0}{R}. \tag{23}$$

Proof. See Appendix B.3. $\square$

Equation (22) 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 (19). 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 (18). 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, i.e. ϵ, must be greater than one.[17]

Equation (23) 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 (23) can be less stringent than Equation (22) 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 utility gain from the subsidy does not decrease.[18]

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:

$$Y_a > Y_b. \tag{24}$$

We use subscripts a and b to represent household 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 5. *The static impact on household a is greater than that on household b*

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[17] See Appendix B.3 for why ϵ is the income elasticity of efficiency price

[18] This result reveals that the incidence of an efficiency standard is not completely the same with the incidence of a tax on inefficiency which does not have the subsidy component. The conclusions reached by Levinson (2019) and West (2004), which approximate efficiency standards by inefficiency taxes, could thus sometimes be incomplete.

when:

$$\epsilon > 1, \tag{25}$$

$$Y_b < Y_a < \epsilon^{1/(\epsilon-1)} Y_0, \tag{26}$$

or

$$\epsilon > 1, \tag{27}$$

$$Y_b < Y_0 < \epsilon^{1/(\epsilon-1)} Y_0 < Y_a, \tag{28}$$

or

$$\epsilon < 1, \tag{29}$$

$$\epsilon^{1/(\epsilon-1)} Y_0 < Y_b < Y_a. \tag{30}$$

Household b experiences an greater impact when the above conditions are met except that the inequalities of ϵ, i.e., Inequalities (25), (27) and (29), are reversed. Irrespective of the value of ϵ, the relation between the two impacts is ambiguous when:

$$Y_0 < Y_b < \epsilon^{1/(\epsilon-1)} Y_0 < Y_a. \tag{31}$$

Proof. See Appendix B.4. ☐

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 in Appendix B.4:[19]

$$IN_R = \frac{\tau_R(R_0 - R)}{Y} = \tau_R R_0 (Y^{-1} - Y_0^{\epsilon-1} Y^{-\epsilon}). \tag{32}$$

IN_R is the incidence of an efficiency standard. Figure 1 (top) shows a representative curve of Equation (32) 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 increases with income, i.e. a bigger negative impact. After $\epsilon^{1/(\epsilon-1)} Y_0$, the impact decreases 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 (23) 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 (32)

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[19] We can establish this by using Equations (108) and (110) in Appendix B.4

when ϵ is smaller than one is shown in Figure 1 (bottom). It can be explained similarly as for the top graph in Figure 1.

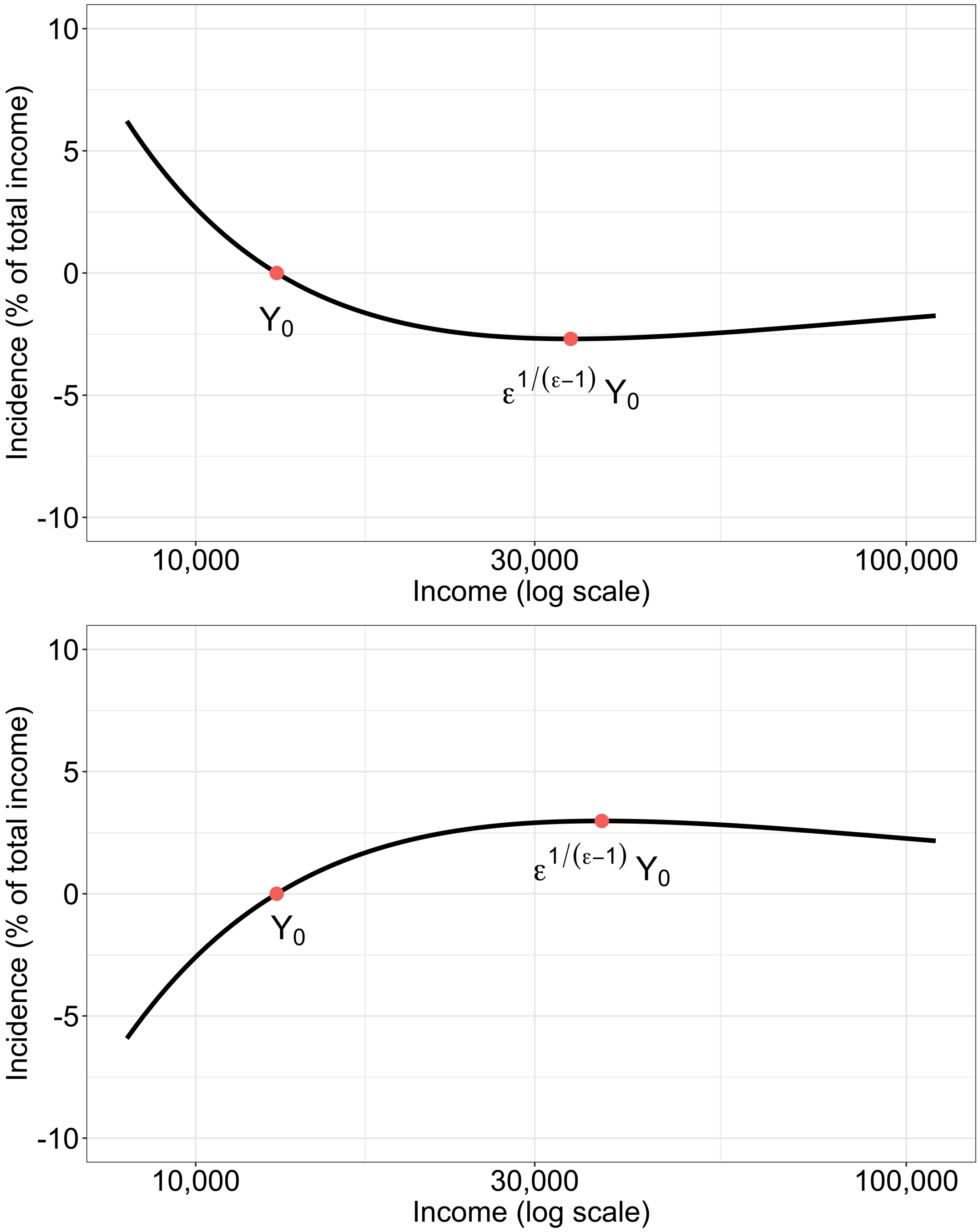

Figure 1: **Incidence of an efficiency standard according to Equation (32) when $\epsilon > 1$ (top); and when $\epsilon < 1$ (bottom).** Positive values indicate income gains and negative values indicate income losses. See Appendix B.5 for the values of parameters for plotting the graphs.

Policy stringency also impacts the outcome displayed in Figure 1. When $\epsilon > 1$, increasing policy stringency R_0 lowers Y_0 and therefore moves the red points in the figure to the left.[20] 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 4 and Proposition 5.

2.4 Estimating the incidence by elasticities

Here we use the data of the automobile sector to show how Propositions 1 and 3 can be tested. We focus on the automobile sector because it is one of the most extensively studied sectors for income elasticities. As this analysis investigates the static incidence of regulations, we use long-run elasticities to capture the static difference in fuel consumption among households.

The range of estimates is large for the income elasticity of fuel consumption. We adopt a value of one and complete a sensitivity test later.[21] 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.

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

$$e_P = e_E + e_R. \tag{33}$$

e_P, e_E and e_R is the income elasticity of the functional energy service, energy and efficiency respectively. 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.

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[20] This is because Y_0 is the income level for households to consume R_0. When $\epsilon > 1$, according to Corollary 4, lower-income households consume more efficiency. Therefore, a rise in R_0 decreases Y_0.

[21] 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.

According to Equation (6), the relation among income elasticities of energy, efficiency and efficiency price is:

$$e_E = e_R + e_{p_R}. \tag{34}$$

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 (9) holds.

With $\frac{\partial E/E}{\partial Y/Y} = 1$ and $\frac{\partial p_R/p_R}{\partial Y/Y} = 1.2$, Inequality (16) in Proposition 3 can be calculated as below:

$$1.2 - \frac{R_0}{R} > 0. \tag{35}$$

Equation (35) 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 and more equitable than a carbon tax. This is because a carbon tax is distribution-neutral at the fuel elasticity of one. 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. This result confirms the U-shape relation found in Section 2.3.

Table 1 provides a sensitivity analysis on e_E. 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).

e_E	e_P	Test of (9) 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	$\frac{R_0}{R} < 1.6 - \frac{0.2}{\eta}$

Table 1: **A sensivity analysis of income elasticities in the automobile sector for Propositions 1 and 3;** 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 1 provides a sensitivity analysis on e_E. It suggests that the relative regressivity between an efficiency standard and a carbon tax is dependent on the policy stringency of the two regulations. Policy stringency determines R_0 and η in the last column of Table 1. If the policy stringency of efficiency standard increases relatively, R_0 and η will rise.[22]

Table 1 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 (33). Additionally, if $e_E > e_P$, the Inequality (16) of Proposition 3 tends to be 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.

2.5 Application: Evidence from the US Vehicle Market

Here we use the data of the US household vehicle ownership to demonstrate an empirical case supporting our theoretical finding that, although richer households could consume more efficiency through demanding functional energy services, their preference for efficiency-decreasing attributes will reverse this tendency (Proposition 3).

We use the 2009 US National Household Travel Survey, 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, as in Levinson (2019). We then drop households with more than five vehicles and those entries with missing data points such as income and fuel economy. The cleaned data have 102,404 households and 148,114 vehicles. Table 2 shows the descriptive statistics of these households and vehicles.

The last two columns of Table 2 show that richer households generally drive less efficient vehicles. This contradicts the prediction of Equation (10)—richer households demand both more efficiency and energy—which ignores the interaction between attributes and efficiency consumption.

Table 3 presents attribute characteristics of vehicles owned by each income group. Richer households 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. With this assumption, our model predicts that richer households can drive less efficient cars, which is supported by Table 2.

We test the implied relation among household income, efficiency consumption and efficiency-decreasing attributes by regressing efficiency consumption against household

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[22] We do not complete a sensitivity analysis on e_P because the logic is similar and the existing research suggests a narrower range,, i. e. between 0.5 to 1 (Goodwin et al., 2004; Burt and Hoover, 2006; Sheng and Sharp, 2019; Dargay, 2007).

Household Income (2009 $)	Number of Households	Number of Vehicles	Gasoline Usage (Gallons)	Miles Driven	Gallons per Hundred Miles	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

Table 2: **Descriptive statistics of household and vehicle information.** 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.

Household Income (2009 $)	Number of Households	Weight (kg)	Engine Power (horsepower)	Height (mm)	Width (mm)	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

Table 3: **Household consumption of efficiency-decreasing attributes of vehicles.** 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.

income and vehicle characteristics, which is shown in Table 4.[23] 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 results suggest that the overall effect of income on fuel economy is negative. Only after blocking the importance of attributes, the income effect becomes positive, as is consistent with our theoretical prediction.[24]

	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

Table 4: **Fuel economy regressed by household income and vehicle attributes.**

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[23] Changing the measurement of efficiency from miles per gallon to gallons per hundred miles demonstrates similar results.

[24] The finding is also implicit in the empirical analysis of Levinson (2019). We add the theoretical implication of household preferences for attributes and their impact on efficiency.

Using the data of fuel consumption and fuel economy, we finally estimate the incidence of carbon taxes and several efficiency standards. For the efficiency standard, we assume four levels of increasing stringency, i.e. 59%, 61%, 63% and 70% quantiles of fuel economy of all vehicles. Following the definition in the theoretical model, we use miles per gallon as the measurement of efficiency. 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. For the tax, the incidence on each group is calculated by dividing average fuel consumption by mean income, i.e. $\tau_E E/Y$. To focus on the distributional impact, we normalise the results by dividing the incidence of each income group by the total absolute incidence of all income groups.[25] Figure 2 illustrates the results.

Efficiency standards can be more progressive than carbon taxes in the US vehicle market. However, the incidence of standards is sensitive to the stringency level as Figure 2 reveals. Standards set the benchmark at 59% and 61% quantiles create a much smaller relative impact on the lower three income groups than what a tax does. When the benchmark increases to 63% or even 70% quantile, the distributional effect of standards becomes increasingly similar to that of a carbon tax. Further raising the benchmark generates similar results to the 70%-quantile standard. The theoretical model predicts this regressive tendency since Inequality (14) in Proposition 2 tends to be violated when R_0 increases. This is also consistent with discussions in Section 2.3. In particular, Figure 1 indicates that rising policy stringency shrinks the progressive region when lower-income households drive more efficient cars. Despite that, a more stringent standard in the US vehicle market is almost as regressive as a fuel tax, not more.[26]

In sum, the empirical evidence from the US household ownership of vehicles supports our theoretical findings. Households prefer efficiency-decreasing attributes. This preference in turn reduces richer households' tendency to consume more efficiency, and may even causes them to use less efficient technologies. When such an efficiency-decreasing preference exists, efficiency standards can be more equitable than a carbon tax without a progressive revenue redistribution, at least for moderate levels of stringency of the standard.

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[25] The normalisation makes τ_R and τ_E irrelevant as they only change the scale of incidence.

[26] It is worth noting that Figure 1 is a continuous and Figure 2 is a discrete representation of the same economic phenomenon. Therefore, groupings in Figure 2 can miss some nuances in distributional impacts. Note also that the analysis in Section 2.3 ignores heterogeneities in household preferences, but which are at play in the US vehicle market.

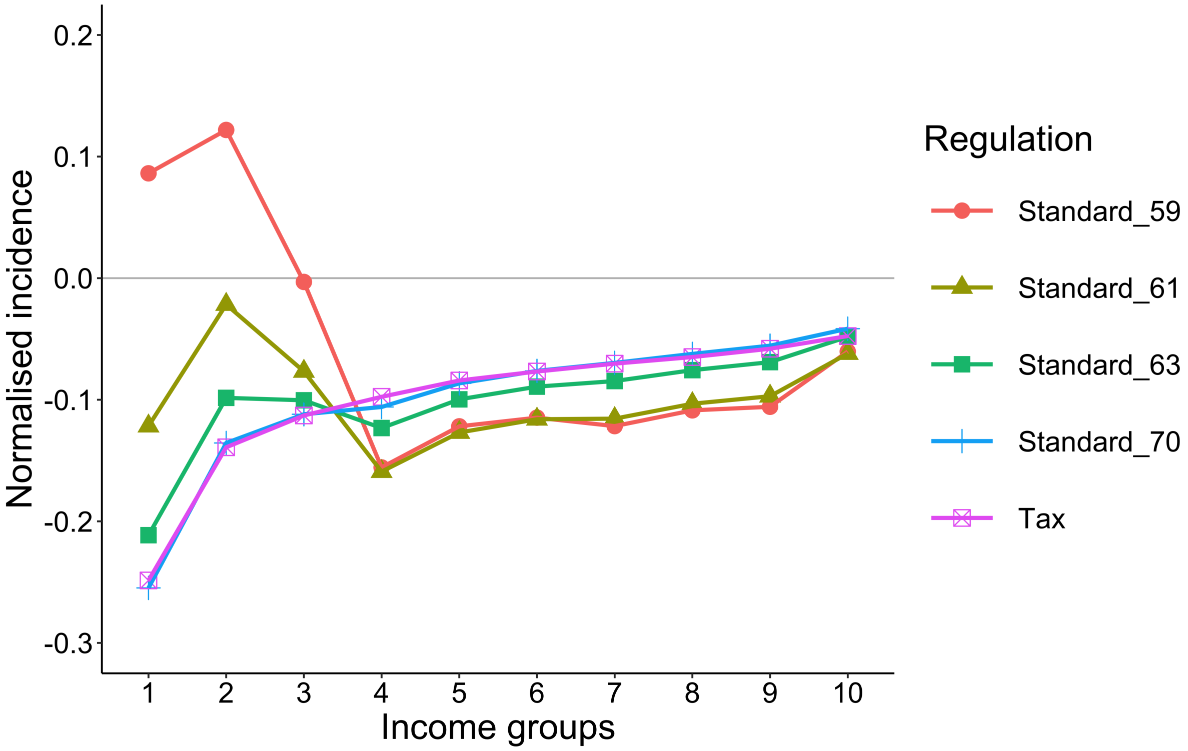

Figure 2: **The incidence of a carbon tax and different levels of efficiency standards for the US vehicle market.** Household income of each income group is defined in Table 2. Incidence is normalised by dividing the incidence of each income group by the total absolute incidence of all groups. *Standard*_59, *Standard*_61, *Standard*_63 and *Standard*_70 represent efficiency standards with the benchmark efficiency set at 59%, 61%, 63% and 70% quantiles of fuel economy of all vehicles; that is from *Standard*_59 to *Standard*_70 policy stringency increases. The efficiency measurement is miles per gallon. *Tax* represents a carbon tax on fuels without a progressive revenue redistribution. Positive values indicate income gains and negative values indicate income losses.

3 Distributional impacts of intensity standards for subsistence and luxury goods

The analysis of the previous section assumes that expenditure shares on goods do not change with income. 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 can be carbon-intensive. In contrast, there are some goods disproportionately consumed by the rich, such as air travels. Many people never take international flights. In developing countries, a large share of households does not own a car. It can be expected that policies reducing emissions in these sectors have a smaller impact on low-income households.

To discuss how these 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 the regulatory perspective. First, the luxury and subsistence goods might be thought 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, especially in low- and middle-income countries, and it generally emits more carbon dioxide. Additionally, private transport may be further segregated into higher-carbon transport like SUVs and lower-carbon transport like compact cars. Consumption patterns of these cars, and correspondingly transport services, could be different for rich and poor households. Regulators may consider how they want to regulate modes of transport 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.[27] 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

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[27] A third regulatory interpretation of luxury and subsistence goods is considering implementing intensity standards in 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, an intensity standard can motivate companies to substitute dirty technologies with clean technologies. We do not discuss this scenario here as its incidence has been analysed before. See Rausch and Mowers (2014) for example.

could be designed as an output-based emissions trading system. Emissions quotas to each sector are not fixed caps but adjustable output-based allocations determined by intensity regulations, i.e. the quotas a firm received is the firm's production output multiplied by the government-set intensity standard. Different sectors may be regulated with different intensity levels.[28]

We use a simple analytical model to elucidate the distributional implications of these two regulatory scenarios. First, we discuss the regressivity of intensity standards and carbon taxes individually, and show conditions for intensity standards to be progressive. Subsequently, we contrast the incidence of carbon taxes and intensity standards. We prove that, in the absence of progressive revenue recycling, intensity standards are generally more equitable than carbon taxes when luxury goods are more carbon-intensive.

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 non-homothetic preferences by introducing a Stone-Geary utility function.

Households have the following utility function:

$$U_i = X_i^{\theta}(S_{1,i} - S_1^0)^{\alpha}(S_{2,i} + S_2^0)^{\beta} l_i^{\gamma}. \tag{36}$$

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 and 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 represents 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 C.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 (36) becomes a normal homothetic utility function.

We consider two policy instruments, i.e. carbon taxes and intensity standards.[29] Carbon taxes charge a fee according to the embodied emissions of goods. Intensity standards

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[28] For example, if an electricity company generates one-million kWhs and the company faces an intensity standard of 500 gram-CO$_2$e per kWh, the emissions quota the company receives is 500 multiplied by one million. Companies can trade with others to comply with these quotas. See Goulder et al. (2019b) for a discussion of such a programme in the Chinese power sector. Also see Fischer (2001) for an analytical discussion of output-based instruments.

[29] We intentionally use "intensity standards" instead of "efficiency standards" for easier comparison with carbon taxes. 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.

set an emissions intensity benchmark for the two types of goods either explicitly through intensity regulations or implicitly through taxing high-emissions goods and subsidising low-emissions goods. The average emissions intensity of the two goods should not exceed the intensity benchmark.

Intensity standards do not generate government revenue. Implicit taxes on high-emissions goods are equal to implicit subsidies to low-emissions goods. Emissions taxes generate government revenue. We consider that the revenue is not returned to households, that 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 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 to good uses (Klenert et al., 2018a; Douenne and Fabre, 2020). Therefore, when households evaluate policy options *ex-ante*, they mostly consider how rising commodity prices would directly affect them.

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

$$I_i = \phi_i \omega (1 - l_i)(1 - \tau_w), \tag{37}$$

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 interested cases.

The budget constraint of households is given by:

$$X_i + S_{1,i}(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)) + S_{2,i}(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0)) = I_i + L_i, \tag{38}$$

with $e_1 < e_0 < e_2$ or $e_2 < e_0 < e_1$. e_1, e_2 and e_0 is the emissions intensity of the subsistence good, the luxury good and the standard. 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 is the price 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 it is endogenously determined.[30]

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[30] Again, the intensity standard must be tradable for τ_r to be constant across companies. See Appendix A for details. See also Footnotes 12 and 28.

As the standard must be revenue neutral, the following equation binds:

$$\sum_{i=1}^{N} S_{1,i}(e_1 - e_0) + \sum_{i=1}^{N} S_{2,i}(e_2 - e_0) = 0. \tag{39}$$

Equation (39) 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.

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 the utility (36) subject to the budget constraint (38):

$$\begin{aligned}
X_i = {} & \theta(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)) \\
& + S_2^0(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0))), && (40) \\
S_{1,i} = {} & \frac{\alpha}{p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)}(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)) \\
& + S_2^0(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0))) + S_1^0, && (41) \\
S_{2,i} = {} & \frac{\beta}{p_2 + \tau_e e_2 + \tau_r(e_2 - e_0)}(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)) \\
& + S_2^0(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0))) - S_2^0, && (42) \\
l_i = {} & \frac{\gamma}{\phi_i\omega(1-\tau_w)}(\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0)) \\
& + S_2^0(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0))). && (43)
\end{aligned}$$

We use the utility ratio of two households as a measure of the distributional impact. We assume that there are two households i and j with discrete earning abilities. Using Equations (40), (41), (42) and (43), we obtain the ratio of the indirect utilities of two households:

$$\begin{aligned}
\frac{U_i}{U_j} = {} & \frac{(S_{1,i} - S_1^0)^\alpha (S_{2,i} + S_2^0)^\beta l_i^\gamma}{(S_{1,j} - S_1^0)^\alpha (S_{2,j} + S_2^0)^\beta l_j^\gamma}, \\
= {} & \left(\frac{\phi_i}{\phi_j}\right)^\gamma \left(\frac{\phi_i\omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0))}{\phi_j\omega(1-\tau_w) + L_j - S_1^0(p_1 + \tau_e e_1 + \tau_r(e_1 - e_0))}\right. \\
& \left.\frac{+S_2^0(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0))}{+S_2^0(p_2 + \tau_e e_2 + \tau_r(e_2 - e_0))}\right). && (44)
\end{aligned}$$

We define the utility ratio before regulations as $\left(\frac{U_i}{U_j}\right)^{\mathrm{BR}}$, the utility ratio after implementing an intensity standard as $\left(\frac{U_i}{U_j}\right)^{\mathrm{AS}}$, 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:

$$\left(\frac{U_i}{U_j}\right)^{\text{BR}} = \left(\frac{\phi_i}{\phi_j}\right)^{\gamma} \left(\frac{\phi_i \omega(1-\tau_w) - S_1^0 p_1 + S_2^0 p_2}{\phi_j \omega(1-\tau_w) - S_1^0 p_1 + S_2^0 p_2}\right), \tag{45}$$

$$\left(\frac{U_i}{U_j}\right)^{\text{AS}} = \left(\frac{\phi_i}{\phi_j}\right)^{\gamma} \left(\frac{\phi_i \omega(1-\tau_w) - S_1^0(p_1 + \tau_r(e_1 - e_0)) + S_2^0(p_2 + \tau_r(e_2 - e_0))}{\phi_j \omega(1-\tau_w) - S_1^0(p_1 + \tau_r(e_1 - e_0)) + S_2^0(p_2 + \tau_r(e_2 - e_0))}\right), \tag{46}$$

$$\left(\frac{U_i}{U_j}\right)^{\text{AT-L}} = \left(\frac{\phi_i}{\phi_j}\right)^{\gamma} \left(\frac{\phi_i \omega(1-\tau_w) + L_i - S_1^0(p_1 + \tau_e e_1) + S_2^0(p_2 + \tau_e e_2)}{\phi_j \omega(1-\tau_w) + L_j - S_1^0(p_1 + \tau_e e_1) + S_2^0(p_2 + \tau_e e_2)}\right), \tag{47}$$

$$\left(\frac{U_i}{U_j}\right)^{\text{AT-N}} = \left(\frac{\phi_i}{\phi_j}\right)^{\gamma} \left(\frac{\phi_i \omega(1-\tau_w) - S_1^0(p_1 + \tau_e e_1) + S_2^0(p_2 + \tau_e e_2)}{\phi_j \omega(1-\tau_w) - S_1^0(p_1 + \tau_e e_1) + S_2^0(p_2 + \tau_e e_2)}\right). \tag{48}$$

For $\left(\frac{U_i}{U_j}\right)^{\text{AT-L}}$, the following condition must bind to stay revenue neutral:

$$\sum_{i=1}^{N} L_i = \tau_e e_1 \sum_{i=1}^{N} S_{1,i} + \tau_e e_2 \sum_{i=1}^{N} S_{2,i}. \tag{49}$$

3.2 Comparing distributional impacts of intensity standards and carbon taxes

From Equations (45), (46), (47) and (48), we can establish several propositions. Taken together, these indicate that the incidence of both standards and taxes depend on carbon intensities and levels 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 6. *An intensity standard for carbon-intensive goods of 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 7. *A carbon tax with lump-sum rebates on carbon-intensive goods of luxury and subsistence properties is always progressive.*

An 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 proofs of Lemmas 6 and 7, see Appendix C.2. ☐

The intuition of Lemma 7 is that the progressivity of a carbon tax with no distribution depends on the carbon content of the subsistence and luxury consumption levels. This is because the subsistence good as defined in the utility function (36) is utility-decreasing relative to the scenario where the subsistence good is an "ordinary" good. It requires every household to spend a minimal amount of money to purchase the subsistence good but receive no utility gain for this minimal consumption. The luxury good is utility-enhancing as households do not need to consume it until they earn a certain level of income. This is why in Equation (45) the subsistence good adds a negative term $-S_1^0 p_1$ to the numerator and the denominator, and the luxury good adds a positive term $S_2^0 p_2$. Similarly, if a carbon tax is in place, the burden of the carbon tax adds a utility-decreasing term $-\tau_e e_1 S_1^0$ and a utility-enhancing term $\tau_e e_2 S_2^0$ according to the carbon content of the subsistence and luxury consumption levels. The relative magnitude of the two terms determines whether the carbon tax is progressive or regressive when no redistribution is considered. A similar interpretation can be given to Lemma 6 where the added term due to the standard is positive when $e_1 < e_2$.[31]

We now contrast the incidence of taxes and standards for equivalent amounts of reducing emissions. The following propositions can be established.

Proposition 8. *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:*

$$\frac{e_1}{e_2} < \frac{\tau_r}{\tau_r - \tau_e} \frac{e_0}{e_2}. \tag{50}$$

On the premise that Inequality (50) *is satisfied, the sufficient condition is:*

$$\frac{S_1^0}{S_2^0} > \frac{\left(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\right)}{\left((1 - \frac{\tau_e}{\tau_r})\frac{e_1}{e_2} - \frac{e_0}{e_2}\right)}. \tag{51}$$

Proof. See Appendix C.3. ☐

Inequality (50) is implausible when an equivalent abatement is achieved. Therefore, Proposition 8 implies that in most cases even a carbon tax with no revenue redistribution

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[31] See Appendix C.2 for details.

is more equitable than an intensity standard when subsistence goods are more carbon-intensive, and when an equivalent amount of emissions reduction is required.

Inequality (50) rarely applies because $\tau_r/(\tau_r - \tau_e)$ is usually close to one when an equivalent emissions reduction is enlisted. The implicit tax τ_r should be many times greater than τ_e to achieve an equivalent abatement.[32] This is because a carbon tax reduces emissions through two channels, i.e. the substitution between high-emissions goods and low-emissions goods and demand reduction. But an intensity standard reduces emissions primarily through the substitution between the two goods.[33] This single abatement channel requires an intensity standard to establish a much larger price difference between the two goods through the implicit tax and subsidy. Therefore, τ_r is much larger than τ_e, making $\tau_r/(\tau_r - \tau_e)$ close to one. e_1/e_2 should be reasonably greater than e_0/e_2 because if there is not a sensible difference between e_0, e_1 and e_2, a technology mandate or no regulation would be enough instead of going through the effort of implementing an intensity standard. Therefore, multiplying e_0/e_2 by a number close to one should not easily make it greater than e_1/e_2. Thus, Inequality (50) is fairly implausible.

Similarly, we have:

Proposition 9. *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:*

$$\frac{e_0}{e_2} > \frac{\tau_r - \tau_e}{\tau_r}. \tag{52}$$

On the premise that Inequality (52) is satisfied, the sufficient condition is:

$$\frac{S_1^0}{S_2^0} < \frac{\left(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\right)}{\left((1 - \frac{\tau_e}{\tau_r})\frac{e_1}{e_2} - \frac{e_0}{e_2}\right)}. \tag{53}$$

Proof. See Appendix C.3. □

Inequality (52) is implausible when an equivalent abatement is achieved. Similar to Proposition 8, Proposition 9 implies that in most cases an intensity standard is more progressive than a carbon tax with no redistribution when luxury goods are more carbon-intensive, and when an equivalent amount of emissions reduction is required.

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[32] See, for example, Goulder et al. (2019b), Goulder et al. (2016) and Landis et al. (2019). Also see Session 3.3 where the numerical case for the British transport sector requires τ_r to be about five times of τ_e.

[33] See Appendix A for why an intensity standard requires less demand reduction.

Again, Equation (52) is unlikely to be satisfied since $(\tau_r - \tau_e)/\tau_r$ is close to one and 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.

What happens in this model when instead considering revenue recycling, even if that is not how citizens usually view environmental taxation? Propositions 6 and 7 jointly demonstrate that carbon taxes with lump-sum rebates would be strictly preferred in terms of equity if subsistence goods have a higher carbon footprint per unit than luxury goods. Further, the relative incidence between carbon taxes and intensity standards is ambiguous when luxury goods have a higher carbon intensity. However, it can be 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.[34]

Finally, we expect that proportionate income tax cuts are mostly utility-ratio-preserving according to each household's productivity or say earning ability. Therefore, proportionate income tax cuts tend to extenuate the impact of carbon taxes but do not often change the regressivity of the impact.[35] In other words, implications from Propositions 7, 8 and 9 for taxes with no redistribution still hold for taxes with proportionate redistribution in most cases. We next explore this numerically.

3.3 A numerical application to the Chinese transport sector

In this section, we illustrate the theoretical results with the data of automobile ownership in China.

The data are provided by the *China Household Finance Survey (CHFS)* published by Southwestern University of Finance and Economics (2019). Note that we do not consider the incidence on households with no car. Since low-income households often do not have a car, all regulations tend to be more progressive if the incidence on households with no car is included. 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 income 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

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[34] See Landis et al. (2019) and Rausch and Mowers (2014) for example

[35] See Klenert and Mattauch (2016) for a theoretical case with only subsistence goods

cars as the subsistence good. Expenditure shares in these two goods are approximated by the expenditure shares in gasoline for driving these two types of cars, i.e. transport services from driving high-emissions and low-emissions 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.[36] S_1^0 and S_2^0 is set to 1 and 0.13 such that the relative expenditure shares for the luxury good and the subsistence good is retained at the lowest income group. Wage w is normalised to 1000. The income tax rate τ_w is set to 0.15.[37] 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 since the average fuel efficiency of the two groups has an about 2:1 relation. Accordingly, the emissions rate e_1 and e_2 is set to 0.5 and 1.

We model four regulations with about the same amount of emissions reduction relative to a no-regulation scenario, 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 each household's earning 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 is set to 0.3 and 0.504 respectively to enable the equivalent emissions reduction. The implicit tax τ_r caused by the standard is determined endogenously as 15, which supports the observation made in Section 3.2, i.e. τ_r tends to be many times larger than τ_e. Programming language *R* is used to simulate the model and R package *DEoptimR* is used for optimisation.

A point worth noting is that the design of intensity standards here is similar to the "feebate" schemes used in European countries such as France. Like a feebate, the intensity standard taxes or subsidises vehicles based on their emissions intensity. See Gillingham (2013) and Durrmeyer and Samano (2018) for a comparison between these two instruments. Also see Appendix D for a further application to the British transport

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

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

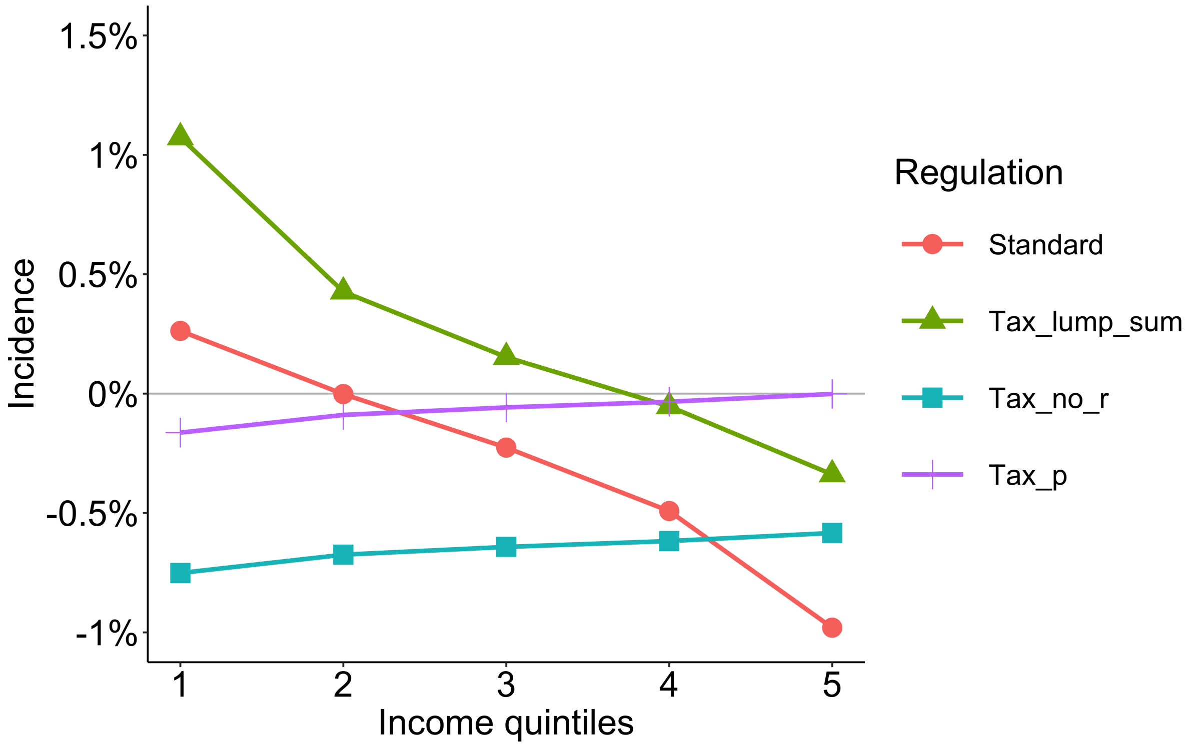

Figure 3: **Comparison of the incidence of an intensity standard (*Standard*), a carbon tax with lump-sum redistribution (*Tax_lump_sum*), a carbon tax with no redistribution (*Tax_no_r*), and a carbon tax with proportionate rebates according to households' productivity (*Tax_p*).** Parameters are calibrated 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.

sector.

Results are given in 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 Propositions 6, 7 and 9. Since $e_1 < e_2$, the efficiency standard should be progressive according to Proposition 6. The carbon tax with no redistribution is regressive as $S_1^0 e_1 > S_2^0 e_2$. The result also supports the argument made in Section 3.2, i.e. proportionate rebates tend to extenuate the impact of taxes but do not change the distributional consequences. Finally, Figure 3 shows that the carbon tax with lump-sum rebates create larger utility gains to low-income households and smaller utility losses to high-income households compared to the intensity standard, suggesting that the cost-effectiveness of carbon taxes is higher than that of intensity standards.

This result provides 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 a utility gain to lower-income households, despite causing a bigger loss 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.

In sum, the model of this section shows that intensity standards can be an equitable alternative to carbon taxes, when they are compared with carbon taxes with no redistribution and proportionate redistribution. In general, however, carbon taxes with a progressive redistribution, such as lump-sum rebates, remain the most equitable option.

4 Discussion

We have shown that regulatory standards can be more progressive than pricing instruments at least on the expenditure side, by which we mean ignoring revenue recycling and general-equilibrium sources-side effects. We review two additional equity aspects relevant to instrument choice between pricing and non-pricing instruments not modelled above and indicate the limitations of our study.

Regarding further equity issues, 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, could be relevant to environmental policy interventions (Pizer and Sexton, 2019; Burtraw et al., 2005; Rausch et al., 2011; Douenne, 2020). The rationale is that for households within an income group, it could be perceived as unfair for policy interventions to burden them differently (Elkins, 2006). Some studies further 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 additional 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, when the welfare loss of perceived unfairness in horizontal equity is included.

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 a long-term investment in capital and labour skills may suffer severely in the short term (Fullerton and Muehlegger, 2019; Castellanos and Heutel, 2019).[38] Household interests also play a role in climate policymaking when the impact is concentrated or associated with other perceived government failures. The Yellow Vests Movement in France, initially kindled by a rise in fuel taxes hurting rural population in particular, grew into an outcry about economic inequality. Indeed, a study by Douenne and Fabre (2020) suggests that French households disapprove of carbon taxes for their distributional impacts and the lack of low-carbon alternatives. Similarly, Anderson et al. (2019) study two failed carbon tax programmes in Washington state and conclude that increased energy costs explain a 20-percentage-point drop in popular support for carbon taxes. Some households may be particularly impacted if they involuntarily live a high-carbon lifestyle. Examples include peri-urban workers who drive a long distance to work and have poor access to public transport, 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.[39]

Our analysis, serving as an initial step to understand the incidence of standards, has not delved into these 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) approach is necessary while our approach is mostly partial equilibrium (PE). Also, GE approaches are useful to reveal the full incidence from both the expenditure side and the income side. For example, Rausch and Mowers (2014) employ 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 PE approach because the complexity of the GE approach will constrain our analysis into numerical studies of specific industry and country without meaningful theoretical insights and intuitive understanding. Also, we intentionally focus on the incidence on the expenditure side because the impacts from rising commodity costs are more

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[38] For example, affected companies may lay off workers. These workers temporarily lose income and need to find new jobs. Their human capital in industry-specific skills may be permanently lost (Topel, 1990; Neal, 1995). Also, the psychological and physical implications of losing jobs can be painful (Sullivan and von Wachter, 2009; Olesen et al., 2013).

[39] A study by Holland et al. (2015) reveals how the distribution of costs can explain the popular support to a low carbon fuel standard and a renewable fuel standard and the unpopularity of cap-and-trade programmes. They argue that the more skewed cost distribution of regulatory standards among US counties and districts means that a small group makes a large gain and costs are dispersed. They show that this skewed distribution can explain the voting behaviours for cap-and-trade reforms.

visible to citizens, and the incidence of the revenue recycling is more uncertain.[40] It is the dominant subject of political debates around how the tax revenue should be used. Future work can complement our analysis by providing more detailed views on the impacts on real income and specific groups, including sources-side effects not discussed here.

A further caveat for interpreting this work is about the design of regulatory standards. Real-world standards are usually more complex than the standards we specify in this analysis. For example, fuel economy standards applied in many countries, including China and the US, may have footprint-adjusted targets. These footprint-based standards will influence equity results. Also, regulators may apply different intensity targets according to industry characteristics instead of the single-level intensity standard we analyse. This flexibility provides another avenue for governments to protect certain industries and help consumers of certain goods by applying looser intensity targets. When analysing distributional impacts of real-world policies, researchers need to build these detailed designs into their models. Our work provides the analytical framework to undertake these more nuanced modellings.

We also 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 countries 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 important for optimal policy responses to climate change. We think, however, that policy burdens shared by the current generation are the obstacle preventing policies being enacted now.

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. Governments can address undesirable equity consequences by using the tax-and-transfer system.[41] Nevertheless, the political economy prospect of achieving a high enough carbon tax and simultaneously reforming the tax-and-transfer system could be low in many governance situations.[42]

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[40] This is also arguably how citizens evaluate policy options (Douenne and Fabre, 2019; Kallbekken et al., 2011).

[41] Over 3500 US economists have endorsed a "carbon dividends" instrument for US climate policy, including 45 Nobel Laureates. Carbon dividends include a carbon tax and a lump-sum redistribution scheme (Carbon Leadership Council, 2020).

[42] Cullenward and Victor (2020) also argue, for example, 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

Richer households and richer countries enjoy better and more energy services. But a tax on carbon often penalises the poor more than the rich—at least without giving the revenue back to the poor. This makes it difficult to follow the advice Pigou (1920) gives us one hundred years ago in delivering on global climate targets. Could regulatory standards do better in asking the rich to pay more than the poor? We answer this question by comparing regulatory standards and carbon pricing for economic inequality, building on recent studies which consider the distributional impacts of pricing and non-pricing instruments (Jacobsen, 2013; Rausch and Mowers, 2014; Levinson, 2019; Davis and Knittel, 2019). Here, we develop two new analytical models, and show that regulatory standards can be progressive and address inequality better than carbon pricing in the absence of an equitable redistribution.

Specifically, we first generalise Levinson's (2019) model by introducing the assumption that consumers prefer attributes of household energy technologies. We prove that efficiency standards can be more equitable than carbon pricing on the expenditure side. We show that richer households may use less efficient technologies when consumers exhibit a significant preference for high-carbon attributes, for example, the engine power of automobiles. We also demonstrate that the distributional impact of efficiency standards can take a U-shape across the income spectrum. Evidence from the automobile sector supports these analytical findings. For the US vehicle market, an efficiency standard can be as equitable as a carbon tax, if not more.

Second, we use a model generalised from 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 between luxury and subsistence goods is critical for distributional impacts. First, we assume that the luxury good is more carbon-intensive than the subsistence good. We prove that, in this case, intensity standards are generally more progressive than carbon pricing in the absence of an equitable revenue redistribution, i.e. when the pricing revenue is used to finance government budget, returned to households proportionately or when policies are evaluated merely by expenditure effects. Second, when the subsistence good is more carbon-intensive than the luxury good, intensity standards generally have less favourable distributional consequences than carbon pricing. 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 tax on fuels, when the revenue is not rebated or only proportionally rebated.

We anticipate some particular relevance of this study to less developed economies. First, some carbon-intensive goods are of luxury characteristics in developing countries despite being subsistence goods in high-income nations. Beyond expensive energy services such as automobiles and aviation, basic energy services such as gas heating and electric cooling could also be “luxuries” (in the theoretical sense) in those economies—only available to rich households in poorer societies. Such a circumstance may increase the progressiveness of mitigation policy. The provision of cleaner and affordable alternatives is key in such regions as basic energy services should nevertheless be enjoyed by everyone. Second, the preference for carbon-intensive goods is emerging and evolving in developing countries. The Western desire for bigger, heavier and more powerful vehicles, for example, does not need to be repeated in developing countries. But it is also reasonable that they will aspire to live a life as people in wealthy countries do. Further applied research is needed, for example, to understand the preference for high-carbon technology attributes and their distributional implications in the developing context. Our models might provide a framework for thinking about appropriate climate regulations on those contexts.

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 legislation and implementation of such instruments, particularly when one acknowledges how citizens think about the equity of taxes (Kallbekken et al., 2011; Douenne and Fabre, 2019). The distributional effects of carbon pricing have been a great concern for a wide variety of political actors. Instead of merely relying on the—at best uncertain—prospect of getting high carbon prices enacted, different forms of regulatory standards at the industry level will play a role in delivering on climate targets. Understanding the equity implications of these standards is therefore important for policymakers who want to ensure public support for decarbonisation.

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Appendix

A 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 for each automaker is:

$$\max_{q_1,q_2\cdots,q_j} \sum_{j=1}^{J} \Big(q_j p_j - c_j(q_j)\Big), \tag{54}$$

where q_j and p_j is 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:

$$\sum_{j=1}^{J} \Big((r_0 - r_j)q_j\Big) + Q = 0, \tag{55}$$

where r_j and r_0 is 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:

$$\mathcal{L} = \sum_{j=1}^{J} \Big(q_j p_j - c_j(q_j)\Big) - \lambda \sum_{j=1}^{J} \Big((r_0 - r_j)q_j + Q\Big). \tag{56}$$

The first-order conditions can be obtained by differentiating Equation (56) by q_j:

$$p_j = c'_j(q_j) + \lambda(r_0 - r_j). \tag{57}$$

λ represents the shadow price of compliance permits. The shadow price is equal across firms if the standard is tradable. Equation (57) 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:

$$p = c_j'(q_j) + \lambda(r_j - r_0). \tag{58}$$

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:

$$p + \lambda r_0 = c_j'(q_j) + \lambda r_j. \tag{59}$$

Equation (59) provides the second interpretation of intensity standards. λr_j is a tax on emissions and λr_0 is a 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. 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.

B Proofs for Section 2

B.1 Proof for Proposition 1

The first order conditions of (5) are:

$$U_X = \lambda, \tag{60}$$
$$RU_S S_P = \lambda p_E, \tag{61}$$
$$EU_S S_P = \lambda p_R(J), \tag{62}$$
$$U_S S_J = \lambda(p_J + p_R'(J)R). \tag{63}$$

We first prove the first part (8). Substituting (61) into (62) gives Equation (6). 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 (6) with respect to income Y gives:

$$p_E \frac{\partial E}{\partial Y} = p_R(J)\frac{\partial R}{\partial Y} + R\frac{\partial p_R(J)}{\partial Y}. \tag{64}$$

Define the marginal expenditure increase in energy as:

$$ME_E = p_E \frac{\partial E}{\partial Y}, \tag{65}$$

and the marginal expenditure increase in efficiency as:

$$ME_R = ME_{R,R} + ME_{R,p_R} = p_R(J)\frac{\partial R}{\partial Y} + R\frac{\partial p_R(J)}{\partial Y}, \tag{66}$$

$$ME_{R,R} = p_R(J)\frac{\partial R}{\partial Y}, \tag{67}$$

$$ME_{R,p_R} = R\frac{\partial p_R(J)}{\partial Y}. \tag{68}$$

In (66), 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 by the income effect on efficiency price ME_{R,p_R}.

(64) becomes:

$$ME_E = ME_R = ME_{R,R} + ME_{R,p_R}. \tag{69}$$

(69) implies that the marginal expenditure on energy is equal to the marginal expenditure on efficiency, which is a natural result of (6).

Rearranging (64) gives:

$$\begin{aligned}\frac{\partial R}{\partial Y} &= (p_E\frac{\partial E}{\partial Y} - R\frac{\partial p_R(J)}{\partial Y})/p_R(J), &(70)\\ &= (p_E\frac{\partial E}{\partial Y} - R\frac{\partial p_R(J)}{\partial J}\frac{\partial J}{\partial Y})/p_R(J). &(71)\end{aligned}$$

The above expression can be expressed also by marginal expenditures:

$$\frac{\partial R}{\partial Y} = (ME_E - ME_{R,p_R})/p_R(J). \tag{72}$$

ME_E and ME_{R,p_R} are both positive since $\partial E/\partial Y$, $\partial J/\partial Y$ and $\partial p_R(J)/\partial J$ in (71) are assumed to be positive. Therefore, from Equation (72), 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 $\partial R/\partial Y$ would be negative. The condition in (8) enables this. This proves the first part.

Second, it remains to prove that (8) is equivalent to (9). We multiply both sides of (8) by Y/E and use (6) to replace E at the right hand side:

$$p_E\frac{\partial E/E}{\partial Y/Y} < R(\frac{p_E}{p_R(J)R})\frac{\partial p_R(J)}{\partial Y/Y}. \tag{73}$$

Rearranging (73) gives (9).

B.2 Proof for Proposition 3

Substituting (7) into (15) and rearranging gives:

$$
\begin{aligned}
Y^2(RG_R - RG_E) =& -\tau_R R\left(\frac{p_E Y}{p_R(J)R}\frac{\partial E}{\partial Y} - \frac{Y}{p_R(J)}\frac{\partial p_R(J)}{\partial Y} + \frac{R_0}{R} - 1\right) \\
& -\tau_E E\left(\frac{Y}{E}\frac{\partial E}{\partial Y} - 1\right). \qquad (74)
\end{aligned}
$$

Using (6) to replace $p_R R$ with $p_E E$ in (74) and rearranging, we obtain:

$$
\frac{Y^2}{\tau_R R + \tau_E E}(RG_R - RG_E) = 1 - \frac{\partial E/E}{\partial Y/Y} + \frac{\tau_R R}{\tau_R R + \tau_E E}\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y} - \frac{\tau_R R_0}{\tau_R R + \tau_E E}. \quad (75)
$$

Using η, we can rewrite (75) as:

$$
\frac{Y^2}{\tau_R R + \tau_E E}(RG_R - RG_E) = 1 - \frac{\partial E/E}{\partial Y/Y} + \eta\left(\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y} - \frac{R_0}{R}\right). \quad (76)
$$

Equation (76) naturally gives Proposition 3.

B.3 Proof for Corollary 4

Our aim is to derive an explicit form of the inequalities in Propositions 1 and 3. First, we get partial derivatives of the utility function:

$$
\frac{\partial U}{\partial X} = \alpha X^{\alpha-1} J^{\theta} (ER)^{\beta}, \quad (77)
$$

$$
\frac{\partial U}{\partial J} = \theta X^{\alpha} J^{\theta-1} (ER)^{\beta}, \quad (78)
$$

$$
\frac{\partial U}{\partial E} = \beta X^{\alpha} J^{\theta} E^{\beta-1} R^{\beta}, \quad (79)
$$

$$
\frac{\partial U}{\partial R} = \beta X^{\alpha} J^{\theta} E^{\beta} R^{\beta-1}. \quad (80)
$$

The derivative of efficiency price (19) with respect to J is:[43]

$$
p'_R(J) = \frac{\epsilon}{J_0}(J/J_0)^{\epsilon-1} p_R^0. \quad (81)
$$

---

[43] We consider the situation that attribute consumption is above the minimum level to have an impact on efficiency price, i.e. (19). The situation of (20) is the case where attribute consumption does not have an impact on efficiency price. In this case, Levinson's (2019) conclusion applies.

First order conditions under a budget constraint are:

$$\left(\frac{\partial U}{\partial E}\right)/\left(\frac{\partial U}{\partial X}\right) = p_E, \tag{82}$$

$$\left(\frac{\partial U}{\partial R}\right)/\left(\frac{\partial U}{\partial X}\right) = p_R(J), \tag{83}$$

$$\left(\frac{\partial U}{\partial J}\right)/\left(\frac{\partial U}{\partial X}\right) = p_J + p'_R(J)R. \tag{84}$$

Substituting partial derivatives of the utility function into first order conditions (82), (83) and (84), and rearranging gives:

$$X = \frac{\alpha p_E E}{\beta}, \tag{85}$$

$$R = \frac{p_E E}{p_R(J)}, \tag{86}$$

$$J = \frac{\theta p_E E}{\beta(p_J + p'_R R)}. \tag{87}$$

Substituting (19), (81) and (86) into (87) and rearranging gives:

$$J(\beta p_J J + (\epsilon\beta - \theta)p_E E) = 0. \tag{88}$$

As J should not be zero, (88) implies:

$$J = \frac{(\theta - \epsilon\beta)p_E E}{\beta p_J}. \tag{89}$$

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

$$\theta - \epsilon\beta > 0. \tag{90}$$

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, (90) 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 (19) and (20) also ensures that this situation would not take place as it sets a minimum level for the attribute to have an impact on efficiency price.

Substituting (85), (86) and (89) into the budget constraint (4) gives:

$$Y = (2 + \frac{\alpha}{\beta} + \frac{(\theta - \epsilon\beta)}{\beta p_J})p_E E. \tag{91}$$

(91) 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 $\frac{\partial E/E}{\partial Y/Y}$ 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 be progressive.

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

According to (91) and (89), we define linear relationships between E, J and Y as:

$$E = k_2 Y, \tag{92}$$

$$J = k_1 k_2 Y, \tag{93}$$

$$J = k_1 E, k_1 = \frac{(\theta - \epsilon\beta)p_E}{\beta p_J}, \tag{94}$$

$$\frac{1}{k_2} = (2 + \frac{\alpha}{\beta} + \frac{(\theta - \epsilon\beta)}{\beta p_J})p_E. \tag{95}$$

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

Substituting (93) into (19), and then differentiating it with respect to Y, we obtain the relation between $p_R(J)$ and Y:[44]

$$p_R(J) = (k_1 k_2 Y/J_0)^{\epsilon} p_R^0, \tag{96}$$

$$\frac{\partial p_R(J)}{\partial Y} = \frac{\epsilon k_1 k_2}{J_0}(k_1 k_2 Y/J_0)^{\epsilon-1} p_R^0. \tag{97}$$

Using (96) and (97), we get the income elasticity of efficiency price:

$$\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y} = \epsilon. \tag{98}$$

Equation (98) looks surprisingly simple. It can be better understood by the equation:

$$\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y} = \frac{\partial p_R(J)/p_R(J)}{\partial J/J}\frac{\partial J/J}{\partial Y/Y}. \tag{99}$$

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 (93), the value of $\frac{\partial p_R(J)/p_R(J)}{\partial Y/Y}$ 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 (19).

Substituting (86), (96), (97) into Inequality (8) of Proposition 1, and using the knowledge that $\partial E/\partial Y$ is equal to k_2 according to (92), we could obtain (22).

For Proposition 3, we substitute (98) into Inequality (16), use the knowledge that income elasticity of energy consumption is equal to one, and obtain (23).

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[44] We consider the situation that attribute consumption is above the minimum level to have an impact on efficiency price, i.e., (19). The situation of (20) is the case where attribute consumption does not have an impact on efficiency price. In this case, Levinson's (2019) conclusion applies.

B.4 Proof for Proposition 5

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:

$$RI = \frac{\tau_R(R_0 - R_a)}{Y_a} - \frac{\tau_R(R_0 - R_b)}{Y_b}. \tag{100}$$

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

Substituting (92) and (96) into (6) gives:

$$R = \frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon} Y^{1-\epsilon}. \tag{101}$$

Substituting (101) into (100) and rearranging, we get:

$$\frac{RI}{\tau_R} = (\frac{R_0}{Y_a} - \frac{R_0}{Y_b}) - (\frac{k_2 p_E}{p_R^0 (k_1 k_2/J_0)^\epsilon} \frac{1}{Y_a^\epsilon} - \frac{k_2 p_E}{p_R^0 (k_1 k_2/J_0)^\epsilon} \frac{1}{Y_b^\epsilon}). \tag{102}$$

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

$$(\frac{R_0}{Y_1} - \frac{R_0}{Y_2}) - (\frac{k_2 p_E}{p_R^0 (k_1 k_2/J_0)^\epsilon} \frac{1}{Y_1^\epsilon} - \frac{k_2 p_E}{p_R^0 (k_1 k_2/J_0)^\epsilon} \frac{1}{Y_2^\epsilon}) > 0. \tag{103}$$

We define:

$$x = \frac{1}{Y}, \tag{104}$$

$$y = x^\epsilon = \frac{1}{Y^\epsilon}, \tag{105}$$

$$k_3 = \frac{k_2 p_E}{p_R^0 (k_1 k_2 / J_0)^\epsilon}. \tag{106}$$

Equations (103) and (101) can be rewritten as:

$$R_0(x_a - x_b) - k_3(y_a - y_b) > 0, \tag{107}$$

$$R = k_3 Y^{1-\epsilon}. \tag{108}$$

Rearranging (107) gives:

$$\frac{y_a - y_b}{x_a - x_b} > \frac{R_0}{k_3}. \tag{109}$$

To obtain Equation (109), we exploit the fact that Y_a is greater than Y_b. Therefore, x_a is smaller than x_b.

Using Equation (108), we can get:

$$k_3 = \frac{R_0}{Y_0^{1-\epsilon}}. \tag{110}$$

Substituting (110), (105) and (106) into (109) gives:

$$\frac{y_a - y_b}{x_a - x_b} > \frac{y_0}{x_0}. \tag{111}$$

For household a to experience a greater impact than household b, Inequality (111) must be met.

Proposition 5 follows from a "geometric" argument on Inequality (111). It can be interpreted from geometry that the left hand side of Inequality (111) 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 (111) 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 5. 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. According to (105), 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 (26) and (28) are satisfied, it can be shown by using the properties of convex functions that Inequality (111) is met.[45] 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 (30) is satisfied, it can be certain that Inequality (111) 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 household a and b is ambiguous when their income satisfies the condition (31). 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 5 is proved.

B.5 Parameters for plotting Figure 1

For the top graph in Figure 1, the parameters in Equation (32) 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 (32). It does not reflect any economies or sectors.

For the bottom graph, all parameters are the same with the parameters used in the top graph, except that ϵ is set to 0.9.

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[45] Here we use the relation (105), i.e., $x = Y^{-1}$.

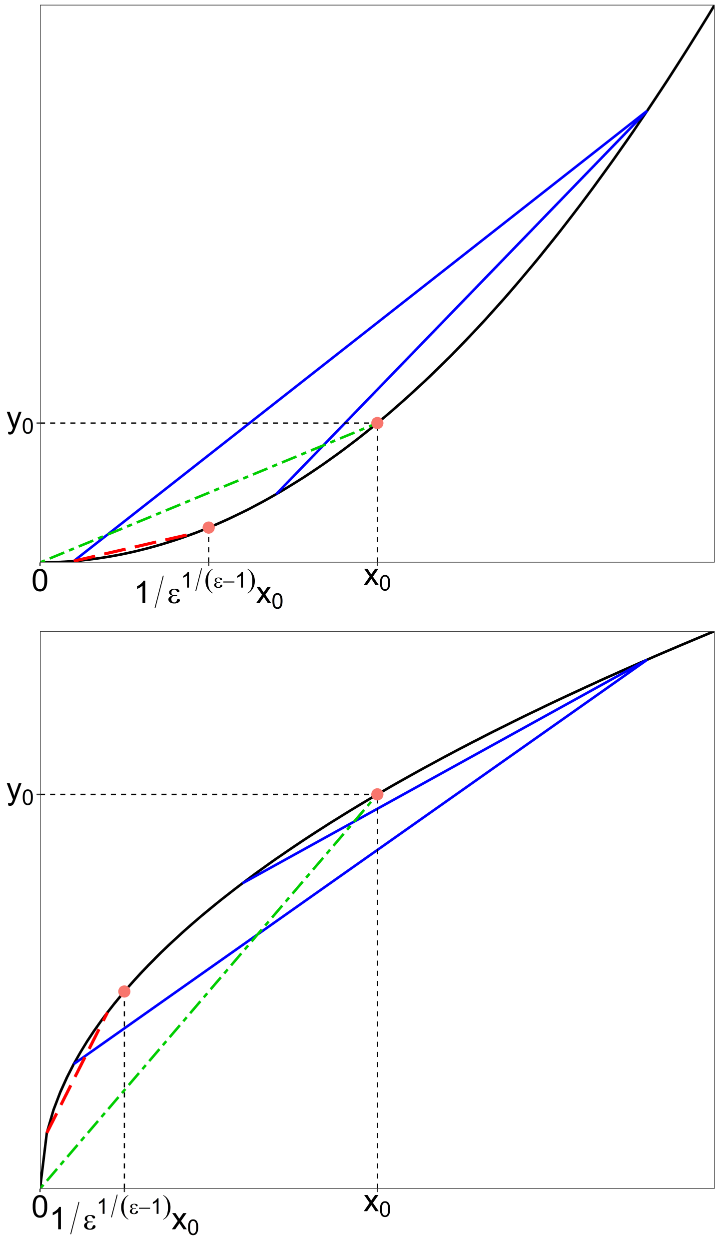

Figure 4: **A representative illustration of function $y = x^{\epsilon}$ when $\epsilon > 1$ (top) and $\epsilon < 1$ (bottom).** The green lines represent y_0/x_0. The blue lines represent $\frac{y_a - y_b}{x_a - x_b}$ when the conditions (26) and (28) are met. The red lines represent $\frac{y_a - y_b}{x_a - x_b}$ when (30) 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.

C Proofs for Section 3

C.1 Proof for the effect of the luxury component

Equation (42) 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 (42) as:

$$S_{2,i} = \frac{\beta}{p_2}(\phi_i \omega(1-\tau_w) - S_1^0 p_1 + S_2^0 p_2) - S_2^0. \tag{112}$$

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

$$\phi_i \geq \frac{S_2^0 p_2 + \beta S_1^0 p_1 - \beta S_2^0 p_2}{\beta \omega (1-\tau_w)} \tag{113}$$

Therefore, for households have earning abilities lower than what the condition (113) requires, they consume no S_2, i.e., the luxury good.

C.2 Proofs for Lemmas 6 and 7

Proof for Lemma 6

We first prove part (a) of Proposition 6. Relative to (45), (46) 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 $\left(\frac{U_i}{U_j}\right)^{\text{AS}} > \left(\frac{U_i}{U_j}\right)^{\text{BR}}$ for $\phi_j > \phi_i$. It implies that the introduction of an intensity standard narrows the relative utility difference between richer and poorer households. $\left(\frac{U_i}{U_j}\right)^{\text{BR}}$ must be smaller than 1 since $\phi_j > \phi_i$. The proof of Proposition 6 is completed by using the below relation:

$$\text{If } \frac{a}{b} < 1, \text{ then } \frac{a}{b} < \frac{a+c}{b+c} \text{ for } c > 0 \text{ and } \frac{a}{b} > \frac{a+c}{b+c} \text{ for } c < 0. \tag{114}$$

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 (114). It has been shown that the second fraction at the right hand side of (45) is smaller than one, i.e. the condition $\frac{a}{b} < 1$ is met. Therefore, Proposition 6 is proved.

Part (b) of Proposition 6 can be proved with a similar process.

Proof for Lemma 7

Klenert and Mattauch (2016) contains a proof for the tax with lump-sum rebates in Proposition 7, 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 (36) 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 7 can be proved by using the relation (114). Relative to (45), Equation (48) 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 (114), 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 7 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 $S_2^0\tau_e e_2 - S_1^0\tau_e e_1 > 0$.

C.3 Proofs for Propositions 8 and 9

Again, we use the relation (114) to prove Propositions 8 and 9. For Proposition 8, 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 (114), it suffices to prove:

$$-S_1^0\tau_r(e_1 - e_0) + S_2^0\tau_r(e_2 - e_0) + S_1^0\tau_e e_1 - S_2^0\tau_e e_2 > 0. \tag{115}$$

Dividing (115) by $S_2^0\tau_r e_2$ and Rearranging, we obtain:

$$\frac{S_1^0}{S_2^0}\Big(\frac{e_1}{e_2}(\frac{\tau_e}{\tau_r} - 1) + \frac{e_0}{e_2}\Big) + \Big(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\Big) > 0. \tag{116}$$

As it is assumed in Proposition 8 that $e_1 > e_0 > e_2$, we could know that the second bracketed term of (116) is surely negative. For (116) to be positive, the first bracketed term must at least be positive. This gives the necessary condition in Proposition 8. On the condition that it has been met, we can rearrange (116) to get the sufficient condition in Proposition 8.

Similarly, for Proposition 9, it suffices to prove:

$$\frac{S_1^0}{S_2^0}\Big(\frac{e_1}{e_2}(\frac{\tau_e}{\tau_r} - 1) + \frac{e_0}{e_2}\Big) + \Big(1 - \frac{\tau_e}{\tau_r} - \frac{e_0}{e_2}\Big) < 0. \tag{117}$$

As Proposition 9 assumes $e_1 < e_0 < e_2$, the first bracketed term in (117) is surely bigger than zero. Therefore, the second bracketed term must at least be negative for (117) to work. This gives the necessary condition in Proposition 9. If the necessary condition is satisfied, rearranging (117) gives the sufficient condition.

D A numerical case of the British transport sector

In this section, we illustrate the theoretical results with 2017-2018 British household expenditure data, provided by the UK Office for National Statistics (2019b).[46] We choose household consumption of international flights as the luxury good and the use of buses and coaches as the subsistence good. Since UK households rarely use domestic flights, international flights can be regarded as UK households' aviation consumption. The two chosen transport services are frequently referenced examples of luxury and subsistence goods. Decreasing aviation emissions is eventually vital for meeting nations' net-zero targets. Decarbonisation of and substitution to public transport are important steps for emissions reduction in the transport sector. Households are grouped into quintiles according to their equalised disposable income.[47] Table 5 gives a summary of the data.

Equalised disposable income group	1st quintile	2nd quintile	3rd quintile	4th quintile	5th quintile	All households
Average weekly expenditure (£)	302.1	413.2	541.9	664.4	957.4	575.7
Weekly expenditure in international airfares (£)	2.45	3.50	4.95	7.60	14.05	6.50
Expenditure share in international airfares (%)	0.81%	0.85%	0.91%	1.14%	1.47%	1.13%
Weekly expenditure in bus and coach fares (£)	1.55	1.55	1.55	1.65	1.35	1.5
Expenditure share in bus and coach fares (%)	0.51%	0.38%	0.29%	0.25%	0.14%	0.26%

Table 5: **UK household weekly expenditure data from April 2017 to March 2018.** The original data are obtained from the UK Office for National Statistics (2019a,b). All number are rounded.

For emissions intensities, we use the data from the UK Department for Transport (2018). We first obtain the total carbon emissions from international aviation and buses and coaches. Then we divide the total emissions by total household expenditure (before environmental regulations) in each sector to get emissions intensities, i.e. tonnes of carbon dioxide emissions per thousand pounds spent (tCO2/k£). The results are 3.96 tCO2/k£

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[46] The expenditure data cover the financial year from April 2017 to March 2018. For the expenditure on international airfares, we use the average from 2016 to 2018 as provided by the UK Office for National Statistics (2019a). We consider it as a reasonable estimate of the flight expenditure in 2018 as the household expenditure on transport does not change much over the period.

[47] The equalised disposable income is the total income of a household, after taxes and deductions, normalised by the number of household members. The normalisation is completed according to the OECD-modified equivalence scale as used in the UK expenditure data. This equalisation process tends to reduce the income gap between wealthier and poorer families since richer households tend to have more family members.

for aviation and 1.48 tCO2/k£ for buses and coaches.[48] A caveat is that the aviation emissions consider inland deliveries of aviation fuels to UK and foreign airlines. UK households are not responsible for all these emissions as some are produced by foreign tourists and international transits. But British citizens similarly use flights in foreign countries. We therefore use the aviation emissions resulted by fuels delivered in the UK as a proxy of the emissions caused by British households. From the regulatory perspective, it would be ideal for all countries to implement mitigation policies, and this resolves the issue of carbon leakage. But even if only the UK puts regulations in place, British consumers will bear some burden despite that the significance would be different from what is estimated here.

For parameterisation, we define the earning abilities ϕ_i of the five household groups by the normalised average expenditure of each income group. The normalised earning abilities from low to high are 0.105, 0.144, 0.188, 0.231 and 0.333. We use the shares that the top income group spends on goods as the share parameters in the utility function. In a Stone-Geary utility function, spending shares are closer to the share parameters as households become richer. Share parameters of goods θ, α and β are therefore set to 0.9861, 0.0026 and 0.0113. We set the leisure share at 0.1. S_1^0 and S_2^0 is set to 0.8 and 1 such that the expenditure shares for the luxury and subsistence goods are retained at the lowest income group.[49] Initial prices of all goods are set to 1, i.e. prices before environmental regulations. This design can be interpreted as that we define the units of goods as the amount we can purchase by one unit of currency before regulations. We normalise the wage w to 4300 to preserve the scale among prices, incomes and consumptions.[50] We set the income tax rate at 25%, i.e. roughly the average income tax rate in the UK. Finally, we set the emissions intensities as suggested above, i.e. 3.96 for aviation (the luxury good) and 1.48 for buses and coaches (the subsistence good).

We model four regulations with about the same amount of emissions reduction relative to a no-regulation scenario, i.e. each achieving approximately a 17.3% 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, and (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 each household's earning 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 is set to 0.05 and 2.88 respectively to enable the equivalent emissions reduction.[51] The implicit tax τ_r caused by the standard is determined endogenously as 0.26, which supports the observation made in Section 3.2, i.e. τ_r tends to be many times larger than τ_e. In this case, it is more than five times. Programming language *R* is used to simulate the model and R package *DEoptimR* is used for optimisation.

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[48] Alternatively, one can use emissions per passenger-mile as the intensity measure if household mileage data are available.

[49] We do this by an iterative simulation process.

[50] We use households' weekly expenditure data as our reference for parameterisation. The initial calibrated simulation outcome approximates UK households' weekly expenditure on goods.

[51] The emissions tax is equivalent to a £50 tax on per tonne of carbon dioxide emissions. This is because we scale up emissions intensities by one thousand to make the numbers more tractable.

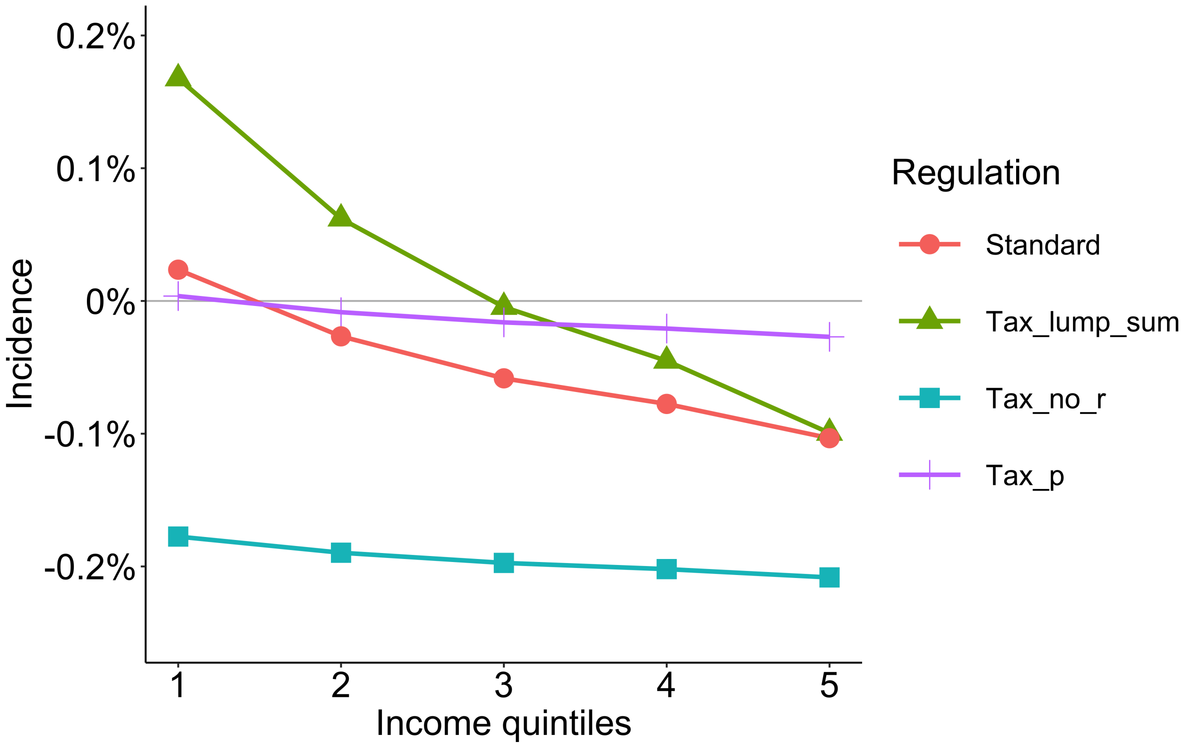

Figure 5: **Comparison of the incidence of an intensity standard (*Standard*), a carbon tax with lump-sum redistribution (*Tax_lump_sum*), a carbon tax with no redistribution (*Tax_no_r*), and a carbon tax with proportionate rebates according to households' productivity (*Tax_p*).** Parameters are calibrated to the sectors of aviation and buses and coaches in the UK. Positive values indicate utility gains and negative values indicate utility losses for each quintile. Incidence is expressed as the percentage of utility changes.

A practical concern here is what the design of an intensity standard could be if it is applied to aviation and buses and coaches. The standard would mean that companies in both sectors need to comply with the unifying standard, and companies may trade with others if they fail to comply by themselves. Alternatively, as shown in Footnotes 12 and 28, the standard could be a tradable performance standard similar to an emissions trading scheme. But the standard allocates emissions quotas based on output instead of a predetermined cap. Finally, using taxes and subsidies can also approximate the effect of a tradable standard as proved in Appendix A (also see Gillingham (2013) and Durrmeyer and Samano (2018)). For example, in some European countries such as France, "feebates" are designed to tax low-efficiency vehicles and subsidise high-efficiency vehicles. Countries can also tax private transport and aviation, and use the revenue to subsidise public transport.

Results are given in Figure 5. It indicates that carbon taxes with no redistribution and proportionate returns are slightly progressive, and the carbon tax with lump-sum rebates and the intensity standard are sharply progressive. The simulation can be used to illustrates Propositions 6, 7 and 9. Since $e_1 < e_2$, the efficiency standard should be progressive according to Proposition 6. The carbon tax with no redistribution is progressive as $S_1^0 e_1 < S_2^0 e_2$. Proposition 9 is supported by the observation that the efficiency standard is more progressive than carbon taxes with no redistribution and proportionate rebates. The result also supports the argument made in Section 3.2, i.e. proportionate rebates tend to extenuate the impact of taxes but do not change the regressivity or progressivity. Finally, Figure 5 shows that the carbon tax with lump-sum rebates creates larger utility gains to low-income households and smaller utility losses to high-income households compared to the intensity standard, suggesting that the cost-effectiveness of carbon taxes, if implemented properly, is higher than that of intensity standards.