The Limits of One-Dimensional Regulation

Wilfried Youmbi Fotso *

Abstract

Standard externality regulation often assumes one-dimensional choice, but firms and consumers adjust along multiple endogenous margins—quantity, quality, technology, and intensity. This paper develops a unified framework in which externalities depend jointly on these margins and shows that inefficiency arises along all relevant dimensions. The central result is an impossibility characterization: policy instruments defined on a single margin—output taxes, quantity standards, intensity regulations, or attribute-specific taxes—can correct at most one distortion and generically fail to implement the socially optimal allocation, inducing substitution along unregulated dimensions. These failures persist under price-taking behavior, oligopolistic competition, and multi-agent settings with aggregate external effects. By contrast, pricing the externality index itself internalizes marginal damages across all endogenous margins, eliminating the externality wedge even under strategic interaction (though market-power distortions may remain). The framework applies symmetrically to production and consumption externalities, negative and positive external effects, and provides a general principle: effective regulation must target the source of the externality rather than rely on single-margin proxies. The analysis explains why many widely used second-best policies systematically underperform and clarifies conditions under which emissions pricing and border carbon adjustments offer structural advantages in climate and environmental policy design.

Keywords: Externalities; Regulation; Endogenous Attributes; Pigouvian Pricing; Policy Design; Multidimensional Choice; Border Carbon Adjustments.
JEL Classification: D62; H23; Q52; Q58; L15

*Department of Economics, Wilfrid Laurier University, E-mail: wyoumbifotso@wlu.ca.

1 Introduction

A central insight of microeconomic theory is that markets often fail to internalize external effects, leading to inefficient outcomes. Since Pigou (1920), this insight has motivated corrective policies such as taxes, subsidies, and standards designed to align private incentives with social costs or benefits. Subsequent work formalized these ideas within public finance and general equilibrium frameworks, emphasizing marginal social damages and benefits as the basis for optimal policy design (Baumol, 1972; Sandmo, 1975). The canonical framework underlying these prescriptions typically treats goods as one-dimensional: firms choose quantities, external damages depend on output or emissions, and regulation operates along a single margin. This perspective remains central in textbook treatments and applied policy analysis in environmental and public economics (Weitzman, 1974; Fullerton, 1998; Stern, 2008).

In practice, however, economic agents respond to regulation along multiple dimensions. Firms adjust not only output but also product quality, design, and technology, while consumers adjust both quantities and consumption attributes. A growing empirical literature documents such multidimensional responses. Early evidence is provided by Peltzman (1975), who shows that automobile safety regulation altered vehicle design and driver behavior in unintended ways. More recent studies demonstrate that fuel economy and emissions standards induce substitution across vehicle attributes, including size, weight, and engine power, partially offsetting intended environmental benefits (Jacobsen, 2013; Ito and Sallee, 2018; Onat et al., 2023). Similarly, sugar-sweetened beverage taxes lead to product reformulation, reducing sugar content but sometimes increasing total consumption or inducing substitution toward untaxed products (Andreyeva et al., 2022). Related work shows that firms may respond to environmental regulation through quality upgrading, product redesign, or technological change rather than pure reductions in output or emissions (Greenstone and Hanna, 2014; Dechezleprêtre et al., 2017). These findings suggest that policy evaluations focusing exclusively on output or emissions may substantially mismeasure welfare effects by neglecting adjustment along unregulated margins.

This paper argues that such outcomes are not anomalies tied to specific industries or policies, but rather a general implication of regulating multidimensional choices with one-dimensional instruments. We develop a unified welfare framework in which

agents choose both quantity and a vector of endogenous attributes, and external effects depend jointly on these choices. On the production side, firms choose output and product attributes that affect demand, costs, and emissions. On the consumption side, consumers choose quantities and attributes such as intensity, quality, or content that jointly determine the magnitude of consumption externalities. In both settings, inefficiency arises along all relevant choice margins whenever external effects depend on endogenous attributes.

A key contribution of the paper is to show that these results are not an artifact of representative-agent modeling. I extend the analysis to environments with multiple firms and multiple consumers whose individual decisions jointly determine aggregate external damages. Even in the presence of strategic interaction through market power on the production side or aggregate consumption externalities on the demand side, one dimensional policy instruments continue to leave at least one distortion uncorrected.

The central theoretical result is an impossibility characterization. Policy instruments defined on a single margin, such as output taxes, quantity standards, intensity regulations, or attribute-only taxes, can correct at most one distortion and generically fail to implement the socially optimal allocation when the externality depends on multiple endogenous margins. Such policies induce substitution along unregulated dimensions, leaving at least one externality wedge unaddressed. By contrast, pricing the externality index directly targets the source of the externality and internalizes social costs or benefits across all endogenous margins. Under price-taking behavior, a Pigouvian externality price implements the first-best allocation; under oligopolistic competition or strategic interaction among consumers, it continues to eliminate the externality wedge while leaving market power distortions intact.

The analysis applies symmetrically to negative and positive externalities and clarifies the limits of commonly used second-best instruments in environmental and public health contexts, including policies targeting emissions, energy use, alcohol content, sugar consumption, or plastic waste. Overall, the paper delivers a clear policy principle: when externalities depend on endogenous attributes, effective regulation must target the source of the externality rather than rely on one-dimensional proxies.

This paper relates to three strands of economic research. First, it builds on the classical literature on externalities and Pigouvian taxation, beginning with Pigou (1920) and formalized in Baumol (1972) and Sandmo (1975). In these models, exter-

nal damages are typically one-dimensional and depend on output or emissions alone. Subsequent work on instrument choice and environmental policy design, including Weitzman (1974), Fullerton and Metcalf (2001), and Goulder and Schein (2013), has largely maintained this one-dimensional perspective, abstracting from endogenous adjustment in quality or other attributes. Fullerton and Metcalf (2001) and Fullerton (2001) explore interactions between environmental taxes and pre-existing distortions (e.g., labor taxes) in general equilibrium, and Fullerton (2001) compares multiple policy instruments (taxes, quotas, subsidies) in a framework with pollution related inputs; however, these analyses do not derive general impossibility results for one-dimensional instruments when firms or consumers adjust simultaneously along multiple endogenous margins.

Second, the paper relates to the industrial organization literature on endogenous quality choice, including Spence (1975), Mussa and Rosen (1978), and Shaked and Sutton (1982), as surveyed in Tirole (1988). While these models study firms' incentives to choose product attributes jointly with output or prices, they do not incorporate externalities or derive efficiency implications for regulatory instruments across multiple margins.

Third, the analysis complements a smaller literature linking environmental regulation to product differentiation and quality choice, including Arora and Gangopadhyay (1995), work by Cremer and Gahvari on tax competition and environmental quality, and Conrad (2005). These contributions provide important insights into quality upgrading or input substitution under specific regulatory designs, but they are typically context-specific (e.g., transboundary pollution or locational choice) and do not deliver general impossibility theorems or necessity results for source based pricing in multidimensional settings.

The core intuition that one-dimensional policies induce substitution or leakage when agents adjust along unregulated margins is well documented in the empirical literature cited above (Peltzman on safety offsets; Jacobsen and Ito and Sallee on fuel-economy standards; Andreyeva et al. on sugary-drink reformulation). The main contribution of this paper is to provide a unified theoretical foundation for these patterns by establishing general impossibility results: policy instruments defined on a single margin (output/quantity or attribute only) can correct at most one distortion and generically fail to implement the socially optimal allocation whenever the

externality depends on multiple endogenous margins. These failures hold under price-taking behavior, oligopolistic competition, and multi-agent aggregate externalities on both the production and consumption sides. In contrast to partial-equilibrium or case-specific analyses in the literature, the paper derives a minimal sufficient statistic corollary showing that any successful one-dimensional instrument must locally be a monotone transformation of the externality index itself, providing a precise rationale for why emissions (or equivalent source-based) pricing emerges as structurally superior.

By integrating these strands, the paper explains why many commonly used second-best instruments perform poorly once endogenous attribute adjustment and aggregate external effects are taken seriously, and offers a general policy principle: when externalities depend on endogenous attributes, effective regulation must target the source of the externality rather than rely on one-dimensional proxies.

The remainder of the paper is structured as follows. Section 2 presents the model and develops intuition. Section 3 extends the framework to multidimensional externalities. Section 4 studies multiple firms and strategic interaction. Section 5 presents the impossibility results, and Section 6 concludes.

2 Production Externalities

In many production environments, external damages depend not only on output levels but also on endogenous technological or product attributes chosen by firms. When firms can adjust these attributes in response to regulation, policy instruments defined on a single margin generally fail to internalize the full external cost of production. This section develops a benchmark analysis that isolates this mechanism and serves as the foundation for the strategic extensions studied later.

2.1 Setup

Demand is generated by a representative consumer with quasi-linear preferences. Inverse demand is

$$p = P(Q, \bar{s}), \tag{1}$$

where Q denotes aggregate output and $\bar{s}$ is an aggregate attribute index. In the single-firm benchmark analyzed here, $Q = q$ and $\bar{s} = s$. The function P is continuously differentiable with $P_Q < 0$ and $P_{\bar{s}} > 0$.

Gross consumer surplus is

$$B(q, s) = \int_0^q P(z, s)\, dz. \tag{2}$$

A representative firm chooses output $q \geq 0$ and attribute $s \in \mathbb{R}$ at cost

$$C(q, s), \tag{3}$$

with $C_q > 0$ and $C_s > 0$. The cross-partial C_{qs} is unrestricted.

Production generates an externality index

$$e = e(q, s), \tag{4}$$

with $e_q > 0$ and e_s unrestricted. External damages (or benefits) are given by

$$\Phi(e), \qquad \Phi'(e) \neq 0, \tag{5}$$

allowing for both negative and positive externalities.

2.2 Unregulated equilibrium

Absent regulation, the firm maximizes profits

$$\pi(q, s) = P(q, s)\, q - C(q, s). \tag{6}$$

Assuming an interior solution, the first-order conditions are

$$P(q, s) + qP_q(q, s) = C_q(q, s), \tag{7}$$

$$\int_0^q P_s(z, s)\, dz = C_s(q, s). \tag{8}$$

The firm trades off marginal revenue and marginal cost in quantity, and balances the marginal revenue effect of improving the attribute against its marginal private cost.

2.3 Socially optimal allocation

A utilitarian planner internalizes the externality and chooses (q, s) to maximize total surplus

$$W(q, s) = B(q, s) - C(q, s) - \Phi(e(q, s)). \tag{9}$$

At an interior optimum, the planner's first-order conditions are

$$P(q, s) + qP_q(q, s) = C_q(q, s) + \Phi'(e(q, s))\, e_q(q, s), \tag{10}$$

$$\int_0^q P_s(z, s)\, dz = C_s(q, s) + \Phi'(e(q, s))\, e_s(q, s). \tag{11}$$

Relative to the unregulated equilibrium, the planner internalizes marginal external effects along both endogenous margins.

2.4 Policy instruments

Here I compare standard regulatory instruments.

Output-based taxation. Consider a per-unit output tax τ. The firm solves

$$\max_{q,s}\ P(q, s)\, q - C(q, s) - \tau q,$$

yielding first-order conditions

$$P(q, s) + qP_q(q, s) = C_q(q, s) + \tau, \tag{12}$$

$$\int_0^q P_s(z, s)\, dz = C_s(q, s). \tag{13}$$

The tax affects the quantity margin but leaves the attribute margin unchanged.

Proposition 1 (Limits of output taxation)**.** *If $e_s(q^\star, s^\star) \neq 0$ at the planner's allocation $(q^\star, s^\star)$, no output tax can implement the socially optimal allocation.*

Proof. The output tax alters only the quantity condition (12) and leaves the attribute condition (13) unchanged. The planner's attribute condition (11) cannot be matched unless the externality wedge on s is zero. □

Externality-index pricing (Pigouvian taxation). Consider a tax t on the externality index $e(q, s)$. The firm solves

$$\max_{q,s} \; P(q, s)\, q - C(q, s) - t\, e(q, s),$$

with first-order conditions

$$P(q, s) + qP_q(q, s) = C_q(q, s) + t\, e_q(q, s), \tag{14}$$

$$\int_0^q P_s(z, s)\, dz = C_s(q, s) + t\, e_s(q, s). \tag{15}$$

Corollary 1 (Externality-index pricing)**.** *Setting $t = \Phi'(e(q^\star, s^\star))$ internalizes the externality wedge along both endogenous margins. In the competitive limit, this implements the planner's allocation; under strategic interaction, it eliminates the externality wedge while leaving any market-power distortion intact.*

Proof. With $t = \Phi'(e(q^\star, s^\star))$, the tax-induced wedges in (14)–(15) coincide with the planner's externality terms in (10)–(11). Under price-taking behavior, this fully implements the planner's allocation; with market power, the remaining difference reflects the standard markup distortion. □

This benchmark highlights the central mechanism of the paper: one-dimensional instruments correct at most one margin of distortion when externalities depend on multiple endogenous choices, whereas pricing the externality index directly targets the source of the inefficiency. Section 3 shows that this logic continues to hold under strategic interaction among multiple firms.

3 Multiple Firms and Strategic Interaction

This section extends the benchmark analysis to an oligopolistic environment with endogenous attributes. The objective is to verify that the paper's central insight persists under strategic interaction: when externalities depend on multiple endogenous margins, one-dimensional instruments generally fail, while pricing the externality index targets the externality wedge along all margins, even though market-power distortions may remain.

3.1 Environment

There are N firms indexed by $i = 1, \ldots, N$. Firm i chooses output $q_i \geq 0$ and an attribute $s_i \in \mathbb{R}$. Aggregate output is

$$Q = \sum_{i=1}^{N} q_i, \tag{16}$$

and the aggregate attribute index is

$$\bar{s} = \bar{s}(s_1, \ldots, s_N), \tag{17}$$

where $\bar{s}$ is continuously differentiable. A leading example is $\bar{s} = \sum_i \omega_i s_i$ with $\omega_i \geq 0$ and $\sum_i \omega_i = 1$.

Inverse demand is

$$p = P(Q, \bar{s}), \tag{18}$$

with $P_Q < 0$ and $P_{\bar{s}} > 0$.

Firm i incurs cost $C_i(q_i, s_i)$ and generates emissions

$$e_i = e_i(q_i, s_i), \tag{19}$$

with $e_{iq} > 0$ and e_{is} unrestricted. Aggregate emissions are

$$E = \sum_{i=1}^{N} e_i(q_i, s_i), \tag{20}$$

and external damages are $\Phi(E)$ with $\Phi'(E) \neq 0$.

3.2 Cournot equilibrium under regulation

Firms compete à la Cournot in quantities and choose attributes simultaneously. Given (q_{-i}, s_{-i}), firm i maximizes

$$\pi_i(q_i, s_i) = P(Q, \bar{s})\, q_i - C_i(q_i, s_i) - \mathcal{T}_i, \tag{21}$$

where $\mathcal{T}_i$ denotes policy payments. Under an emissions tax t, $\mathcal{T}_i = t\, e_i(q_i, s_i)$.

Assuming interior solutions, the first-order conditions are

$$P(Q,\bar{s}) + q_i P_Q(Q,\bar{s}) + q_i P_{\bar{s}}(Q,\bar{s})\frac{\partial \bar{s}}{\partial q_i} = C_{iq}(q_i,s_i) + t\, e_{iq}(q_i,s_i), \tag{22}$$

$$q_i P_{\bar{s}}(Q,\bar{s})\frac{\partial \bar{s}}{\partial s_i} = C_{is}(q_i,s_i) + t\, e_{is}(q_i,s_i). \tag{23}$$

If $\bar{s}$ does not depend on q_i, the term $q_i P_{\bar{s}} \partial \bar{s}/\partial q_i$ drops out.

3.3 Planner benchmark

A utilitarian planner chooses $\{(q_i,s_i)\}_{i=1}^N$ to maximize total surplus

$$W = \int_0^Q P(z,\bar{s})\, dz - \sum_{i=1}^N C_i(q_i,s_i) - \Phi(E). \tag{24}$$

At an interior optimum, the planner's first-order conditions are

$$P(Q,\bar{s}) + \left(\int_0^Q P_{\bar{s}}(z,\bar{s})\, dz\right)\frac{\partial \bar{s}}{\partial q_i} = C_{iq}(q_i,s_i) + \Phi'(E)\, e_{iq}(q_i,s_i), \tag{25}$$

$$\left(\int_0^Q P_{\bar{s}}(z,\bar{s})\, dz\right)\frac{\partial \bar{s}}{\partial s_i} = C_{is}(q_i,s_i) + \Phi'(E)\, e_{is}(q_i,s_i). \tag{26}$$

Relative to the Cournot equilibrium, the planner internalizes both the demand effects of aggregate attributes and the marginal external damages associated with each firm's choices.

The next proposition presents the externality-index pricing in oligopoly.

Proposition 2 (Externality-index pricing in oligopoly)**.** *Under an emissions tax $t = \Phi'(E)$, the marginal externality wedges in each firm's first-order conditions* (22)–(23) *coincide with the planner's externality terms in* (25)–(26)*. Consequently, externality-index pricing internalizes marginal external damages along both the quantity and attribute margins for every firm.*

By contrast, any policy instrument that conditions only on output (e.g. a per-unit tax τq_i) cannot generally eliminate the externality wedge in the attribute condition whenever $e_{is}(q_i^\star, s_i^\star) \neq 0$.

Externality-index pricing therefore targets the source of the externality even under strategic interaction, while leaving market-power distortions intact. One-dimensional output-based instruments continue to fail whenever emissions depend on endogenous attributes.

4 Consumption Externalities

Many economically important externalities—such as those associated with sugar intake, alcohol consumption, energy use, plastic waste, or driving—depend not only on how much is consumed, but also on endogenous attributes of consumption. This section shows that the logic undermining one-dimensional regulation on the production side applies symmetrically to consumers.

4.1 Setup

A representative consumer chooses consumption quantity $q \geq 0$ and an attribute $s \in \mathbb{R}$ (e.g., sugar concentration, alcohol content, or energy intensity). Utility is

$$U(q, s) - pq - K(s), \tag{27}$$

where $U(q, s)$ is increasing and concave in q, $p > 0$ is an exogenous price, and $K(s)$ is the private cost of choosing attribute s.

Consumption generates an externality index

$$e = e(q, s), \tag{28}$$

with external damages $\Phi(e)$, where $\Phi'(e) \neq 0$.

4.2 Unregulated consumer choice

Absent regulation, the consumer maximizes utility. Assuming an interior solution, the first-order conditions are

$$U_q(q, s) = p, \tag{29}$$
$$U_s(q, s) = K'(s). \tag{30}$$

The consumer equates marginal private benefits and costs, ignoring the external effects of consumption.

4.3 Socially optimal allocation

A social planner internalizes the externality and maximizes social welfare

$$W(q, s) = U(q, s) - pq - K(s) - \Phi(e(q, s)). \tag{31}$$

At an interior optimum, the planner's first-order conditions are

$$U_q(q, s) = p + \Phi'(e(q, s))\, e_q(q, s), \tag{32}$$
$$U_s(q, s) = K'(s) + \Phi'(e(q, s))\, e_s(q, s). \tag{33}$$

Relative to the unregulated outcome, the planner internalizes marginal external effects along both endogenous margins.

4.4 Policy instruments

We now compare standard regulatory approaches.

Quantity-based taxation. A per-unit tax τ on quantity yields

$$U_q(q, s) = p + \tau, \tag{34}$$
$$U_s(q, s) = K'(s). \tag{35}$$

The tax affects the quantity margin but leaves the attribute margin unchanged.

Proposition 3 (Limits of quantity-based taxation)**.** *If $e_s(q^\star, s^\star) \neq 0$ at the planner's allocation $(q^\star, s^\star)$, no quantity-based tax can implement the socially optimal allocation.*

Proof. The quantity tax alters only the condition (34) and leaves (35) unchanged. The planner's attribute condition (33) cannot be matched unless the externality wedge on s is zero. □

Attribute-based taxation. A tax $T(s)$ on the attribute yields

$$U_q(q, s) = p, \tag{36}$$
$$U_s(q, s) = K'(s) + T'(s). \tag{37}$$

The tax affects the attribute margin but leaves the quantity margin unchanged.

Proposition 4 (Limits of attribute-based taxation)**.** *If $e_q(q^\star, s^\star) \neq 0$ at the planner's allocation $(q^\star, s^\star)$, no attribute-based tax can implement the socially optimal allocation.*

Proof. The attribute tax alters only the condition (37) and leaves (36) unchanged. The planner's quantity condition (32) cannot be matched unless the externality wedge on q is zero. □

Externality-index pricing (Pigouvian taxation). A tax t on the externality index yields

$$U_q(q, s) = p + t\, e_q(q, s), \tag{38}$$
$$U_s(q, s) = K'(s) + t\, e_s(q, s). \tag{39}$$

Corollary 2 (Externality-index pricing)**.** *Setting $t = \Phi'(e(q^\star, s^\star))$ implements the planner's allocation.*

Proof. With $t = \Phi'(e(q^\star, s^\star))$, the consumer's conditions (38)–(39) coincide with the planner's conditions (32)–(33). □

As on the production side, one-dimensional instruments correct at most one margin of distortion when the externality depends on multiple endogenous choices. Pricing the externality index directly targets the source of the inefficiency by internalizing marginal external effects along all relevant margins.

5 Multiple Consumers and Strategic Interaction

This section extends the analysis to an environment with multiple consumers whose individual choices jointly determine the externality. The purpose is to verify that the failure of one-dimensional instruments, and the advantage of externality-index pricing, persist under strategic interaction.

5.1 Environment

There are N consumers indexed by $i = 1, \ldots, N$. Consumer i chooses quantity $q_i \geq 0$ and attribute $s_i \in \mathbb{R}$. Individual utility is

$$U(q_i, s_i) - pq_i - K(s_i), \tag{40}$$

where $p > 0$ is exogenous.

Aggregate external damages depend on

$$E = \sum_{i=1}^{N} e(q_i, s_i), \tag{41}$$

with external damage $\Phi(E)$ and $\Phi'(E) \neq 0$. Each consumer treats p and E as given.

5.2 Equilibrium behavior

In a Nash equilibrium, each consumer chooses (q_i, s_i) to satisfy

$$U_{q_i}(q_i, s_i) = p, \tag{42}$$

$$U_{s_i}(q_i, s_i) = K'(s_i). \tag{43}$$

5.3 Planner benchmark

A utilitarian planner chooses $\{(q_i, s_i)\}_{i=1}^N$ to maximize

$$W = \sum_{i=1}^{N} \Big[U(q_i, s_i) - pq_i - K(s_i)\Big] - \Phi(E). \tag{44}$$

At an interior optimum, the planner's conditions are

$$U_{q_i}(q_i, s_i) = p + \Phi'(E)\, e_{q_i}(q_i, s_i), \tag{45}$$
$$U_{s_i}(q_i, s_i) = K'(s_i) + \Phi'(E)\, e_{s_i}(q_i, s_i). \tag{46}$$

5.4 Policy instruments

Under a quantity-based tax or an attribute-based tax, only one of the planner's two conditions can generally be matched. By contrast, an externality-index tax t yields

$$U_{q_i}(q_i, s_i) = p + t\, e_{q_i}(q_i, s_i), \tag{47}$$
$$U_{s_i}(q_i, s_i) = K'(s_i) + t\, e_{s_i}(q_i, s_i). \tag{48}$$

Setting $t = \Phi'(E)$ internalizes marginal external damages along both margins for every consumer.

Thus, even under strategic interaction among consumers, one-dimensional instruments leave at least one externality wedge unaddressed whenever the externality depends on multiple endogenous choices, while pricing the externality index directly targets the source of the inefficiency.

Proposition 5 (Efficiency of Externality-Index Pricing under Strategic Interaction)**.** *Consider the multi-consumer environment defined by equations* (40)–(41)*.*

1. *One-Dimensional Failure: Any tax τ levied solely on quantity q_i or solely on attribute s_i fails to implement the social optimum $(q_i^\star, s_i^\star)$ whenever $e_{s_i} \neq 0$ or $e_{q_i} \neq 0$, respectively.*

2. *Index Pricing Success: An externality-index tax t levied on individual contributions $e(q_i, s_i)$ implements the socially optimal allocation for all $i = 1, \ldots, N$ if*

and only if:

$$t = \Phi'\left(\sum_{i=1}^{N} e(q_i^\star, s_i^\star)\right).$$

Proposition 5 demonstrates that the superiority of index pricing is not a byproduct of the representative-agent assumption. In a multi-agent setting, the externality is a collective outcome, yet the inefficiency is driven by *individual* marginal choices. Because each agent's contribution to the aggregate damage $\Phi(E)$ is mediated through their specific emissions function $e(q_i, s_i)$, a uniform tax on the externality index t correctly aligns private incentives with the social marginal damage across all $2N$ endogenous margins.

Remark. *The production and consumption environments analyzed above share a common structure: private agents choose a vector of endogenous variables, while the externality index depends on multiple components of that choice. In both settings—whether with a single decision-maker, many consumers, or strategic interaction among firms—policy instruments defined on a single margin affect at most one first-order condition and therefore leave at least one externality wedge uncorrected whenever the externality responds along multiple dimensions. These examples are not special cases, but instances of a general phenomenon. The next section formalizes this insight by establishing impossibility results showing that, under mild regularity conditions, no one-dimensional policy instrument can generically implement the planner's allocation when the externality index depends on multiple endogenous margins.*

6 Impossibility Results

The results in previous sections show that one-dimensional policy instruments generally fail to implement the planner's allocation when externalities depend on multiple endogenous margins. This section sharpens that insight by establishing general impossibility theorems for both production and consumption externalities. These results show that the failure is structural: no policy defined on a single margin (output/quantity or attribute only) can generically replicate the planner's first-order conditions whenever the externality index depends on both margins.

Assumption 1 (Interior optimum and regularity: production)**.** *The functions P, C, e, and Φ are continuously differentiable. The planner has an interior solution $(q^\star, s^\star)$*

with $q^\star > 0$, $\Phi'(e(q^\star, s^\star)) \neq 0$, *and*

$$\Big(e_q(q^\star, s^\star),\, e_s(q^\star, s^\star)\Big) \neq (0, 0).$$

Assumption 2 (Interior optimum and regularity: consumption)**.** *The functions* U, K, e, *and* Φ *are continuously differentiable. The planner has an interior solution* $(q^\star, s^\star)$ *with* $q^\star > 0$, $\Phi'(e(q^\star, s^\star)) \neq 0$, *and*

$$\Big(e_q(q^\star, s^\star),\, e_s(q^\star, s^\star)\Big) \neq (0, 0).$$

These assumptions ensure an interior first-best allocation exists and rule out knife-edge cases where one-dimensional policies coincidentally work. Differentiability and interiority are standard and allow us to characterize first-order conditions without boundary issues.

6.1 Production-Side Impossibility Results

We begin by establishing impossibility results on the production side. When emissions depend on both output and endogenous attributes, the planner's first-order conditions feature distinct wedges along each margin. The following results show that any policy instrument that conditions on only one of these margins—output or attributes—can at best replicate one wedge and must generically fail to implement the planner's allocation.

Theorem 1 (Impossibility of output-only instruments in production)**.** *Maintain Assumption 1. Consider any policy instrument that affects the firm only through output, i.e., the firm solves*

$$\max_{q,s}\; P(q, s)q - C(q, s) - T(q)$$

for some differentiable function $T(\cdot)$. *If* $e_s(q^\star, s^\star) \neq 0$, *then no choice of* $T(\cdot)$ *can implement the planner's allocation* $(q^\star, s^\star)$.

The next result establishes the symmetric impossibility for attribute-only instruments.

Theorem 2 (Impossibility of attribute-only instruments in production)**.** *Maintain Assumption 1. Consider any policy instrument that affects the firm only through the*

attribute, i.e., the firm solves

$$\max_{q,s} \; P(q,s)q - C(q,s) - S(s)$$

for some differentiable function $S(\cdot)$. If $e_q(q^\star, s^\star) \neq 0$, then no choice of $S(\cdot)$ can implement the planner's allocation $(q^\star, s^\star)$.

Theorems 1 and 2 jointly show that one-dimensional regulation on the production side is generically insufficient when emissions depend on multiple endogenous margins. Output-based instruments leave the attribute externality uncorrected, while attribute-based instruments leave the output externality uncorrected. Unless the externality is degenerate along the unregulated margin, no choice of a scalar policy can replicate the planner's conditions. These results motivate policies that price the externality index itself, which is the only way to internalize marginal damages along all endogenous production margins.

6.2 Consumption-Side Impossibility Results

We now consider the consumption externalities developed in Section 4. Like in the producer side, I will propose an impossibility of quantity-only instruments in consumption and and an impossibility of attribute-only instruments in consumption.

Theorem 3 (Impossibility of quantity-only instruments in consumption)**.** *Maintain Assumption 2. Consider any policy instrument that affects the consumer only through quantity, i.e., the consumer solves*

$$\max_{q,s} \; U(q,s) - pq - K(s) - T(q)$$

for some differentiable function $T(\cdot)$. If $e_s(q^\star, s^\star) \neq 0$, then no choice of $T(\cdot)$ can implement the planner's allocation $(q^\star, s^\star)$.

Theorem 4 (Impossibility of attribute-only instruments in consumption)**.** *Maintain Assumption 2. Consider any policy instrument that affects the consumer only through the attribute, i.e., the consumer solves*

$$\max_{q,s} \; U(q,s) - pq - K(s) - S(s)$$

for some differentiable function $S(\cdot)$. If $e_q(q^\star, s^\star) \neq 0$, then no choice of $S(\cdot)$ can implement the planner's allocation $(q^\star, s^\star)$.

6.3 Minimal Sufficient Statistic Result

The two pairs of impossibility theorems (Theorems 1–2 for production and 3–4 for consumption) establish that one-dimensional instruments defined on either margin alone are generically insufficient. The following corollary sharpens this conclusion.

Corollary 3 (Externality index as a minimal sufficient statistic (local necessity))**.** *Suppose the regulator is restricted to a one-dimensional index policy of the form*

$$\max_{q,s} \ \textit{(firm or consumer objective)} - \tau\Big(I(q,s)\Big),$$

where $I(q,s)$ and $\tau(\cdot)$ are differentiable. Maintain the relevant regularity assumption (Assumption 1 or 2) and suppose such a policy implements the planner's allocation $(q^\star, s^\star)$. Then, locally around the first-best allocation*, the index I must be a strictly monotone transformation of the externality index $e(q,s)$. That is,*

$$\nabla I(q^\star, s^\star) = \alpha \, \nabla e(q^\star, s^\star) \quad \textit{for some } \alpha \neq 0. \tag{49}$$

Non-monotone or discontinuous policies could in principle satisfy the global first-order conditions in knife-edge cases, but such instruments are typically impractical, non-transparent, and ruled out under standard assumptions on regulatory design (e.g., differentiability and monotonicity for incentive compatibility and verifiability).

Among all one-dimensional regulatory instruments, only those that condition on the externality index (up to a monotone transformation) can generically implement the planner's allocation when externalities depend on multiple endogenous margins. This result provides a precise sense in which emissions (or equivalent exposure/content indices) are a minimal sufficient statistic for regulation in multidimensional environments.

Remark (Boundary cases)**.** *The analysis focuses on interior planner optima under standard differentiability and regularity conditions. Boundary cases—such as corner solutions in which output or attributes are constrained, or situations in which*

the externality index is locally flat along one margin—may permit one-dimensional instruments to replicate the planner's allocation. These cases are nongeneric and correspond precisely to environments in which the externality effectively depends on a single endogenous dimension in a neighborhood of the optimum. In such situations, the planner's wedges collapse to a scalar and can be matched by a one-dimensional policy. The impossibility results therefore characterize the generic limitations of one-dimensional regulation and do not rule out isolated boundary implementations in degenerate cases.

Remark (Symmetry for Positive Externalities)**.** *The framework is fully symmetric with respect to the sign of the externality. For positive externalities (e.g., knowledge spillovers from R&D, benefits from vaccination, network effects, or adoption of cleaner technologies), the social planner's first-order conditions feature* positive *marginal wedges:* $\Phi'(e)e_q > 0$ *and* $\Phi'(e)e_s > 0$ *(assuming* $\Phi'(e) > 0$ *to denote marginal social benefit). In unregulated markets, agents therefore under-provide both quantity* q *and the socially valuable attribute* s*, generating inefficiency along multiple margins.*

One-dimensional instruments subsidies tied only to output/quantity or to a specific attribute generically correct at most one of these distortions and fail to implement the first-best allocation whenever the externality index responds along both dimensions (analogous to the impossibility results for taxes in the negative case). By contrast, a Pigouvian subsidy $t = \Phi'(e)$ *on the externality index internalizes marginal social benefits across all endogenous margins, mirroring the role of Pigouvian taxation in the damage case.*

This symmetry underscores the paper's central policy principle: when externalities (positive or negative) depend on endogenous attributes, effective regulation must target the source of the externality directly rather than rely on one-dimensional proxies. The result applies broadly to environmental innovation subsidies, public-health interventions (e.g., vaccination or nutrition programs), and technology-adoption policies.

7 Discussion

The analysis establishes a general limitation of one-dimensional regulation. When externalities depend on multiple endogenous margins, policy instruments defined on

a single margin—such as output or quantity taxes, standards, or attribute-specific regulations—generically fail to implement the socially optimal allocation. The impossibility theorems (Theorems 1 and 4) show that this failure is structural rather than context-specific: no differentiable policy that conditions solely on quantity or solely on attributes can reproduce the planner's first-order conditions whenever the externality index responds along more than one dimension. By contrast, pricing the externality index itself emerges as a minimal sufficient statistic (Corollary 3), internalizing marginal damages across all relevant margins while remaining robust under price-taking behavior, oligopolistic competition, and multi-agent strategic interaction. The result is local in nature it applies in a neighborhood of the first-best allocation under standard differentiability assumptions but non-monotone or discontinuous index policies are typically impractical due to verification constraints, incentive-compatibility concerns, and limited transparency for regulated agents and enforcers.

These results provide a unified theoretical explanation for well documented empirical patterns. Output-based taxes, quantity standards, and intensity regulations frequently induce substitution toward dirtier production processes, heavier vehicles, higher sugar concentrations, or increased total consumption rebound and leakage effects that erode intended environmental or public-health benefits (Jacobsen, 2013; Ito and Sallee, 2018; Onat et al., 2023; Andreyeva et al., 2022). The model clarifies that such responses are not policy failures in an operational sense, but predictable consequences of regulating multidimensional choices with single margin instruments. Importantly, these failures arise even in the absence of close substitutes: they follow from endogenous adjustment along attributes of the regulated good itself (e.g., vehicle weight and power, product reformulation, production-process choice), rather than from substitution across distinct goods.

Carbon taxes and emissions trading systems (ETS) provide prominent real-world applications of the principle developed in this paper. Jurisdictions with sustained carbon pricing such as Sweden (since 1991), British Columbia (since 2008), Switzerland, and Canada's federal backstop have achieved measurable emissions reductions with modest macroeconomic costs, particularly when revenues are recycled transparently through dividends or tax cuts. The framework explains their relative effectiveness: by targeting the externality index (CO_2 emissions) directly, these policies avoid the substitution distortions that plague quantity-based or attribute-specific measures. Nev-

ertheless, much of global climate policy continues to rely on second-best instruments, including sectoral fuel taxes, performance standards, intensity targets, output caps, and technology-specific subsidies policies that the model predicts will leave residual wedges and induce offsetting behavioral responses. Political-economy considerations, such as lobbying by affected industries, distributional concerns, and perceived implementation simplicity, often favor these partial measures despite their theoretical limitations.

A natural objection is that emissions pricing is already well established, potentially limiting the novelty of the analysis. On the contrary, the paper strengthens the case for externality-index pricing by providing a general microfoundation for why it outperforms most alternatives and why many existing policies remain partial or hybrid. Coverage gaps (e.g., exemptions for trade exposed sectors, agriculture, or international aviation), overlapping regulations, and political constraints continue to limit the reach of pure emissions pricing. The impossibility results clarify why these compromises while often politically expedient—generate inefficiencies that broader, more comprehensive pricing schemes could avoid.

The analysis also speaks directly to current debates over border carbon adjustments (BCAs). The European Union's Carbon Border Adjustment Mechanism (CBAM), scheduled to become fully operational in 2026, imposes carbon costs on imports of selected high-emission goods to reduce leakage as free ETS allowances are phased out. While early evidence suggests that CBAM has encouraged decarbonization investments among exporters, its limited sectoral scope creates evasion risks and compliance challenges, particularly for developing countries. The framework predicts that shallow BCAs leave leakage channels open along unregulated margins, whereas deeper coverage, broader sectoral scope, and harmonized embedded-emissions measurement would more closely approximate the first-best principle of uniform carbon pricing. Similar proposals in the United States and Canada indicate that the design of BCAs will remain a central policy issue.

Several extensions merit future research. The static framework abstracts from dynamics, stock pollutants, and endogenous technological change; incorporating these features could shed light on interactions between pricing and innovation incentives. Political-economy determinants of instrument choice why second-best policies persist despite their inefficiency also warrant further study. Finally, relaxing assumptions of

perfect information and enforcement could illuminate the role of monitoring costs, asymmetric information, and strategic evasion in regulatory design.

Overall, the paper delivers a clear and general policy principle: when externalities depend on endogenous attributes, effective regulation must target the source of the externality rather than rely on one-dimensional proxies. This insight reconciles empirical evidence of unintended behavioral responses with standard economic theory and provides guidance for improving climate, environmental, and public-health policy. More broadly, the framework offers a foundation for evaluating regulatory effectiveness in any setting where agents adjust along hidden or multidimensional margins, from environmental policy to public health, digital markets, and financial regulation.

8 Conclusion

This paper develops a general framework for regulation in environments where externalities depend on multidimensional choices. Firms and consumers adjust along multiple endogenous margins quantity and attributes while external damages depend jointly on these decisions. The central contribution is a set of impossibility and necessity results: policy instruments defined on a single margin, such as output or quantity taxes, attribute-specific taxes, or standards, generically fail to implement the socially optimal allocation whenever the externality index responds along more than one dimension. By contrast, pricing the externality index itself internalizes marginal damages across all endogenous margins and emerges as a minimal sufficient statistic for efficient regulation, even in the presence of strategic interaction among firms or consumers.

The results apply symmetrically to production and consumption externalities, negative and positive external effects, and settings with price-taking behavior, oligopolistic competition, and multi-agent aggregate damages. They provide a structural explanation for why many widely used second-best policies induce substitution along unregulated dimensions, generate rebound or leakage effects, and achieve only partial internalization. More broadly, they clarify why instruments that directly target the source of the externality such as emissions pricing or equivalent source-based policies—systematically outperform one-dimensional alternatives when properly de-

signed.

The policy implication is simple but general. When externalities depend on endogenous attributes, effective regulation must target the source of the externality rather than rely on proxies defined on single margins. While political and administrative constraints often favor partial or hybrid measures, the theoretical limits identified here highlight the efficiency gains from moving closer to source-based pricing and from broadening the scope of such instruments where feasible.

Several extensions remain open. Incorporating dynamics, stock pollutants, or endogenous technological change could illuminate interactions between pricing and innovation incentives. Political-economy forces shaping instrument choice, as well as enforcement and information constraints, also warrant further study. By providing a rigorous foundation for understanding the structural advantages of externality-index pricing, this paper contributes to the positive and normative analysis of regulatory design in environmental and public economics, and more broadly to settings in which agents adjust along hidden or multidimensional margins.

9 Appendix

Proof of Proposition 2

Proof. Under an emissions tax $\mathcal{T}_i = t\, e_i(q_i, s_i)$, firm i's first-order conditions are (22)–(23), namely

$$P(Q,\bar{s}) + q_i P_Q(Q,\bar{s}) + q_i P_{\bar{s}}(Q,\bar{s})\frac{\partial \bar{s}}{\partial q_i} = C_{iq}(q_i,s_i) + t\, e_{iq}(q_i,s_i),$$
$$q_i P_{\bar{s}}(Q,\bar{s})\frac{\partial \bar{s}}{\partial s_i} = C_{is}(q_i,s_i) + t\, e_{is}(q_i,s_i).$$

Comparing these conditions with the planner's first-order conditions (25)–(26), the only difference is the presence of the marginal external damage terms $\Phi'(E)e_{iq}$ and $\Phi'(E)e_{is}$ in the planner's problem. Setting

$$t = \Phi'(E)$$

aligns the firms' marginal-emissions terms exactly with the planner's externality wedges. Thus, emissions pricing internalizes marginal external damages along both the quantity and attribute margins for every firm.

The remaining discrepancy between the firms' and planner's quantity conditions is the Cournot markup term $q_i P_Q(Q,\bar{s})$, which reflects market power rather than the externality. Emissions pricing does not eliminate this distortion.

By contrast, consider a policy that conditions only on output, such as a per-unit tax τq_i. Under such a policy, firm i's attribute condition becomes

$$q_i P_{\bar{s}}(Q,\bar{s})\frac{\partial \bar{s}}{\partial s_i} = C_{is}(q_i,s_i),$$

which omits the planner's externality term $\Phi'(E)e_{is}(q_i,s_i)$. Hence, unless $e_{is}(q_i^\star, s_i^\star) = 0$, no output-based instrument can replicate the planner's attribute condition.

Therefore, externality-index pricing eliminates the externality wedge along all endogenous margins in oligopoly, while one-dimensional instruments generically fail. □

Proof of Proposition 5

Proof. Consider the planner's benchmark. The utilitarian social planner maximizes aggregate welfare by choosing the allocation $\{(q_i, s_i)\}_{i=1}^N$ to solve:

$$\max_{\{q_i,s_i\}} W = \sum_{i=1}^{N} [U(q_i, s_i) - pq_i - K(s_i)] - \Phi\left(\sum_{i=1}^{N} e(q_i, s_i)\right).$$

The first-order conditions (FOCs) for each agent i at an interior social optimum $(q_i^\star, s_i^\star)$ are:

$$U_{q_i}(q_i^\star, s_i^\star) = p + \Phi'(E^\star) e_{q_i}(q_i^\star, s_i^\star), \tag{50}$$
$$U_{s_i}(q_i^\star, s_i^\star) = K'(s_i^\star) + \Phi'(E^\star) e_{s_i}(q_i^\star, s_i^\star). \tag{51}$$

1. One-Dimensional Failure. Suppose the regulator applies a tax τ only on quantity q_i. Agent i maximizes $U(q_i, s_i) - (p + \tau)q_i - K(s_i)$, treating aggregate damages E as given. The agent's FOCs are:

$$U_{q_i}(q_i, s_i) = p + \tau, \tag{52}$$
$$U_{s_i}(q_i, s_i) = K'(s_i). \tag{53}$$

To implement the social optimum, (53) must coincide with (51). This requires $K'(s_i^\star) = K'(s_i^\star) + \Phi'(E^\star) e_{s_i}(q_i^\star, s_i^\star)$. Since $\Phi'(E^\star) \neq 0$ by assumption, this equality holds if and only if $e_{s_i}(q_i^\star, s_i^\star) = 0$. Thus, if the externality depends on the attribute ($e_{s_i} \neq 0$), a quantity tax generically fails as it leaves the attribute margin unregulated. A symmetric argument holds for a tax levied solely on s_i.

2. Index Pricing Success. Under an individual externality-index tax t, agent i maximizes:

$$\pi_i = U(q_i, s_i) - pq_i - K(s_i) - t \cdot e(q_i, s_i).$$

The agent's Nash equilibrium FOCs are:

$$U_{q_i}(q_i, s_i) = p + t \cdot e_{q_i}(q_i, s_i), \tag{54}$$
$$U_{s_i}(q_i, s_i) = K'(s_i) + t \cdot e_{s_i}(q_i, s_i). \tag{55}$$

Comparing (54)–(55) to (50)–(51), the decentralized equilibrium exactly matches the social optimum if and only if the tax rate is set to the marginal social damage at the optimum:

$$t = \Phi'(E^\star) = \Phi'\left(\sum_{i=1}^{N} e(q_i^\star, s_i^\star)\right).$$

At this rate, the tax correctly prices the marginal externality contribution of each endogenous choice (q_i and s_i), internalizing the damage across all $2N$ margins. □

Proof of Theorem 1

Proof. Under the policy, the firm's interior first-order conditions are

$$P(q,s) + qP_q(q,s) = C_q(q,s) + T'(q), \tag{56}$$

$$\int_0^q P_s(z,s)\,dz = C_s(q,s). \tag{57}$$

The planner's attribute condition is

$$\int_0^{q^\star} P_s(z,s^\star)\,dz = C_s(q^\star,s^\star) + \Phi'(e(q^\star,s^\star))\,e_s(q^\star,s^\star). \tag{58}$$

Because the policy does not affect the attribute margin, the firm's condition (57) cannot match the planner's condition (58) unless $\Phi'(e(q^\star,s^\star))\,e_s(q^\star,s^\star) = 0$, which contradicts Assumption 1. □

Proof of Theorem 2

Proof. Under the policy, the firm's interior first-order conditions are

$$P(q,s) + qP_q(q,s) = C_q(q,s), \tag{59}$$

$$\int_0^q P_s(z,s)\,dz = C_s(q,s) + S'(s). \tag{60}$$

The planner's quantity condition is

$$P(q^\star,s^\star) + q^\star P_q(q^\star,s^\star) = C_q(q^\star,s^\star) + \Phi'(e(q^\star,s^\star))\,e_q(q^\star,s^\star). \tag{61}$$

Because the policy does not affect the quantity margin, the firm's condition (59) cannot match the planner's condition (61) unless $\Phi'(e(q^\star,s^\star))\,e_q(q^\star,s^\star) = 0$, which

contradicts Assumption 1. □

Proof of Theorem 3

Proof. Under the policy, the consumer's interior first-order conditions are

$$U_q(q, s) = p + T'(q), \tag{62}$$

$$U_s(q, s) = K'(s). \tag{63}$$

The planner's attribute condition is

$$U_s(q^\star, s^\star) = K'(s^\star) + \Phi'(e(q^\star, s^\star))\, e_s(q^\star, s^\star). \tag{64}$$

Because the policy does not affect the attribute margin, the consumer's condition (63) cannot match the planner's condition (64) unless $\Phi'(e(q^\star, s^\star))\, e_s(q^\star, s^\star) = 0$, which contradicts Assumption 2. □

Proof of Theorem 4

Proof. Under the policy, the consumer's interior first-order conditions are

$$U_q(q, s) = p, \tag{65}$$

$$U_s(q, s) = K'(s) + S'(s). \tag{66}$$

The planner's quantity condition is

$$U_q(q^\star, s^\star) = p + \Phi'(e(q^\star, s^\star))\, e_q(q^\star, s^\star). \tag{67}$$

Because the policy does not affect the quantity margin, the consumer's condition (65) cannot match the planner's condition (67) unless $\Phi'(e(q^\star, s^\star))\, e_q(q^\star, s^\star) = 0$, which contradicts Assumption 2. □

Proof of Corollary 3

Proof. For the firm (or consumer), the policy induces first-order conditions of the

form

$$\text{(marginal benefit w.r.t. } q) = \text{(marginal cost w.r.t. } q) + \tau'(I)\, I_q(q,s), \tag{68}$$

$$\text{(marginal benefit w.r.t. } s) = \text{(marginal cost w.r.t. } s) + \tau'(I)\, I_s(q,s). \tag{69}$$

To match the planner's conditions (which include the externality wedges $\Phi'(e)e_q$ and $\Phi'(e)e_s$), we require

$$\tau'(I^\star)\,(I_q^\star, I_s^\star) = \Phi'(e^\star)\,(e_q^\star, e_s^\star)$$

at $(q^\star, s^\star)$. Since $\Phi'(e^\star) \neq 0$ and $(e_q^\star, e_s^\star) \neq (0,0)$, the gradients must be proportional. Local monotonic equivalence follows from the implicit function theorem and the fact that $\tau(\cdot)$ is strictly monotone (without loss of generality) in a neighborhood of the first-best allocation. □

References

Andreyeva, T., Marlow, M. L., Moore, T. E., and Powell, L. M. (2022). Outcomes of sugar-sweetened beverage taxes in jurisdictions that have implemented them: A systematic review. *Obesity Reviews*, 23(6):e13425.

Arora, S. and Gangopadhyay, S. (1995). Toward a theoretical model of voluntary overcompliance. *Journal of Economic Behavior & Organization*, 28(3):289–309.

Baumol, W. J. (1972). On taxation and the control of externalities. *American Economic Review*, 62(3):307–322.

Conrad, K. (2005). Price competition and product differentiation when consumers care for the environment. *Environmental and Resource Economics*, 31(1):1–19.

Dechezleprêtre, A., Martin, R., and Mohnen, M. (2017). The impacts of environmental regulations on competitiveness. *Review of Environmental Economics and Policy*, 11(2):183–206.

Fullerton, D. (1998). How should the tax burden be divided? *National Tax Journal*, 51(1):27–37.

Fullerton, D. (2001). A framework to compare environmental policies. *Southern Economic Journal*, 68(2):224–248.

Fullerton, D. and Metcalf, G. E. (2001). Environmental controls, scarcity rents, and pre-existing distortions. *Journal of Public Economics*, 80(2):249–267.

Goulder, L. H. and Schein, A. R. (2013). Carbon taxes versus cap and trade: A critical review. *Journal of Economic Perspectives*, 27(4):87–110.

Greenstone, M. and Hanna, R. (2014). Environmental regulations, air and water pollution, and infant mortality in india. *American Economic Review*, 104(10):3038–3072.

Ito, K. and Sallee, J. M. (2018). The economics of attribute-based regulation: Theory and evidence from fuel-economy standards. *Review of Economics and Statistics*, 100(2):319–336.

Jacobsen, M. R. (2013). Evaluating u.s. fuel economy standards in a model with producer and household heterogeneity. *American Economic Journal: Economic Policy*, 5(2):148–187.

Mussa, M. and Rosen, S. (1978). Monopoly and product quality. *Journal of Economic Theory*, 18(2):301–317.

Onat, N. C., Kucukvar, M., Tatari, O., and Egilmez, G. (2023). Rebound effects in electric vehicle adoption: A review and directions for future research. *Transportation Research Part D: Transport and Environment*, 115:103589.

Peltzman, S. (1975). The effects of automobile safety regulation. *Journal of Political Economy*, 83(4):677–725.

Pigou, A. C. (1920). *The Economics of Welfare*. Macmillan, London.

Sandmo, A. (1975). Optimal taxation in the presence of externalities. *Swedish Journal of Economics*, 77(1):86–98.

Shaked, A. and Sutton, J. (1982). Relaxing price competition through product differentiation. *Review of Economic Studies*, 49(1):3–13.

Spence, M. (1975). Monopoly, quality, and regulation. *Bell Journal of Economics*, 6(2):417–429.

Stern, N. (2008). The economics of climate change. *American Economic Review*, 98(2):1–37.

Tirole, J. (1988). *The Theory of Industrial Organization*. MIT Press, Cambridge, MA.

Weitzman, M. L. (1974). Prices vs. quantities. *Review of Economic Studies*, 41(4):477–491.