

Fast, Furious, and Dirty: Gaming, Fuel Choice Behaviour, and the Welfare Cost of Dual-Fuel Subsidies*

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Abstract

Subsidies for dual-fuel vehicles – flex-fuel cars then, plug-in hybrids now – routinely deliver environmental outcomes opposite to their intent. Where fuel is already taxed, the failure has a fiscal twin: the fossil fuel these vehicles keep burning preserves the tax base that genuine abatement would erode. I formalise this *Fiscal Loop Premium* – the fiscal mirror image of the double dividend – in a second-best framework in which firm-side gaming (θ) and consumer-side fossil-fuel utilisation (ϕ) enter the optimal subsidy through an effective abatement share $(1 - \theta\phi)$ that nests the standard benchmarks. The critical carbon price below which the optimal subsidy turns negative depends only on the fuel tax, the cost of public funds and the net carbon content of the fuel displaced: EUR 87 per tonne for Swedish ethanol, EUR 47.6 for a carbon-free alternative. Evaluating Sweden’s 2007–2009 Green Car Rebate, I find that 98.6 percent of induced vehicles were incumbent gasoline models reclassified at negligible cost and driven 36 percent of the time on gasoline; the Premium recovers three-fifths of the rebate’s gross social cost, yet a technology-neutral feebate dominates it at any carbon price above EUR 31 per tonne. Two later Swedish regimes test the design conditions out of sample: gaming migrates to the certified rating through the company-car tax channel under a symmetric rebate, and its categorical form disappears under a continuous feebate. Calibrated to five European plug-in-hybrid markets on official on-board fuel-consumption data, the utilisation failure preserves EUR 202 mn a year of fuel-tax revenue that the type-approval rating assumed away.

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1 Introduction

After a decade of subsidising plug-in hybrid electric vehicles (PHEVs) as a low-carbon technology – through purchase rebates, company-car tax relief, and favourable treatment under fleet-wide CO2 standards – regulators in China, Europe, and the United States are now tightening PHEV eligibility, in response to evidence that real-world PHEV emissions substantially exceed type-approval ratings (Chu et al. 2025). PHEVs reached 19 percent of new-car sales in China by 2024 and remain widely sold in Europe (European Alternative Fuels Observatory 2026), against annual subsidy outlays in the billions of euros. The premise underlying these subsidies – that a vehicle able to run on electricity will be driven on electricity – fails systematically, and fails most where the subsidies are most generous. The failure is a structural feature of subsidising any *dual-fuel* technology, PHEVs included, whose environmental outcome turns on how the vehicle is subsequently driven as much as on whether it is purchased.

A natural concern is that an underused PHEV is a dynamic stepping stone to full electrification, so that static welfare accounting overstates the loss. The evidence runs the other way in the markets where the mechanism studied here is strongest: PHEV electric range has stagnated near 70 km and real-world emissions have not fallen (Chu et al. 2025), and the high-emission company-car models that drive the loss are the least plausible electrification on-ramps.

This paper develops a framework for dual-fuel subsidies that separates two independent failure channels: supply-side regulatory gaming (θ), in which manufacturers qualify vehicles without genuine abatement; and demand-side fuel arbitrage (ϕ), in which consumers drive subsidised vehicles on fossil fuel. The two channels combine multiplicatively through an *effective abatement share* $(1 - \theta\phi)$ that enters a closed-form optimal subsidy, reducing to the partial-equilibrium analogue of Parry’s (1998) second-best subsidy when gaming vanishes ($\theta\phi = 0$) and the deadweight loss from attribute manipulation result of Ito and Sallee (2018) when pre-existing fuel taxes are absent. Three structural conditions – an asymmetric eligibility threshold, a low-cost compliance technology, and a binding budget – are individually necessary and jointly sufficient for all four failure modes to activate simultaneously (the Anatomy Proposition). The central result is the *Fiscal Loop Premium* (FLP): in a second-best world with distortionary taxation, gaming preserves the fuel-tax base that genuine abatement would erode. The Premium is first-order – it recovers three-fifths of the gross social cost of the Swedish rebate – but it does not rescue the instrument: a technology-neutral feebate dominates the gamed subsidy at any carbon price above EUR 31 per tonne, and the critical carbon price below which the optimal subsidy is negative, $\tau_E^{crit} = \mu\tau_f/\Delta c$, depends only

on the fuel tax, the cost of public funds and the net carbon content of the displaced fuel – higher, therefore, the dirtier the alternative fuel’s lifecycle.

I take the framework to data using Sweden’s 2007-2009 Green Car Rebate (GCR), which offered SEK 10,000 to vehicles meeting fuel-type-specific thresholds on type-approval CO₂, the certified figure measured on gasoline: 120 gCO₂/km for conventional vehicles and 220 gCO₂/km for alternative fuel vehicles. Four empirical results stand out. First, 98.6 percent of the cohort consisted of incumbent gasoline models converted to FFVs at negligible cost, with a regression discontinuity confirming a 36 percentage point drop in conversion probability at the upper threshold and a difference-in-differences (DiD) estimating a 14.2 gCO₂/km causal increase in treated fleet emissions. Second, the welfare-maximising rebate is *negative* at every carbon price below EUR 87 per tonne (47.6 if the alternative fuel is carbon-free): the regulator should have taxed rather than subsidised the gaming cohort, and although the preserved tax base offsets three-fifths of the gross social cost, a feebate calibrated to the same budget would have cost the public half as much. This is, to my knowledge, the first empirical evaluation of a second-best environmental subsidy that jointly incorporates regulatory gaming and behavioural fuel choice into the welfare formula. Third, I test the Anatomy Proposition out of sample on the two Swedish regimes that followed (Section 8), where the escalation runs as the design conditions predict: certified-attribute gaming routed through the company-car tax channel under the symmetric Super Green Car Rebate (2012–2017), and categorical gaming eliminated under the continuous Bonus-Malus feebate (2018–2022), with the utilisation failure remaining. Fourth, the framework generalises beyond Swedish flex-fuel: the same two parameters govern contemporary plug-in-hybrid subsidies, and a calibration of five European markets to official on-board fuel-consumption data puts the annual Excess Fiscal Loop Premium, the fuel-tax revenue the type-approval rating assumed away, at EUR 202 mn, concentrated in the company-car fleets whose principal-agent friction drives ϕ towards one (Section 7.5).

Related literature. This paper connects four strands of the literature. The compliance gaming literature documents how firms exploit regulatory thresholds through bunching (Sallee and Slemrod 2012), test-cycle optimisation (Reynaert 2021), collusion to weaken emissions control technology (Alé-Chilet et al. 2026), and adjustment of the regulated *attributes* themselves – weight, footprint, power – under attribute-based standards (Klier and Linn 2012; Whitefoot et al. 2017). I identify a distinct channel: discrete reclassification across fuel-type *categories* at negligible cost, which distorts the CO₂ distribution rightward rather than leftward.

The welfare analysis of attribute-based regulation builds on Ito and Sallee (2018), who

formalise the costs of attribute-based notches but abstract from binding policy budgets, pre-existing fuel taxes, and behavioural utilisation – the three directions in which I extend their framework: binding budgets transform localised efficiency losses into allocative displacement; pre-existing fuel taxes generate the Fiscal Loop Premium; and behavioural fuel choice adds a consumer-side margin that interacts multiplicatively with supply-side gaming.

The optimal subsidy formula extends Parry’s (1998) second-best environmental subsidy – and the broader pre-existing-distortions framework of Bovenberg and Goulder (1996) – to incorporate firm-side gaming (θ) and behavioural underutilisation (ϕ), reducing to the partial-equilibrium analogue of Parry’s expression as $\theta\phi \rightarrow 0$.¹ The consumer-side analysis builds on the fuel-choice literature in flex-fuel (Anderson 2012; Salvo and Huse 2013; Huse 2018) and plug-in hybrid (Grigolon et al. 2023; Plötz et al. 2022) markets. I calibrate a structural fuel-choice model using the 2008 oil price collapse as exogenous price variation, recovering the shares of ethanol lovers, gasoline lovers, and fuel arbitrageurs from aggregate ethanol sales data.²

2 The GCR and Its Incentive Structure

During the 2000s, the European auto industry reduced CO2 emissions largely through the widespread adoption of diesel technology.³ Sweden was an outlier: an older, heavier fleet, passenger-car emissions at 19 percent of the national total (versus an EU average of 12), and average new-car emissions higher than all but two EU-25 countries (European Federation for Transport and Environment 2009). This environmental imperative conflicted with the industrial reality of the domestic manufacturers Volvo and Saab, which specialised in exactly the large, heavy vehicles that made the fleet an outlier, and which – given diesels’ unfavourable domestic tax treatment – had not followed their European competitors down the diesel route.

Against this backdrop, the Swedish government launched the Green Car Rebate (GCR, *Miljöbilspremie*) in April 2007. Following the autumn 2006 general elections, the newly formed government passed the programme in Parliament (in March 2007) with effect from April 2007. The policy provided a rebate of 10,000 SEK (EUR 1,081) to private individuals purchasing a

¹This literature derives its results with the labour tax as the pre-existing distortion; the base-erosion channel operates through the subsidy’s effect on the real wage and hence labour supply. I specialise the analysis to a sector with a pre-existing *fuel* tax as the operative distortion, so that abatement erodes fuel-tax revenue directly. The mechanism is the same – a clean subsidy shrinks a pre-existing tax base – with the fuel tax substituting for the labour tax as the channel.

²The directed technical change literature argues that optimal environmental policy should favour clean innovation (Acemoglu et al. 2012). The present paper takes direction at the innovation margin as given and shows that direction at the *compliance margin* creates gaming opportunities that a technology-neutral instrument eliminates (see Remark 3).

³Regulation 1753/2000/EC required 120 gCO2/km by 2010; later relaxed to 130 gCO2/km by 2015.

new “green vehicle,” representing roughly 6 percent off the price of a representative model like the VW Golf 1.6 FFV.⁴

2.1 The Asymmetric Eligibility Design

The GCR’s eligibility criteria created the regulatory asymmetry at the heart of the paper – Assumption 1 of the framework (Section 3.6):

- **Regular Fuel Vehicles (RFVs).** To qualify, vehicles running only on fossil fuels (gasoline or diesel) were required to meet a stringent emissions threshold of **120 gCO₂/km** (approximately 47 mpg for gasoline).
- **Alternative Fuel Vehicles (AFVs).** Vehicles capable of running on alternative fuels (ethanol, CNG, electric hybrids) faced a much more lenient threshold of **220 gCO₂/km** (approximately 25.5 mpg for gasoline).⁵

Both thresholds apply to type-approval CO₂ – the figure certified on the regulatory test cycle with the vehicle running on gasoline, and the unit in which every emissions comparison in this paper is made; a fuel-type conversion leaves it unchanged. By defining “green” to include high-emission AFVs, the policy created a 100 gCO₂/km loophole interval between 120 and 220 gCO₂/km. Manufacturers could qualify their existing heavy fleet for subsidies simply by introducing Flex-Fuel (FFV) variants, without needing to downsize engines or significantly improve efficiency.⁶

2.2 The Low-Cost Gaming Technology

The asymmetric eligibility design was exploitable precisely because the technology required to convert a gasoline model into an FFV was available at trivial cost. FFVs – the dominant alternative fuel technology in the Swedish market – are built upon captive gasoline vehicles and can readily operate on gasoline, ethanol, or any blend of the two following small engineering modifications. The necessary modifications are primarily ethanol-compatible fuel lines and software sensors. These cost manufacturers less than USD 200 (EUR 150) per vehicle (U.S. Department of Energy 2008), compared to EUR 1,200-3,000 for the physical abatement required to move a heavy gasoline model down to the 120 gCO₂/km RFV threshold (TNO et al. 2006). This cost gap maps directly onto Assumption 2 of the theoretical framework

⁴I use the exchange rates prevailing at the inception of the programme: 6.984 SEK/USD and 9.25 SEK/EUR.

⁵This was close to the emissions of a contemporary high-performance sports car.

⁶This asymmetry is linked to the EU Renewable Fuel Standard and to concessions to the Green Party, but the concentration of domestic models just below the 220 gCO₂/km threshold also suggests a motive of industrial protection. As Ito and Salée (2018) note, emissions standards are often tailored to the attributes of domestic fleets. In 2006, Volvo and Saab had almost zero models meeting the 120 gCO₂/km target, but multiple heavy gasoline models sitting around or slightly below 220 gCO₂/km.

(Section 3.6).

The combination of near-zero gaming cost and a EUR 1,081 rebate created a powerful regulatory arbitrage. Firms could unlock a government subsidy with minor technical adjustments, and typically offered the FFV upgrade to consumers as a “no-cost option.” Demand-side conditions favoured take-up: Sweden had built an extensive E85 retail network by the GCR years – the 2005 “pump act” (*Pumplagen*, Lag 2005:1248) obliged larger filling stations to offer a renewable fuel from 2006, and the number of stations selling E85 rose from 300 in December 2005 to 1,332 by December 2008, some 41 percent of the 3,245 stations then in operation, and to 1,493 by September 2009 (Riksdagen 2010, Table 23, SPI data) – and E85 carried a lower excise than gasoline, so fuel optionality was real at the pump rather than nominal, subject to the cold-weather frictions of E85 taken up in Section 7.2.

2.3 The Fiscal Envelope

The government initially allocated 250 mn SEK for the programme (50 mn for 2007, 100 mn each for 2008 and 2009). The quick uptake of gamed FFVs – driven by the loophole documented in this paper – forced supplementary appropriations (*tilläggsbudgetar*) in 2007, 2008, and 2009, bringing the cumulative ex post expenditure to 815 mn SEK (Riksrevisionen 2020). During 2007–2008 the rebate was paid to every eligible buyer as of right, and the appropriation was topped up rather than rationed, so the budget did not bind in real time: no buyer was turned away, and a gamed vehicle did not directly deny the subsidy to a genuine abater. The budget bound *ex post*, through the political economy of its own cost: the escalating bill led the government to terminate the policy in June 2009 – six months ahead of schedule – and to replace it with a five-year vehicle-tax exemption that required no cash outlay (Förordning 2007:380, as amended by SFS 2009:699). This feature maps directly onto Assumption 3 of the theoretical framework (Section 3.6).

2.4 The Three Structural Conditions

The GCR thus combined three design features: an asymmetric eligibility threshold, a low-cost gaming technology, and a binding budget. Section 3.6 formalises these as Assumptions 1–3 and shows (Proposition 5) that they are individually necessary and jointly sufficient for the four failure modes the paper documents. Section 6 tests those predictions on 2005–2009 data, and Section 8 out of sample on the two Swedish policies that followed: the Super Green Car Rebate kept the certified-attribute asymmetry but removed the fuel-type one, and the Bonus-Malus removed the categorical threshold altogether.

The consequences are visible in the raw data. A sizeable regulatory gap between 120 and 220

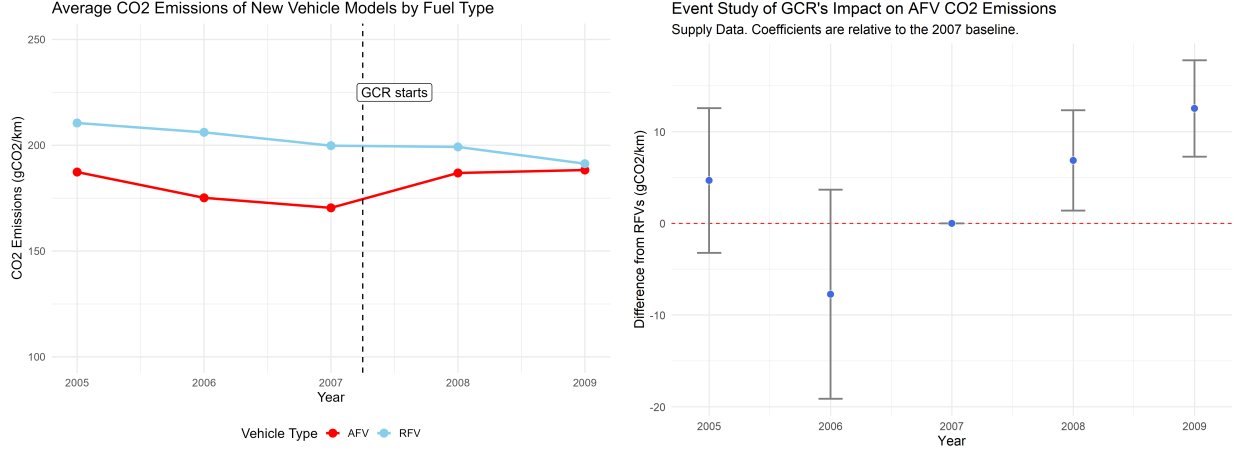


Figure 1: **Supply-side response to the GCR.** *Left:* average CO2 emissions (gCO2/km) of new car models in Sweden, 2005–2009, for Alternative Fuel Vehicles (red) and Regular Fuel Vehicles (blue); the dashed vertical line marks the April 2007 rebate. Trends are parallel pre-policy; AFV emissions diverge upward afterwards. *Right:* event-study coefficients from a regression of CO2 emissions on year-by-AFV interactions with model and year fixed-effects (reference year 2007; 95% confidence intervals clustered at the model level). Insignificant pre-2007 coefficients support parallel trends; the sharp positive divergence in 2008–2009 confirms a policy-induced rise in AFV emissions relative to the RFV counterfactual. The specification and estimates are developed in Section 6.

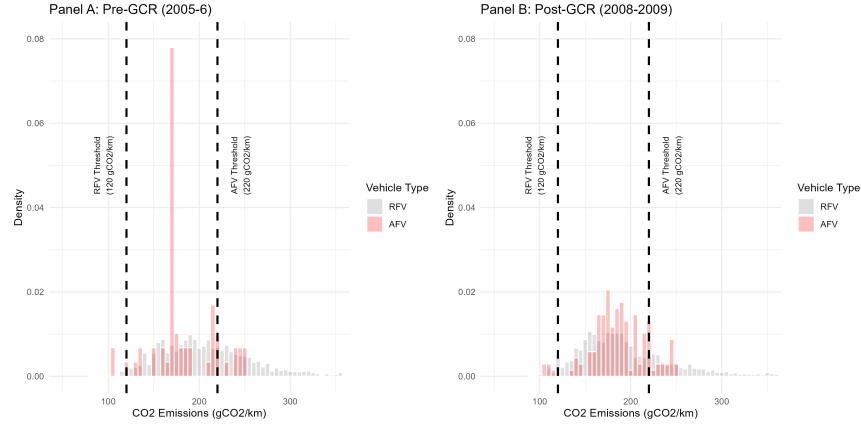


Figure 2: **CO2 Emission Histograms: Pre- and Post-GCR.** Density of CO2 emissions for new vehicle models. **Grey:** Regular Fuel Vehicles (RFV, threshold 120 gCO2/km); **red:** Alternative Fuel Vehicles (AFV, threshold 220 gCO2/km); the interval between the dashed threshold lines is the regulatory loophole. **Panel A (2005–2006):** pre-GCR, the AFV market is small with few high-emitting models. **Panel B (2008–2009):** post-GCR, a large mass of new AFV models clusters in the 180–220 gCO2/km loophole.

gCO2/km gave firms a strong incentive to fill it with converted models, and Figure 1 shows AFV emissions – parallel to RFVs before the GCR – trending upward from 2008 in absolute terms and relative to the RFV control. The histograms in Figure 2 show the mechanism: rather than shifting towards efficiency, a new mass of AFV models emerges specifically in the 180–220 gCO2/km band as manufacturers strategically converted high-emitting vehicles within the loophole.

3 A Model of Firm Compliance

Before turning to the empirical evidence, I develop a stylized theoretical model that formalises the mechanism linking the GCR’s asymmetric design to the three key outcomes documented in Sections 6 and 7: the dominance of intensive-margin gaming, the distributional shift towards the upper loophole threshold, and the allocative welfare loss arising from budget exhaustion. The model builds, through a series of intermediate results, to a single organising proposition: the three structural conditions of the preceding section are individually necessary and jointly sufficient for the policy failure. The model abstracts from demand-side behaviour – which is treated separately in Section 7 – and focuses on the supply-side strategic response of a representative automaker. All proofs are found in Appendix B.

3.1 Setup

Consider a market with a set of vehicle models i , each characterised by a baseline CO2 emissions level e_i drawn from a pre-policy distribution $F_0(e)$ on support $[\underline{e}, \bar{e}]$; nothing below requires F_0 to be continuous, and its empirical counterpart is the discrete distribution of models in the register. The regulator offers a unit subsidy $S > 0$ to consumers purchasing eligible vehicles, i.e., those emitting below a threshold. Under the GCR’s asymmetric design, eligibility thresholds differ by fuel type: $\bar{e}^{RFV} = 120$ gCO2/km for conventional vehicles and $\bar{e}^{AFV} = 220$ gCO2/km for alternative-fuel vehicles.

The regulator operates under a hard budget constraint: the total number of subsidised vehicles cannot exceed $\bar{N} = B/S$, where $B > 0$ is the total policy budget.

The compliance problem. A manufacturer with an incumbent Regular Fuel Vehicle (RFV) whose baseline emissions fall in the *loophole zone*, $e_i \in (\bar{e}^{RFV}, \bar{e}^{AFV}]$, may capture the subsidy through one of two strategies:

- **Abatement (A):** Invest $c^A(e_i, \bar{e}^{RFV})$ to re-engineer model i , reducing its emissions from e_i to $\bar{e}^{RFV}$ to qualify under the stringent RFV threshold. Abatement costs are strictly increasing and strictly convex in the required abatement ($c_e^A > 0$, $c_{ee}^A > 0$), with the boundary condition $c^A(\bar{e}^{RFV}, \bar{e}^{RFV}) = 0$: zero abatement is required, and costs nothing, for a vehicle already at the threshold.
- **Strategic Gaming (G):** Convert model i to an Alternative Fuel Variant (AFV) at a fixed cost $c^G > 0$, independent of e_i . Since $e_i \leq \bar{e}^{AFV}$, the vehicle immediately qualifies under the lax threshold without any physical emissions reduction.

Further, I assume $c^A(\bar{e}^{AFV}, \bar{e}^{RFV}) > c^G$: the cost of abating a vehicle at the upper loophole threshold all the way to the RFV threshold strictly exceeds the gaming cost. This ensures

that case (i) of Proposition 1 admits an interior crossing $\hat{e} \in (\bar{e}^{RFV}, \bar{e}^{AFV})$ rather than allowing gaming to dominate throughout by construction. The assumption is empirically unrestrictive: abating a vehicle near 220 gCO₂/km to 120 gCO₂/km requires substantial platform re-engineering, with a cost that far exceeds the $c^G \leq \text{EUR } 150$ FFV conversion.⁷

Payoffs. The subsidy S is paid directly to consumers as a post-purchase rebate; the manufacturer receives only the posted list price p_i . The rebate reduces the consumer’s effective out-of-pocket cost, generating a demand expansion $\Delta D > 0$. If manufacturers anticipate the rebate and raise list prices, the effective consumer price reduction is ρS rather than S , where $\rho \in (0, 1]$ is the pass-through rate.

Gaming leaves the vehicle’s powertrain unchanged: an FFV conversion modifies fuel-line components and engine control software without affecting displacement, power output, or vehicle weight.⁸ The consumer therefore faces a similar product at a lower effective price, and the demand expansion ΔD is determined by the rebate.

Revenue equivalence between the two strategies requires that ΔD is identical under gaming and abatement. It holds exactly for gaming, where the product is physically unchanged; for abatement it requires that downsizing to $\bar{e}^{RFV}$ not reduce market value – plausible with turbocharging, less so for naturally aspirated engines. In the GCR this is moot: case (ii) of Proposition 1 dominates – gaming occurs in 98.6 percent of the sample – so the abatement margin is never tested, and compliance reduces to *pure cost minimisation*.

3.2 The Compliance Choice: Gaming vs. Abatement

Proposition 1 (Compliance Cost Dominance). *Let $c_0^A \equiv \lim_{e_i \rightarrow \bar{e}^{RFV+}} c^A(e_i, \bar{e}^{RFV})$ denote the infimum physical abatement cost and assume $c^A(\bar{e}^{AFV}, \bar{e}^{RFV}) > c^G$. For any vehicle with baseline emissions $e_i \in (\bar{e}^{RFV}, \bar{e}^{AFV}]$, gaming strictly dominates abatement if and only if $c^G < c^A(e_i, \bar{e}^{RFV})$. Within the loophole interval $(\bar{e}^{RFV}, \bar{e}^{AFV}]$, two cases arise, differing by whether physical abatement entails a fixed setup cost $F_A \geq 0$ that governs c^A at the lower boundary.*

⁷For perspective, TNO et al. (2006) estimate that the manufacturer costs to reduce emissions from the 2008-2009 baseline average of 140 gCO₂/km down to the 2012 target of 120 gCO₂/km at roughly EUR 1,700 per vehicle (their Figure 3.10). The report also estimates a series of cubic polynomial specifications based on engineering data (their Table 3.11); these imply that the indifference point $\hat{e}$ is between 128 and 133 gCO₂/km depending on the specification, so abatement dominates only for vehicles already close to compliance and gaming dominates across most of the loophole – consistent with the near-unity gaming share estimated below. The upper cost estimate $c^A(\bar{e}^{AFV}, \bar{e}^{RFV})$ is between EUR 3,630 and 22,200, with a central estimate of EUR 8,800 – one to two orders of magnitude of c^G .

⁸The conversion cost is a few percentage points of the list price of a model; concretely, it is approximately 0.9 percent of the price of a baseline VW Golf at the start of the policy.

- (i) **Low fixed abatement cost** [$c_0^A = F_A < c^G$, including the continuous case $F_A = 0$]: since $\lim_{e_i \rightarrow \bar{e}^{RFV+}} c^A = F_A < c^G$ while c^A is strictly increasing with $c^A(\bar{e}^{AFV}, \bar{e}^{RFV}) > c^G$, there is a unique interior threshold $\hat{e} \in (\bar{e}^{RFV}, \bar{e}^{AFV})$ at which the firm is indifferent. Gaming strictly dominates for $e_i \in (\hat{e}, \bar{e}^{AFV}]$; abatement strictly dominates for $e_i \in (\bar{e}^{RFV}, \hat{e})$.
- (ii) **Large fixed abatement cost** [$c_0^A = F_A \geq c^G$]: gaming is strictly cheaper throughout the loophole interval, yielding the corner solution $\hat{e} = \bar{e}^{RFV}$; gaming strictly dominates for all $e_i \in (\bar{e}^{RFV}, \bar{e}^{AFV}]$.

At the interior $\hat{e}$ in case (i), and at $e_i = \bar{e}^{RFV}$ in case (ii), the firm is indifferent; I assign indifferent firms to gaming without loss of generality.

Case (i) predicts an interior $\hat{e}$ – some manufacturers in the lower loophole interval should abate; case (ii) predicts none should. The engineering cost of reducing a vehicle’s emissions by 80-100 gCO₂/km to clear the 120 gCO₂/km threshold is orders of magnitude larger than gaming. Thus, in the empirically relevant case, the threshold $\hat{e}$ should lie close to $\bar{e}^{RFV}$.

This result extends Reynaert (2021), who models compliance as a continuous interior choice between physical abatement and test-cycle optimisation based on relative marginal costs. The GCR’s asymmetric notch eliminates the interior solution by creating a discrete compliance option at near-zero cost. The only vehicles for which abatement could rationally dominate are those already very close to the RFV threshold – a small and empirically trivial subset.

3.3 The Distributional Shift

Proposition 2 (Distributional Shift). *Let $\hat{e} \in [\bar{e}^{RFV}, \bar{e}^{AFV})$ denote the compliance threshold characterised in Proposition 1, and let $p_0 \equiv \Pr_{F_0}[e \in (\hat{e}, \bar{e}^{AFV}]] < 1$ denote the pre-policy AFV mass in $(\hat{e}, \bar{e}^{AFV}]$. The introduction of the asymmetric threshold generates a strict increase in AFV mass within $(\hat{e}, \bar{e}^{AFV}]$: the post-policy distribution places strictly more weight on this interval than the pre-policy distribution.*

Remark 1 (Relation to the bunching literature). The distortion established in Proposition 2 differs fundamentally from the standard bunching documented by Sallee and Slemrod (2012) and formalised in the attribute-based regulation framework of Ito and Sallee (2018). In those settings, a *single* eligibility threshold generates mass migration from above the cutoff to just below it: manufacturers compress product attributes *leftward* towards efficiency.

By contrast, the GCR’s asymmetric dual-threshold design creates a categorical loophole in $(\bar{e}^{RFV}, \bar{e}^{AFV}]$: manufacturers migrate into the AFV category by converting existing models at their original, unreduced baselines, producing a *rightward* shift in average AFV emissions – the

structural opposite of the efficiency-enhancing leftward compression that standard bunching produces. Classical bunching does also occur at the 220 gCO₂/km boundary (Section 6.2), but Section 7.1 shows it is secondary to the categorical influx of heavy incumbents from below. Since both channels push mass towards $\bar{e}^{AFV}$, and the welfare accounting of Section 7 counts only the categorical shift, its costs are a lower bound on the full distortion: adding the bunching at 220 gCO₂/km would raise them.

3.4 Allocative Welfare Loss Under Budget Exhaustion

The welfare analysis of attribute-based regulation typically abstracts from binding policy budgets (Ito and Sallee 2018). The GCR introduces a qualitatively distinct channel, an *allocative failure* driven by budget exhaustion: because the budget strictly binds, each of the N_G vehicles that capture the subsidy via strategic gaming crowds out a genuinely efficient RFV that would otherwise have received it.⁹

Proposition 3 (Allocative Welfare Loss). *Under a binding budget constraint B , the allocative displacement of subsidy slots generates a strict environmental welfare loss, bounded below by (abstracting from above-threshold bunching, which reinforces the distortion; see Remark 1):*

$$W_{loss} = \tau_E \cdot N_G \cdot \frac{(\bar{e}_G^{AFV} - \bar{e}^{RFV}) \times VKT}{10^6} \quad (1)$$

where τ_E is the social cost of carbon (EUR per tonCO₂), $\bar{e}_G^{AFV}$ is the average baseline emissions of the N_G gamed vehicles, $\bar{e}^{RFV} = 120$ gCO₂/km is the RFV eligibility threshold, and VKT is the lifetime vehicle kilometres travelled.

Two bounds pull in opposite directions: relative to the full distortion the expression is a lower bound, because above-threshold bunching is left out (Remark 1), while relative to the allocative loss it books it is an upper bound, because it assumes the marginal displaced vehicle would have emitted exactly at the eligibility threshold $\bar{e}^{RFV}$.¹⁰ Throughout, $\mu \equiv \lambda - 1 \geq 0$ denotes the excess burden of taxation, where λ is the marginal cost of public funds; $\mu = 0$ is the first-best benchmark and $\mu > 0$ the distortionary case.

Remark 2 (The perverse fiscal dividend). Proposition 3 captures only the allocative environmental loss. The same gaming that inflates emissions simultaneously *preserves* the

⁹Under the GCR, the (cumulative) budget $B = 815$ mn SEK finances exactly $\bar{N} = B/S$ vehicles. A gamed vehicle captures the subsidy through fuel-type conversion without physical abatement, so it displaces an RFV emitting at or below $\bar{e}^{RFV} = 120$ gCO₂/km; Appendix B.3 derives the result in full.

¹⁰If marginal RFV adopters would have purchased vehicles emitting somewhat above 120 gCO₂/km absent the subsidy, the true displacement gap narrows. The bootstrap exercise in Section 7.1 uses the statutory threshold as the benchmark, making this an intentionally conservative (i.e., damage-maximising) counterfactual.

pre-existing fuel-tax base that genuine abatement would have eroded – a second-best offset worth more than its face value when taxation is distortionary ($\mu > 0$). This Fiscal Loop Premium enters the optimal policy response in Proposition 4; its novelty relative to the double-dividend and attribute-based-regulation literatures is discussed in Section 3.9.

3.5 Second-Best Optimal Subsidy With Partial Compliance

The transition to the optimal policy response (Proposition 4) requires reconciling the physical and behavioural dimensions of gaming. While Proposition 1 establishes that gamers bypass physical re-engineering (certified emissions e_i are unchanged), dual-fuel vehicles retain the capacity to run on alternative fuels. The parameter ϕ captures the extent to which this capacity goes unrealised (e.g., $\phi = 1$ denoting pure fossil-fuel driving, and anticipating the calibration of Section 7.2, $\phi = 0.359$ for the GCR). Proposition 4 integrates this behavioural utilisation (ϕ) with the structural gaming share by firms (θ), a pre-existing fuel tax (τ_f), and a marginal cost of public funds ($\lambda > 1$) to formalise the perverse fiscal dividend. Specifically, when a genuine abater reduces fuel consumption by Δq_A , the government loses $\tau_f \Delta q_A$ in tax revenue, imposing an excess social cost of $\mu \tau_f \Delta q_A$. Conversely, a gamer who continues to rely on fossil fuels ($\Delta q_G = 0$) preserves this lucrative tax base. This asymmetry – where genuine abatement erodes the tax base while behavioural gaming preserves it – constitutes the Fiscal Loop Premium at the heart of the optimal subsidy formula.

Note that the optimal subsidy derivation abstracts from the pass-through rate ρ . While the empirical literature generally finds near-complete pass-through for direct consumer vehicle rebates (Sallee 2011; Durrmeyer 2022), ρ governs the distributional incidence of the rebate rather than its optimal aggregate level. Because the government incurs the fiscal cost S (and its associated deadweight loss μS) regardless of how the surplus is divided between lower consumer prices and higher manufacturer margins, ρ does not alter the welfare-maximising instrument design.

Proposition 4 (Second-Best Optimal Subsidy with Partial Compliance). *Consider a regulator designing a unit subsidy S prior to the realisation of demand, in an environment where the policy budget does not bind. The distortionary tax system has a Marginal Cost of Public Funds $\lambda > 1$, where $\mu \equiv \lambda - 1 > 0$ is the excess burden of taxation. Let τ_E denote the social cost of carbon and τ_f the pre-existing fuel tax.*

The subsidy induces a marginal cohort consisting of genuine abaters (share $1 - \theta$) and strategic gamers (share $\theta \in [0, 1]$), where θ is determined by the cost structure of Proposition 1 and is independent of S . Genuine abaters achieve physical reductions $(\Delta q_A, \Delta E_A) > 0$ in fuel consumption and emissions relative to the unsubsidised baseline. Gamers realise only a

fraction of these reductions through behavioural fuel choice: they rely on fossil fuels for a share $\phi \in [0, 1]$ of their driving, achieving expected reductions $(\Delta q_G, \Delta E_G) = (1 - \phi)(\Delta q_A, \Delta E_A)$, where ϕ is also independent of S .

The welfare-maximising second-best optimal subsidy is:

$$S^* = \underbrace{\left[\frac{\tau_E \Delta E_A}{\mu} - \tau_f \Delta q_A \right]}_{\text{Benchmark Second-Best Subsidy}} - \underbrace{\theta \phi \frac{\tau_E \Delta E_A}{\mu}}_{\text{Environmental Penalty}} + \underbrace{\theta \phi \tau_f \Delta q_A}_{\text{Fiscal Loop Premium}} \quad (2)$$

Equivalently, the optimal subsidy admits the compact form:

$$S^* = (1 - \theta \phi) \cdot S^{\text{benchmark}}, \quad S^{\text{benchmark}} \equiv \frac{\tau_E \Delta E_A}{\mu} - \tau_f \Delta q_A \quad (3)$$

where $(1 - \theta \phi)$ is the effective abatement share of the subsidised cohort, capturing the deadweight loss from attribute manipulation (θ) and behavioural underutilisation (ϕ).¹¹

The optimal rebate is independent of the pass-through rate ρ : pass-through determines how the consumer surplus generated by the rebate is divided between lower effective prices and higher manufacturer margins, but the government's fiscal expense – and hence the social cost μS – is invariant to this division.

In the proposition, $(\Delta q_A, \Delta E_A)$ are the intended per-vehicle abatement of the target technology – for a flex-fuel vehicle, the litres of gasoline that running on ethanol displaces over its lifetime and the emissions those litres carry, $\Delta E_A = \Delta c \Delta q_A$, where Δc is the net carbon content per litre displaced (the lifecycle emissions of gasoline less those of the alternative fuel). Setting $S^* = 0$ with $\theta \phi < 1$ gives the critical carbon price $\tau_E^{\text{crit}} = \mu \tau_f / \Delta c$, below which the optimal subsidy is negative; it is higher the dirtier the alternative fuel's lifecycle, because a smaller Δc leaves less environmental benefit per litre to set against the fiscal erosion $\mu \tau_f$.

The formula presupposes a distortionary tax system, $\mu > 0$. As $\mu \rightarrow 0$ the two fiscal terms – base erosion and the Fiscal Loop Premium – vanish, because preserving a tax base is worth nothing when public funds are not costly, while S^* itself is unbounded, because transfers are free; the Premium is a second-best object and exists only because $\mu > 0$.

The three terms map onto distinct literatures: Term 1 is the partial-equilibrium counterpart of

¹¹The share averages over the cohort under a common lifetime mileage for gamed and genuine vehicles. If gamed vehicles – the larger platforms of Section 6.3 – are driven more than genuine abaters, the effective share is lower still and S^* with it; if less, the reverse. The price-elastic-mileage correction of Appendix D.4 adjusts VKT for the fuel-price response but not for a mileage-size correlation, whose sign is clear and whose magnitude the data do not identify.

Parry’s (1998) second-best subsidy under a pre-existing fuel tax; Term 2 formalises the erosion of environmental effectiveness documented in the attribute-based-regulation literature (Ito and Sallee 2018; Reynaert 2021); Term 3 – the Fiscal Loop Premium – is new. Gamers reduce fuel consumption by only $(1 - \phi)\Delta q_A$, preserving fuel-tax revenue that genuine abatement would have destroyed; in a distorted economy ($\mu > 0$) this spares the government replacement revenue raised through other distortionary taxes, pushing S^* *up*. The net effect of a marginal increase in either gaming margin is the difference between the Environmental Penalty and the Premium: the regulator should set a *higher* subsidy than the Penalty alone suggests if and only if

$$\tau_f \Delta q_A > \frac{\tau_E \Delta E_A}{\mu} \quad (4)$$

– the fiscal value of preserved fuel consumption per gamer under full fossil utilisation exceeding the scaled environmental cost of foregone abatement. Equation (4) is an empirical condition that the GCR data directly identify; Section 7 evaluates it. Remark A2 (Appendix B) develops the term-by-term mapping in full, Remark A3 the observational equivalence of the two gaming margins in S^* – separating θ from ϕ requires the disaggregated identification of Section 7 – and Remark A4 the endogenous- θ extension.

Corollary 1 (Limiting cases). *Equation (2) nests three benchmarks.*¹²

- (i) **No effective gaming** ($\theta\phi = 0$): *both the Environmental Penalty and the Fiscal Loop Premium vanish and S^* collapses to the benchmark second-best subsidy, the partial-equilibrium analogue of Parry (1998).*
- (ii) **No fuel tax** ($\tau_f = 0$): *the base-erosion and Fiscal Loop terms vanish and $S^* = (1 - \theta\phi)\tau_E \Delta E_A / \mu$, the deadweight loss from attribute manipulation of Ito and Sallee (2018).*
- (iii) **Pure, fully fossil-fuelled gaming** ($\theta\phi \rightarrow 1$): *expected environmental benefit and tax-base erosion both vanish, $S^* \rightarrow 0$, and the optimal policy is to abandon the subsidy.*

The comparative statics of S^* (Corollary A1, Appendix B) all run through the same net condition: the response of S^* to either gaming margin takes the sign of (4), with the

¹²Case (i) is reached whether no firm games ($\theta = 0$) or gamers drive exclusively on the alternative fuel ($\phi = 0$); the benchmark is the Pigouvian benefit discounted by the excess burden of raising public funds, minus the fiscal cost of eroding the pre-existing fuel-tax base. The two routes are observationally equivalent in S^* (Remark A3) but differ in kind: a gamed vehicle harms the environment only to the extent it is driven on fossil fuel, so certification alone does no harm; what the gamed cohort still costs at $\phi = 0$ is the excess burden μS of the transfers to it, which scales with θ (Corollary 2). Case (iii), unlike an interior value of $\theta\phi$, which many (θ, ϕ) pairs share, is reached only as both $\theta \rightarrow 1$ and $\phi \rightarrow 1$.

counterintuitive implication that when the Benchmark is negative, *more gaming raises welfare conditional on the policy being in place* – though the first-best response remains to abandon the subsidy. The cross-jurisdiction implications are quantified in Appendix F.

3.5.1 The Role of the Budget Constraint

Proposition 4 characterises the ex ante design problem with the budget slack, where gaming is fiscally costly but not allocatively destructive: a gamed vehicle does not crowd out an efficient one. The GCR, however, operated under a cumulative fiscal envelope ($B = 815$ mn SEK) that bound *ex post* via the political-economy channel, triggering premature termination in June 2009, so gaming additionally imposes the allocative displacement cost of Proposition 3. The following result integrates both channels and shows that the Fiscal Loop Premium operates in both regimes, with identical magnitude.

Corollary 2 (Unified Welfare Evaluation Under Alternative Budget Regimes). *Consider the actual policy with subsidy S , gaming share θ , fossil utilisation ϕ , and $N_G = \theta \bar{N}$ gamed vehicles. Define the **Net Social Cost of the gamed cohort**, Π , as the aggregate welfare loss attributable to the N_G vehicles that captured the subsidy via strategic gaming rather than genuine abatement. Under two alternative budget regimes:*

(i) *Non-binding budget. When the budget does not bind, the gamed cohort imposes no displacement cost – per gamed vehicle, the excess burden μS of financing the transfer and the foregone abatement $\phi \tau_E \Delta E_A$ of the fossil share of its driving, less the Fiscal Loop Premium $\phi \mu \tau_f \Delta q_A$ from the preserved fuel-tax base:*

$$\Pi^{NB} = N_G [\mu S + \phi \tau_E \Delta E_A - \phi \mu \tau_f \Delta q_A] \quad (5)$$

(ii) *Binding budget. When the budget binds ($N_G + N_A = \bar{N} = B/S$), each gamer additionally displaces a genuinely efficient vehicle. The Net Social Cost acquires the allocative displacement channel of Proposition 3, evaluated at certified emissions:*

$$\Pi^B = \Pi^{NB} + \underbrace{N_G \cdot \tau_E \cdot \frac{(\bar{e}_G^{AFV} - \bar{e}^{RFV}) \times VKT}{10^6}}_{\text{Allocative displacement (certified emissions)}} \quad (6)$$

The Fiscal Loop Premium and the foregone-abatement term are identical across regimes; both are priced on the same litres, the whole tank a vehicle on the alternative fuel would have displaced, and the foregone-abatement term is the welfare-unit counterpart of the Environmental

Penalty of Proposition 4. The displacement term (absent under regime (i)) is evaluated at certified emissions ($\bar{e}_G^{AFV} - \bar{e}^{RFV}$): the gamer occupies a budget slot a genuine abater would have filled, and the displaced abatement is booked in the regulator's own accounting unit (type-approval CO2), independent of how the gamer subsequently drives. It vanishes only as $\bar{e}_G^{AFV} \rightarrow \bar{e}^{RFV}$, i.e. when gaming itself disappears.

This has three implications. First, the Premium arises in either budget regime – it is a general second-best phenomenon: whenever $\theta, \tau_f, \mu > 0$, gaming partially self-finances whether or not the budget binds. Second, a binding budget scales the cost up without changing its composition: in the GCR's Central Scenario the displacement channel (EUR 21.1 mn) is 2.6 times the fiscal channel (EUR 8.0 mn; Table 3). Third, relaxing the budget is therefore a second-order remedy – it removes displacement but leaves the excess burden and the Premium intact; the first-order remedy is eliminating the asymmetric threshold itself (Section 3.8).

The two results answer different questions through one mechanism: Proposition 4 asks what subsidy the regulator should set (S^*); Corollary 2 asks what the realised policy's gaming cost is (Π). The Fiscal Loop Premium links them, *raising S^* and lowering Π* ; setting $\tau_f = 0$ removes it from both (Remarks A5 and A6, Appendix B, develop the link and the row-by-row mapping of Π^B onto Table 3 – including that under a non-binding budget the gamed cohort would have been a *net gain* of EUR 5.9 mn).

3.6 The Anatomy of Policy Failure

The preceding propositions establish a causal chain running from asymmetric instrument design through equilibrium gaming to allocative failure and partial fiscal self-financing. The following proposition establishes that this chain arises whenever three conditions hold simultaneously, in Sweden or elsewhere – and that each condition is necessary. Appendix A.1 catalogues the gaming mechanism across dual-fuel technologies.

Assumption 1 (Asymmetric Threshold). *The eligibility thresholds satisfy $\bar{e}^{RFV} < \bar{e}^{AFV}$, creating a loophole interval $(\bar{e}^{RFV}, \bar{e}^{AFV}]$ in which vehicles qualify under the lax threshold but not the stringent threshold. The economic content of the assumption is a rating-road asymmetry: eligibility is granted on a certified attribute that can be met without the physical outcome the policy targets, and the GCR's fuel-type threshold is its categorical special case.¹³*

Assumption 2 (Low-Cost Compliance Technology). *The cost of strategic gaming is strictly*

¹³Under the GCR the certified attribute is the administrative fuel class, so the loophole is an interval of emissions. Under a policy that rates emissions directly, such as the Super Green Car Rebate or the Bonus-Malus of Section 8, the certified attribute is the type-approval value itself and the asymmetry is the gap between that rating and the emissions on the road (Section 7.5); a continuous schedule removes the categorical component of the assumption but not this gap.

less than the cost of maximal physical abatement: $c^G < c^A(\bar{e}^{AFV}, \bar{e}^{RFV})$.

Assumption 3 (Finite Fiscal Envelope). *The total public expenditure on the subsidy is bounded: $\sum_t S \cdot N_t \leq B$, where B is the cumulative fiscal envelope. The constraint binds either mechanically (the appropriation is exhausted and not replenished) or through political economy (the fiscal cost triggers premature programme termination). In either case, the total number of subsidised vehicles is finite at $\bar{N} = B/S$, determined at programme termination.*

The following proposition organises these conditions into a characterisation of the policy failure.

Proposition 5 (Anatomy of Dual-Fuel Subsidy Failure). *Under the maintained conditions $\tau_f > 0$ (pre-existing fuel tax) and $\phi > 0$ (partial fossil fuel utilisation), Assumptions 1-3 are individually necessary and jointly sufficient for the following four outcomes to occur simultaneously:*

- (i) **Compliance Cost Dominance** (Prop. 1): *Gaming strictly dominates abatement for a strictly positive mass of models in the loophole interval.*
- (ii) **Distributional Shift** (Prop. 2): *The post-policy AFV distribution places strictly more mass in the upper loophole interval than the pre-policy distribution ($p_1 > p_0$, where p_t denotes the probability mass in $(\hat{e}, \bar{e}^{AFV}]$ at time t).*
- (iii) **Allocative Crowding-Out** (Prop. 3): *The allocative displacement by gamers crowds out genuinely efficient vehicles, generating a strict environmental welfare loss ($W_{loss} > 0$).*
- (iv) **Perverse Fiscal Dividend** (Prop. 4): *Assuming pre-existing fuel taxes ($\tau_f > 0$) and behavioural underutilisation ($\phi > 0$), the welfare cost of gaming is (partially) self-financed through the preservation of the fuel tax base, generating a strictly positive Fiscal Loop Premium.*

While Proposition 5 gives the conditions under which gaming occurs, the three Anatomy assumptions determine *whether* $\theta > 0$ and the cost structure of Proposition 1 its *magnitude*. Corollary A2 (Appendix B) maps each condition onto the welfare expression of Proposition 4: relaxing the asymmetric-threshold or low-cost-technology condition sets $\theta = 0$ outright, while relaxing only the budget condition leaves θ intact but removes the allocative displacement channel (Π^{NB} rather than Π^B). The Anatomy conditions restrict θ alone: ϕ is set separately by relative fuel prices, infrastructure, and – most sharply – principal-agent frictions in company fleets, where the decision-maker does not bear the marginal fuel cost (Plötz et al. 2022). The two channels are independent: a policy with $\theta \rightarrow 1$ can still succeed if $\phi \rightarrow 0$, and one with $\theta = 0$ can still fail if the vehicles are driven on fossil fuel.

3.7 The Framework Across Dual-Fuel Technologies

The two parameters have the same definition in any dual-fuel setting; only the gaming mechanism and the utilisation margin change. The gaming share θ is the fraction of subsidised vehicles that obtain eligibility through low-cost attribute manipulation rather than genuine abatement (Assumptions 1–2); the fossil-utilisation share ϕ is the fraction of real-world driving done on the fossil fuel despite the vehicle’s nominal clean capability. The Swedish GCR is the case in which both parameters are cleanly identified – fuel-type reclassification at negligible cost pins down θ , and the fuel-choice calibration pins down ϕ – but the same two parameters govern every dual-fuel technology, plug-in hybrids above all. Table A1 (Appendix A.1) shows them at work in three technologies chosen to span the mechanism space – flex-fuel, PHEV, and the single-fuel diesel defeat-device contrast in which the ϕ -channel is absent.

The PHEV row of that table is the one that matters most. It connects directly to the billion-euro contemporary programmes flagged in the Introduction: the same θ and ϕ that the GCR identifies cleanly in the flex-fuel case govern PHEVs, where independent evidence puts ϕ even higher in the company-car settings where subsidies are most generous (Appendix G). The GCR therefore identifies the parameters of a general dual-fuel failure, one that operates, with identical welfare logic, in the policies regulators are tightening today.

3.8 Resolving the Anatomy of Failure: The Continuous Feebate

Propositions 1-5 characterise the necessary and sufficient conditions under which a dual-fuel subsidy program generates the composite failure documented in the GCR. The natural next step is to identify an alternative instrument that satisfies none of these conditions by design. The most theoretically grounded candidate is a continuous, technology-neutral feebate, which the environmental economics literature has long identified as welfare-superior to binary step functions for attribute-based regulation (Weitzman 1974; Goulder and Parry 2008). Proposition 6 establishes that the feebate eliminates regulatory arbitrage.

Proposition 6 (Feebate Eliminates Regulatory Arbitrage). *Under a technology-neutral linear feebate $T(e_i) = r(e_i - e^*)$, with $r > 0$ and pivot point e^* , fuel-type conversion without physical abatement yields a strictly zero marginal policy transfer. For any conversion cost $c^G > 0$, the regulatory net return to gaming is strictly negative, and the firm’s optimal response is inaction.*

The intuition is as follows. The feebate’s schedule depends solely on physical emissions e_i , with no distinction by administrative fuel type. A firm converting an RFV emitting 185 gCO₂/km to an AFV classification at unchanged emissions produces $\Delta T = 0$: the policy

transfer is invariant to the conversion. Since the conversion incurs cost $c^G > 0$, the net return is strictly negative and no firm undertakes it. The categorical component of Assumption 1 is violated by construction, and categorical gaming is eliminated at its source.

The feebate eliminates discrete fuel-type reclassification but not continuous test-cycle optimisation: tied to official ratings, it still rewards laboratory calibration without on-road improvement – a channel Reynaert (2021) puts at roughly 30 percent of the 2007–2014 European fleet-emissions decline. The two margins coexist, and while the NEDC-to-WLTP transition narrowed the laboratory–road gap, residual manipulation persists (Reynaert and Sallee 2021). Closing both would require a feebate tied to on-road rather than type-approval emissions, and hence real-world monitoring that most jurisdictions still lack.

Eliminating gaming is necessary but not sufficient for welfare dominance. Corollary A3 (Appendix B.8) gives the condition: a budget-equivalent feebate welfare-dominates the binary instrument if and only if the eliminated net social cost of gaming, Π^B , exceeds the physical abatement cost the feebate induces. Calibrated to the GCR, the feebate dominates at both carbon prices considered, by a wide margin at $\tau_E = 75$ and more narrowly at $\tau_E = 40$; only below a carbon price of about EUR 31 per tonne does the GCR’s fiscal windfall let the gamed subsidy prevail (Remark A7) – the Fiscal Loop Premium at work in an instrument-choice problem.¹⁴

Remark 3 (Technology neutrality at the compliance margin). The GCR’s failure lies in the margin it directed, the compliance margin rather than the innovation margin: it funded fuel-line modifications that left emissions unchanged, contributing nothing to the clean knowledge stock A_c despite EUR 88.1 mn (815 mn SEK) of cumulative expenditure – compliance-margin direction decoupling fiscal outlay from innovation entirely.

3.9 Discussion

What is new relative to the benchmarks. Corollary 1 already nests the two benchmarks – Parry (1998) at $\theta\phi = 0$, Ito and Sallee (2018) at $\tau_f = 0$, with their $(1 - \theta)$ baseline at $\phi = 1$. The two channels absent from both – the binding budget (displacement) and the pre-existing fuel tax (the Fiscal Loop Premium) – are precisely what the GCR activates. The Premium is the fiscal mirror image of the double-dividend result (Bovenberg and de Mooij 1994; Goulder

¹⁴Technology neutrality here does not conflict with the directed technical change literature (Acemoglu et al. 2012), which holds that optimal policy should be *directed* towards the clean sector to overcome innovation path-dependence. The two margins differ: at the *innovation margin* direction is welfare-improving, since subsidising clean over dirty R&D corrects the path-dependence externality; at the *compliance margin* it creates gaming, since technology-specific thresholds reward categorical reclassification (Proposition 1) whereas outcome-based instruments reward only physical abatement.

1995; Bovenberg and Goulder 1996): where an environmental tax raises revenue and eases distortionary costs, a clean subsidy erodes the fuel-tax base and raises them. That base erosion is *itself* the standard second-best correction – it is the $-\tau_f \Delta q_A$ of Term 1, already present in Parry (1998) and Bovenberg–Goulder. What is new is that *gaming partially undoes it*: because a gamer keeps burning taxed fuel, the base is preserved by $\theta \phi \tau_f \Delta q_A$ – a positive second-best correction that rises in the gaming $\times$ utilisation interaction and is therefore absent from any framework lacking a compliance-gaming margin. I have not seen this sign-flip – base preservation as a welfare gain conditional on policy failure – documented in either the attribute-based-regulation or the double-dividend literature.¹⁵

Two adjacent literatures price non-compliance without containing this object. In public finance, Chetty (2009) shows that evasion and avoidance responses which are transfers rather than resource costs reduce the welfare cost of taxation below the standard sufficient-statistic formula; the Premium is the environmental-subsidy counterpart, with the preserved fuel-tax base playing the role of the transfer – but the margin there is the taxpayer’s own reporting, and no instrument-ranking implication follows. In environmental economics, Sandmo (2002) characterises when the efficiency properties of emission taxes survive evasion, and Rousseau and Proost (2009) and Liu (2013) show that imperfect compliance, and differences across instruments in how easily they are evaded, interact with pre-existing labour taxes through enforcement and recycling revenue. All three operate on a *tax* instrument’s enforcement margin; none features a subsidy whose compliance margin preserves a pre-existing fuel-tax base, and none delivers the comparative static here – that more gaming raises welfare conditional on the policy being in place whenever the Benchmark is negative, reversing the subsidy–feebate ranking at carbon prices low enough for the Premium to outweigh the gaming cost (Section 7.4, Appendix H.3).

The hierarchy of conditions. The three Anatomy conditions do not carry equal weight: relaxing either the asymmetric threshold or the low-cost compliance technology sets $\theta = 0$ and eliminates all four failure modes, while relaxing the binding budget removes only the allocative displacement – so instrument re-design is the first-order remedy and budget relaxation a second-order one (Section 3.8). The conditions are also testable *ex ante*: a policymaker need only ask whether the programme creates an asymmetric threshold, whether a low-cost compliance technology exists, and whether the budget binds, and then separately what

¹⁵The preserved-base mechanism is a general property of proxy-based corrective taxes: it arises whenever the taxed rating and real behaviour part company, whoever moves the number – the firm (θ), the consumer (ϕ), or the regulator. In the companion paper (Huse 2026), the 2017–2020 NEDC-to-WLTP re-rating raised every new car’s certified CO₂ by about a fifth while on-road fuel use was unchanged; buyers responded to the re-based tax rather than to the restated label, so the restatement created a CO₂-tax base with no abatement behind it.

fraction of driving will occur on the cleaner fuel.

Roadmap to the empirics. Proposition 5 maps the empirics onto one mechanism: Sections 6.3, 6.4, 7.1 and 7.2–7.3 test failure modes (i)–(iv) in turn, and Section 8 repeats the test on the Super Green Car Rebate (2012–2017) and the Bonus–Malus feebate (2018–2022), whose outcomes vary as the Anatomy conditions predict.

4 Data

I evaluate the Swedish Green Car Rebate (GCR, 2007–2009) using administrative registration data, vehicle characteristics, fuel data, and air pollutant data for the 2005–2009 period. The three-regime validation of Section 8 draws on a separate contemporary sample covering 2010–2022, built from the same administrative sources at the model-variant level: registrations, fuel type and powertrain, and certified CO₂ emissions, with all post-2020 emissions harmonised back to NEDC after Sweden’s adoption of WLTP as its tax basis, so that treatment definitions and outcomes are measured on a consistent scale across regimes. The 2010–2022 registrations and characteristics come from Statistics Sweden (SCB). The certified CO₂ value in that sample is the vehicle register’s type-approval figure, with the ADAC/EEA type-approval value matched at year, make, fuel and rated power substituted where the register records none; variant-years with neither (12.5 percent of conventional variant-years, 1.7 percent of registrations) are dropped. The details of the primary GCR data are as follows.

Vehicle registrations (primary GCR). Vehicle registration data is obtained from Vroom, a consulting firm. The data on privately owned vehicles is recorded at the monthly frequency from January 2005 to December 2009. An observation is a vehicle registration consisting of a combination of year, month, brand, model, engine size, fuel type, and CO₂ emissions rate.

Vehicle characteristics. Vehicle characteristics are obtained from two sources: *Nybilsguiden* (New Car Guide), a consumer guide issued yearly by Konsumentverket (the Swedish Consumer Agency), and Vroom. For every car model available on the Swedish market, the information available includes standard characteristics such as fuel type, engine power (HP), engine size, curb weight, number of cylinders, fuel economy under EU-determined driving cycles (measured in L/100 km, or 100 m³/km for CNG cars), CO₂ emissions (in gCO₂/km under EU-determined driving conditions), vehicle tax, and list prices.

Fuel data. I use market-level data on fuels recorded at the monthly frequency and national level. Recommended retail prices for gasoline, diesel, and ethanol are obtained from the two largest distributors in Sweden, OKQ8 and Statoil. Quantities sold for gasoline, ethanol, and diesel are obtained from the Swedish Petroleum Institute (SPI).

Local pollutants. Local pollutant data is obtained from the UK Vehicle Certification Agency,¹⁶ and data comparing the exhaust pollutants of gasoline- and ethanol-fuelled vehicles from the US Environmental Protection Agency (EPA). They enter only the fuel-choice social-cost calculation of Appendix D, where they prove second-order relative to CO₂.

Combining datasets (primary GCR). I merge the characteristics and registration datasets at the model-version level. Although registrations are recorded more coarsely than characteristics, the aggregation still identifies the purchased version accurately, and I manually verified fuel economy and CO₂ across versions sharing fuel, engine, and green-car status in *Nybilsguiden*; since the administrative source ties vehicle taxes to fuel, engine, and CO₂, aggregation bias is minimal. Local pollutants are joined by exact keys (year, brand, fuel, engine size) plus fuzzy model-string matching, and imputed by regression where missing.

Contemporary PHEV data (Appendix G). For the contemporary PHEV calibration I combine real-world and type-approval fuel consumption of plug-in hybrids from the EU on-board fuel-consumption monitoring data for registration years 2021–2024 (European Environment Agency 2026), PHEV stocks at end-2023 from Eurostat’s road-vehicle stock statistics, the private/company consumption ratio from Plötz et al. (2022), and company shares of the stock from the national registries where published.

5 Empirical Strategy

To identify the causal impact of the GCR on vehicle CO₂ emissions, this paper’s primary empirical strategy is a DiD design. This approach compares the evolution of CO₂ emissions for alternative-fuel vehicles (AFVs), the “treated” group that benefited from the loophole, to that of regular-fuel vehicles (RFVs), the “control” group. This method allows me to construct a data-driven counterfactual: what would have happened to the average emissions of the AFV portfolio if it had followed the same market-wide trends as the RFV portfolio? The result is thus a “relative change” compared to this counterfactual trend. The validity of this approach is supported by the event-study (Figure 1, right panel), which shows that the two groups followed parallel trends before the policy’s implementation.

Identifying the precise causal impact of the GCR is complicated by the complex strategic behaviour of firms and consumers. Since a single empirical model is unlikely to satisfy all identification assumptions, I adopt a portfolio approach to build a cohesive narrative. My strategy consists of the following steps: (1) I use an event-study to document the timing and dynamics of the market’s reaction; (2) I employ a regression discontinuity (RD) design to test

¹⁶Available at <https://carfueldata.vehicle-certification-agency.gov.uk/>

for sharp structural breaks in conversion probability at the 120 and 220 gCO₂/km boundaries of the regulatory loophole; (3) I use a DiD framework to decompose the supply-side response into its intensive-margin (re-tuning existing models) and extensive-margin (introducing new models) components; (4) I examine the aggregate distributional shift implied by the micro-level responses; (5) I investigate heterogeneity across fuel segments, brand origins, and price segments; (6) I perform robustness tests including placebo and matched DiD specifications; (7) I extend the analysis to the registration data as a complementary equilibrium outcome. In what follows, I describe each component of my empirical strategy, leaving details and robustness to the Appendix.

Event-Study. The event-study consists of a specification of the form

$$y_{it} = \alpha_m + \lambda_t + \sum_{k=2005, k \neq 2007}^{2009} \delta_k (1[t = k] \times AFV_{it}) + \gamma' x_{it} + \varepsilon_{it}$$

where y_{it} are the CO₂ emissions (gCO₂/km) of model-variant i at time t ; α_m are model fixed-effects; λ_t time fixed-effects; AFV_{it} an AFV indicator; x_{it} time-varying product characteristics; and δ_k the event-study coefficients, each measuring the AFV–RFV difference at time k relative to the omitted base year 2007 – jointly assessing pre-trends and the policy’s dynamic effects.¹⁷

DiD. This model quantifies the average effect of the GCR on AFVs relative to RFVs in the post-treatment period by estimating

$$y_{it} = \alpha_m + \lambda_t + \beta(GCR_t \times AFV_{it}) + \gamma' x_{it} + \varepsilon_{it}$$

where GCR_t is a dummy variable equal to 1 for the post-GCR period, and 0 otherwise; β is the DiD coefficient of interest, which measures the average change in y for AFVs after the policy, relative to the change for RFVs.¹⁸

The model fixed-effects α_m absorb every time-invariant characteristic of a brand–model and the time effects λ_t absorb common shocks and market-wide trends, so β is identified from *within-model* variation alone: it compares, say, the AFV and RFV versions of a Volvo V70 in the same year, further netting out time-varying observables such as weight. Cross-model differences – a heavy SUV versus a compact – never enter the estimate.

¹⁷The classification of each model variant remains strictly constant throughout the panel: no product switches treatment status during the sample period.

¹⁸In the supply-side analysis, which is based on yearly data, $GCR_t = 1[t \geq 2008]$ whereas with registration data, which is based on monthly data, $GCR_t = 1[t \geq \text{April } 2007]$.

Heterogeneous effects. I also probe heterogeneity three ways: a fuel-type interaction across AFV technologies (FFV, Gasoline/CNG, Gasoline/Electric); separate domestic- and foreign-brand sub-samples (the brand-origin fixed-effects are collinear in the pooled sample); and a triple difference in pre-policy inflation-adjusted price quartiles. The full tables are in Appendix C.1.

Placebo Test. I estimate a specification to assess the robustness of the results, which reads

$$y_{it} = \alpha_m + \lambda_t + \beta(Placebo_t \times AFV_{it}) + \gamma'x_{it} + \varepsilon_{it}$$

where $Placebo_t$ equals 1 for a counterfactual post-GCR period (e.g. $t \geq 2006$); under the null of correct specification, $\beta = 0$.

Regression Discontinuity. To test the prediction of Proposition 1 that manufacturers targeted the specific (120, 220] gCO₂/km loophole interval, I estimate a sharp regression discontinuity design on the cross-section of pre-policy (2005-2006) incumbent models. The running variable is the model’s pre-policy baseline emissions, defined as the entry-level (lowest-price) trim CO₂ emissions. The outcome is an indicator for whether the model received a fuel-type conversion to AFV status in 2008-2009. I test for discontinuities at both thresholds of the loophole interval (120 and 220 gCO₂/km), using local linear regression with a data-driven MSE-optimal bandwidth where applicable, and cluster standard errors at the brand level.

The primary analysis focuses on the supply-side data, where the event-study provides a clean test of firm response. The supply-side DiD estimand is the Average Treatment Effect on the Treated – the causal impact of the loophole on the models manufacturers chose to offer as AFVs – which is the policy-relevant parameter, since it measures the gaming by exactly the firms and products the asymmetric standard targeted. Because treatment timing is common to all treated units (a single adoption date, no staggering), the two-way fixed-effects estimand is a convex, properly weighted ATT, free of the negative-weighting problem heterogeneous timing induces (Goodman-Bacon 2021; de Chaisemartin and D’Haultfoeuille 2020); parallel trends, tested by the event study, is the sole identifying assumption.

In contrast, I analyse the registration data as important equilibrium outcomes. For these, I interpret the estimates as policy-relevant correlations that complement the story of the GCR’s impact, without claiming strict causality.

6 Results

This section evaluates the supply-side response to the GCR. The event-study (Section 6.1) establishes the aggregate temporal divergence; the regression discontinuity (Section 6.2) examines manufacturer behaviour at the loophole boundaries; the DiD (Section 6.3) quantifies the gaming and its intensive-margin composition; and the distributional analysis (Section 6.4) traces how these micro-responses add up to a shift of the whole Swedish emissions distribution. Robustness, heterogeneity, and registration responses follow in Sections 6.5–6.7.

6.1 Event-Study

To quantify the strategic supply-side response, I first conduct an event-study on vehicle-level CO₂ emissions. The specification controls for model and year fixed-effects, along with standard vehicle performance attributes.¹⁹ The coefficients are plotted in the right panel of Figure 1 (Section 2): the pre-GCR coefficients are statistically insignificant, supporting the parallel trends assumption, while the post-GCR coefficients are positive and significant, confirming a sharp, policy-induced divergence.²⁰

While the event-study documents *when* the change in trends occurred and establishes that it was policy-induced, it does not explain *how* manufacturers achieved it. To verify the intensive-margin gaming mechanism formalised in Proposition 1, the analysis must shift from the aggregate timeline to the micro-level analysis of the policy.

6.2 Strategic Response at the Thresholds

Propositions 1 and 2 posit a specific mechanism behind the descriptive evidence of Section 2: manufacturers selectively exploited the discrete (120, 220] gCO₂/km loophole by converting incumbent models. If so, the probability of an incumbent gasoline model receiving an AFV conversion should break exactly at the loophole’s boundaries. Figure 3 tests this with a sharp regression discontinuity on the cross-section of pre-policy (2005–2006) incumbent models. Because model lines comprise multiple trims, averaging emissions across a line blurs the threshold; I define each model’s baseline as its highest-volume configuration – the entry-level (lowest-price) trim – the platform manufacturers target for price-sensitive subsidy consumers.

Panel A shows the lower bound (120 gCO₂/km). Below it the subsidy is already secured and

¹⁹I include standard controls for vehicle power (HP, Engine Size), a widely used proxy for acceleration (HP/Weight), and a proxy for size (Weight). The results are robust to alternative specifications, such as including a linear time trend or controls for the number of cylinders.

²⁰Stricter fixed-effects (model-engine and model-engine-HP interactions) attenuate but do not eliminate the estimates; because they absorb engine size and HP, they partly “control away” the re-tuning mechanism under study, which is why the reported specifications condition on these attributes rather than absorb them.

the conversion probability is identically zero – a corner solution that precludes local linear inference – while just above it, where automakers face the choice between costly abatement and cheap conversion, the probability jumps to roughly 20 percent.²¹

Panel B examines the upper bound of the eligibility notch (220 gCO₂/km). Because models above this threshold were legally barred from the GCR rebate regardless of fuel-type, Proposition 2 predicts a mechanical drop in gaming probability. Using local linear regression with a data-driven MSE-optimal bandwidth, I estimate a 36.3 percentage point drop in the probability of conversion exactly at the threshold. Since automakers make correlated compliance decisions across their model lineups, I cluster standard errors at the brand level ($G = 41$ clusters), yielding a conservatively robust estimate ($p = 0.071$). Adjusting exclusively for integer mass-points in the running variable (heteroskedasticity-robust standard errors) yields $p = 0.034$.²²

Two standard RD concerns do not bind. Sorting is ruled out by construction: the running variable is each model’s *pre-policy* (2005–2006) certified emissions, fixed before the thresholds existed, so it cannot have been manipulated towards a notch that did not yet bind – a McCrary (2008) density test is not the relevant diagnostic, and what varies at the cutoff is the *ex post* conversion decision alone. On functional form, the 220 gCO₂/km estimate is not an artefact of the bandwidth or kernel choice.²³

Together, the discontinuities at the 120 and 220 gCO₂/km boundaries confirm the regulatory coordinates of the gaming mechanism. To quantify its average magnitude across the fleet, Section 6.3 turns to the DiD. As the welfare analysis (Section 7) shows, the localised boundary bunching typically studied in the literature (e.g., Sallee and Slemrod 2012) accounts for less than 10 percent of the total allocative distortion here; the rest is driven by categorical loophole exploitation.

²¹With zero variance below the threshold (< 120 gCO₂/km) the local variance-covariance matrix is singular, so I rely on the visual discontinuity at the lower bound and estimate the formal RD at the upper bound.

²²The running variable drives this precision. Alternative baselines (the within-model mean or minimum CO₂) blur it: with the model mean, high-emitting, non-converted performance trims smear the density across the 220 gCO₂/km threshold and the attenuated RD estimate is indistinguishable from zero ($p = 0.898$). The discontinuity appears only when the baseline isolates the high-volume, entry-level trim manufacturers targeted.

²³Across one-half, one, and two times the MSE-optimal bandwidth, triangular and uniform kernels, and robust bias-corrected inference, the estimate ranges from -36.5 to -15.2 percentage points, significant at the MSE-optimal bandwidth and attenuating without changing sign. Higher-order local polynomials are omitted (Gelman and Imbens 2019).

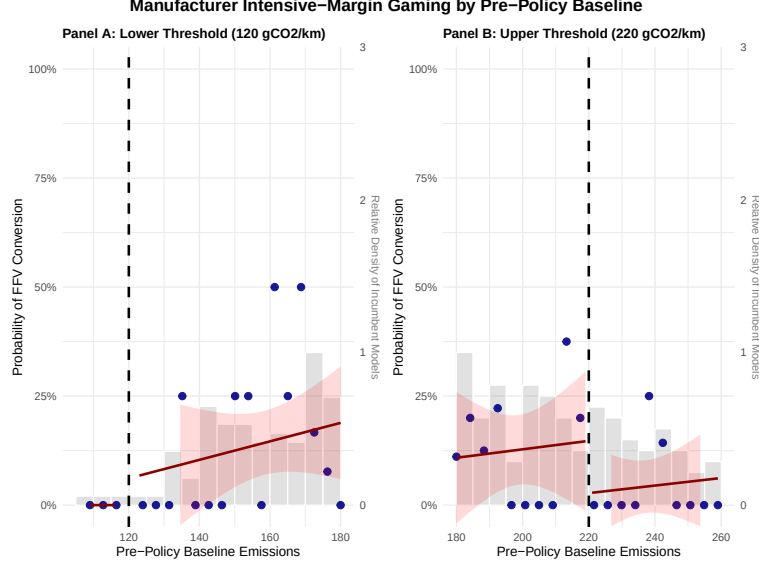


Figure 3: **Intensive-Margin Gaming by Pre-Policy Baseline Emissions.** The figure plots the probability of an incumbent gasoline model (2005-2006) receiving an AFV variant during the policy window (2007-2009) as a function of its pre-policy baseline CO₂ emissions. Panel A tests the lower bound of the loophole (120 gCO₂/km), showing zero probability to the left (mechanically compliant RFVs). Panel B tests the upper bound (220 gCO₂/km), estimating a 36.3 percentage point drop ($p = 0.034$) in conversion probability exactly at the cutoff, confirming the reaction to the regulation. The shaded background histogram depicts the relative density of the incumbent model distribution. I deploy a local linear RD estimator with a triangular kernel, an MSE-minimising bandwidth, and heteroskedasticity-robust standard errors.

Table 1: Decomposing Supply Responses

	Full Sample	Intensive Margin Only	Incumbent AFVs Only
DiD Estimate (GCR x AFV)	14.238*** (3.417)	14.122*** (3.121)	14.731*** (2.788)
Num.Obs.	9282	7501	9253
R ²	0.881	0.870	0.882

Note: All specifications include time and model fixed-effects, plus HP, weight, HP/weight, and engine size. Standard errors clustered at the model level (355 clusters) in parentheses. Wild-cluster bootstrap p -values (Roodman et al. 2019; 999 Rademacher draws) confirm the core interaction is robust across specifications (e.g. $p = 0.003$, 95% CI [4.82, 15.25] in Column 1). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6.3 Decomposing the Supply-Side Strategy

To quantify magnitude of the supply response and decompose the underlying firm strategy, I employ a DiD framework. I estimate the main specification on the full sample and then on subsamples of pre-existing models to isolate the intensive margin (modifying existing product lines) from the extensive margin (introducing new models).

Table 1 quantifies the magnitude of the supply-side response. The baseline DiD estimate

suggests a statistically significant ~ 14 gCO₂/km relative increase in AFV emissions for the full sample (Column 1).²⁴

Restricting the sample to models available pre-GCR (Column 2) – a pure intensive-margin test – leaves the effect statistically indistinguishable from the full-sample estimate. The primary strategic response was therefore the active worsening of existing models to exploit the loophole, rather than the introduction of new “dirty” AFVs.

Finally, I confine the analysis to the full RFV Sample and the sub-sample of AFVs existing prior to the GCR. This is a slightly different cut that isolates the effect on the incumbent AFV models. Once again, the estimate is positive and significant, being slightly larger than full sample estimate. This supports the view that even models that were already AFVs prior to the GCR were made more polluting.

In sum, Table 1 documents that the bulk of the reactions to the loophole came from manufacturers modifying their existing models rather than introducing new products.

Extending the framework to separate interaction terms for the two post-GCR years shows a stronger response in 2009 than in 2008 – 16.6 vs. 10.9 gCO₂/km in the full sample, with the intensive-margin and incumbent-AFV cuts within a point of these – see Table A8 (Appendix C).²⁵

The DiD estimates confirm a sizeable, targeted supply-side response within the loophole, inflating the emissions of the treated fleet relative to the counterfactual. However, point estimates alone cannot capture the full aggregate consequence of this gaming for the Swedish vehicle fleet. Section 6.4 visualises the ultimate impact of the policy on the distribution of CO₂ emissions of the new car fleet.

6.4 The Aggregate Distributional Shift

Figure A1 (Appendix C) sets the kernel density of post-policy (2008–2009) AFV emissions against the counterfactual obtained by projecting the pre-policy AFV distribution forward with the RFV efficiency trend, under the same parallel-trends assumption as the DiD: had AFVs followed the market-wide trend the distribution would have centred near 165 gCO₂/km,

²⁴Standard errors are clustered at the vehicle-model level (355 clusters) here and in every DiD specification below. Because observations are unbalanced across clusters, finite-sample cluster-robust standard errors may over-reject (MacKinnon and Webb 2017); wild-cluster-bootstrap p-values and confidence intervals (Roodman et al. 2019) leave the significance levels unchanged.

²⁵As above, I estimate the dynamic specification for the full sample, the intensive margin, and the sub-sample with all RFVs but only incumbent AFVs; all three show the stronger 2009 response. This is consistent with a time-to-build effect: adjusting a portfolio product usually takes time, so the path of least resistance for car manufacturers is to act on the intensive margin.

whereas the actual distribution clusters in the 180–220 gCO₂/km loophole, the missing mass of efficient vehicles in the 130–160 gCO₂/km range reappearing as excess mass at the top of the loophole – the concentration that, under the capped budget, Section 7 prices as displacement.

6.5 Heterogeneity: Who Exploited the Loophole?

Three cuts of the data – by fuel type, by brand origin, and by price segment – locate the gaming in the FFV segment, across both domestic and foreign brands, and in the upper-middle price tier where the domestic manufacturers concentrate their best-sellers (Tables A5–A7, Appendix C.1).²⁶

6.6 Robustness of Causal Identification

The preceding results – the event-study, RD, DiD, and distributional shift – collectively document a substantial intensive-margin response, and they survive the alternative specifications and identification checks reported in Appendix C.3.²⁷

6.7 Registration Responses

On the demand side, the equilibrium (registration) response is smaller than the 14.2 gCO₂/km supply estimate – consumers partially absorbed the heavier gamed FFVs rather than taking them up in proportion to supply – with a significant pre-trend that reflects buyer-pool composition rather than anticipation, which is why I report the registration evidence as descriptive corroboration rather than a causal estimate; the full tables are in Appendix C.5.

7 Welfare Analysis and Environmental Impact

With the theoretical framework and empirical evidence established, I now quantify the welfare effects of the policy. I first quantify the CO₂ damages attributable to the supply side and the allocative welfare loss of Proposition 3 (Section 7.1), then the losses from consumer fuel choice (Section 7.2) and the bounds for the Fiscal Loop Premium that yield the total social cost of the GCR (Section 7.3). I evaluate the welfare-maximising subsidy of Proposition 4 against the actual rebate (Section 7.4) and close by discussing the external validity of Proposition 5

²⁶The FFV concentration reflects the low conversion cost of a captive gasoline model; the larger foreign-brand increase (14.0 vs. 9.0 gCO₂/km) reflects the domestic fleet’s heavier starting position. By price, the rebate was a genuine incentive in the value-oriented Q2 tier (−10.1 gCO₂/km) and a subsidy for stagnation in the Q3 tier of Volvo’s and Saab’s best-sellers (+4.2, insignificant), though price quartiles correlate strongly with the model fixed-effects, so these estimates are suggestive.

²⁷Beyond the event-study of Figure 1, a 2006 placebo test yields a null effect, ruling out pre-existing divergent trends, and matched DiD specifications comparing AFVs to more similar RFVs leave the estimates qualitatively unchanged, ruling out simple compositional differences.

for contemporary PHEV markets (Section 7.5). Appendix G documents that the FFV results carry over to today’s PHEVs.

Counterfactuals. Three distinct baselines enter the accounting, each stated where it is used. The *allocative* cost is measured against the efficient vehicle a gamer displaces from the capped budget – an RFV at the statutory $\bar{e}^{RFV} = 120$ gCO₂/km threshold (Section 7.1). The *Fiscal Loop Premium* is measured against a genuine abater ($\phi = 0$, full alternative-fuel use): it is the fuel-tax revenue a gamer’s fossil driving preserves that a pure abater would have destroyed. Only the *consumer fuel-choice damages* (Section 7.2) are measured against the informal policy expectation that FFVs would run on ethanol about 75 percent of the time ($\phi^{\text{benchmark}} = 0.25$); Section 7.2 sets out this benchmark and its sensitivity. The fuel-choice emissions cost that enters the net social cost (Section 7.3) is, like the Premium, measured at $\phi = 0$, so the two sides of that ledger share one baseline; the optimal-subsidy evaluation (Section 7.4) likewise uses the full-abatement world rather than the 25 percent benchmark.

7.1 The Environmental Cost of Gaming

The supply-side gaming documented in Section 6.3 generates two distinct environmental costs: a direct emissions penalty from the DiD-estimated CO₂ increase, and an allocative displacement cost from budget exhaustion.²⁸

Direct emissions cost. I value the excess CO₂ from supply-side gaming across the two DiD estimates (14 and 17 gCO₂/km, from Tables 1 and A8), three carbon prices (EUR 10, 40, and 75 per tonne), and two lifetime-mileage assumptions (230,000 and 300,000 km; Huse and Lucinda 2014), evaluating volumes at the bootstrapped median of $N_G = 36,924$ gamed units (the full scenario grid is produced by the replication code).

Direct gross damages span EUR 1.2–14.1 mn. Two focal scenarios carry forward: a Central Scenario (14 gCO₂/km, EUR 40/tonCO₂, 230,000 km) at EUR 4.8 mn and a High-Cost Scenario (17 gCO₂/km, EUR 75/tonCO₂, 300,000 km) at EUR 14.1 mn.²⁹ These figures value the re-design channel only; they do not yet account for the opportunity cost of the exhausted budget.

Allocative displacement cost. To quantify the opportunity cost W_{loss} without relying on

²⁸The displacement operates through the programme’s total fiscal envelope rather than through instantaneous crowding-out (Assumption 3): the budget was expanded to meet 2007-2008 demand, so displacement was deferred until the gamed cohort’s cumulative draw forced premature termination in June 2009, shutting genuine abatements out in the final months.

²⁹The EUR 10/tonCO₂ alternative reflects the EU ETS price and the ex-ante information at the GCR’s design, but is very low by current standards; adopting EUR 40 as the primary benchmark subjects the policy to a stricter modern ex-post evaluation.

ad-hoc baseline assumptions, I fix the counterfactual at the statutory $\bar{e}^{RFV} = 120$ gCO₂/km threshold and estimate the allocative welfare loss with a non-parametric bootstrap – in the spirit of the bunching and notch estimators (Chetty et al. 2011; Kleven and Waseem 2013) – of 1,000 resampling iterations, drawing vehicles with replacement at the model-month (the cluster) level from the post-policy dataset. For each draw, I calculate the gamed volume (N_G), the sales-weighted baseline emissions ($\bar{e}_G^{AFV}$), and the resulting W_{loss} under the same two scenarios (Central and High-Cost). Point estimates are bootstrap medians; confidence intervals are the 2.5th and 97.5th percentiles.

Allocative loss. Under the broad definition – every subsidised AFV emitting above $\bar{e}^{RFV}$ displaces an efficient RFV – the median gamed volume is 36,924 units at a sales-weighted 182.2 gCO₂/km, each displacing an RFV emitting 62.2 gCO₂/km less (Panel A, Table 2); the 95 percent interval for the opportunity cost is EUR 18.1–24.1 mn (central) and EUR 44.3–59.0 mn (high-cost). A secondary bootstrap restricted to incumbent RFV-to-AFV conversions – pre-2007 gasoline models subsequently offered as FFV variants at unchanged certified emissions, matched to their pre-policy counterparts by model and engine – captures 98.6 percent of that volume (Panel B). The gaming share θ is defined on this loophole-zone cohort – the 36,924 subsidised AFVs certified above $\bar{e}^{RFV}$ – and $\theta = 0.986$ is its strict incumbent-conversion share (36,422/36,924); the remaining 502 units are new-entrant AFV variants above 120 gCO₂/km, gamers on the broad definition ($\theta = 1.00$) and non-gamers only if gaming means relabelling an incumbent.³⁰ The loss was driven almost entirely by strategic relabelling of existing high-emission platforms, as Proposition 1’s corner solution predicts, rather than by newly engineered or genuinely efficient alternative-fuel models.

Bunching versus the loophole. The RD design confirms classical bunching at the 220 gCO₂/km cutoff (Figure 3, Panel B), but under a binding budget its welfare arithmetic differs from the standard single-threshold case: a buncher engineered down to $e_{\text{post}} \approx 212$ gCO₂/km still displaces a vehicle at $\bar{e}^{RFV} = 120$, so its net penalty against that benchmark is at least 84 gCO₂/km – the displacement cost exceeds the maximum possible abatement benefit elevenfold. Isolating the bunchers (Panel C of Table 2), the 2,338 bunched vehicles are 6.3 percent of the gamed volume but only about 9 percent (EUR 4.8 mn) of the broad allocative loss; the remaining 91 percent comes from loophole gamers who converted high-emission

³⁰Three facts make the share a gaming share rather than a reclassification count: no subsidised FFV variant emits at or below 120 gCO₂/km, so none qualified through abatement; the matched conversions carry unchanged certified emissions by construction; and the 36 percentage point drop in conversion probability at the 220 gCO₂/km edge (Figure 3) signals threshold targeting. The identification is tight for the GCR and loose for plug-in hybrids, where the battery is a real attribute (Section 7.5). θ enters S^* as a cohort average; the welfare-unit ledger uses only the gamed count N_G .

models without any marginal abatement. The welfare cost of the GCR’s asymmetric design is thus dominated by the displacement gap integrated over the entire loophole interval, which W_{loss} in equation (1) already captures, with localised bunching at the upper threshold a minor component. Appendix B.3 gives the per-vehicle penalty and its aggregation in full.

Table 2: **Bootstrap Estimates: Allocative Welfare Loss by Gaming Definition**

Sample Definition	Median Volume (N_G)	Median Emissions ($\bar{e}_G^{AFV}$, gCO ₂ /km)	Central SCC (€40/t, 230k km)		High SCC (€75/t, 300k km)	
			Median (€ mn)	95% CI	Median (€ mn)	95% CI
Panel A: Broad Definition						
All AFVs > 120 gCO ₂ /km	36,924	182.2	21.13	[18.12, 24.12]	51.67	[44.31, 59.00]
Panel B: Strict Definition						
Incumbent RFVs only	36,422	182.3	20.89	[17.86, 23.90]	51.08	[43.67, 58.45]
Panel C: The “Bunchers”						
AFVs ∈ (210, 220] gCO ₂ /km	2,338	212.0	1.98	[1.18, 2.79]	4.84	[2.89, 6.83]
AFVs ∈ (200, 220] gCO ₂ /km	7,824	207.5	6.29	[4.52, 8.21]	15.39	[11.07, 20.08]

Notes: Estimates are derived from a non-parametric bootstrap with 1,000 resampling iterations at the model-month level to account for sampling variance and compositional market shifts. Point estimates represent the median of the bootstrap distribution; confidence intervals represent the 2.5th and 97.5th percentiles of the bootstrap distribution. The allocative opportunity cost is calculated relative to the statutory 120 gCO₂/km standard (the threshold for genuine abatement) using $W_{\text{loss}} = \tau \cdot N_G \cdot (\bar{e}_G^{AFV} - 120) \cdot \text{VKT}/10^6$. The “Central SCC” scenario assumes $\tau_E = \text{EUR } 40/\text{ton}$ and a lifetime VKT of 230,000 km. The “High SCC” scenario assumes $\tau_E = \text{EUR } 75/\text{ton}$ and a lifetime VKT of 300,000 km. The “Strict” definition restricts the sample exclusively to incumbent RFV models converted to AFVs post-policy, capturing 98.6% of the broad allocative failure.

7.2 Consumer Fuel Choice and the Arbitrage Problem

The defining feature of dual-fuel technologies is fuel optionality – the physical capacity to switch between the fossil and the alternative fuel on any trip based on relative prices and convenience (Anderson 2012; Salvo and Huse 2013). An asymmetric subsidy granted at acquisition therefore pays for the *capacity* to run clean without securing its *utilisation*, creating a post-purchase moral hazard. The entire justification for the loophole rested on the implicit assumption that eligible vehicles would run predominantly on renewable fuel. No target was codified, but Swedish transport authorities routinely evaluated FFVs at 70–80 percent renewable use,³¹ the benchmark against which I measure the behavioural failure; a sensitivity analysis (Table A14) shows the conclusions hold across a 60–90 percent range.

To determine the actual share of lifetime vehicle kilometres (VKT) driven on gasoline by the subsidised AFV fleet – the empirical counterpart of the model’s utilisation parameter ϕ , which I denote $\hat{\phi}$ – I conduct a structural calibration based on observed aggregate fuel sales and price variation. Specifically, I *calibrate* this share by exploiting the 2008 oil price collapse as a source of exogenous variation in relative fuel prices. The recession-driven drop in global oil prices passed through to Swedish gasoline prices, shifting the energy-adjusted price ratio p_e/p_g from below the no-arbitrage threshold $k \approx 0.70$ in July–August 2008 to

³¹Part of that residual gasoline use was expected on cold-weather grounds: E85 starts poorly at low temperatures, and winter grades add gasoline, so FFVs were anticipated to run partly on gasoline through the coldest months – roughly a quarter of the year – broadly matching the 25 percent gasoline benchmark. The 35.9 percent gasoline share estimated below exceeds even this weather-adjusted allowance.

above it in November-December 2008, as depicted in Figure 4. This price reversal provides two distinct fuel-choice regimes from which the shares of ethanol lovers, gasoline lovers, and fuel arbitrageurs can be recovered.³²

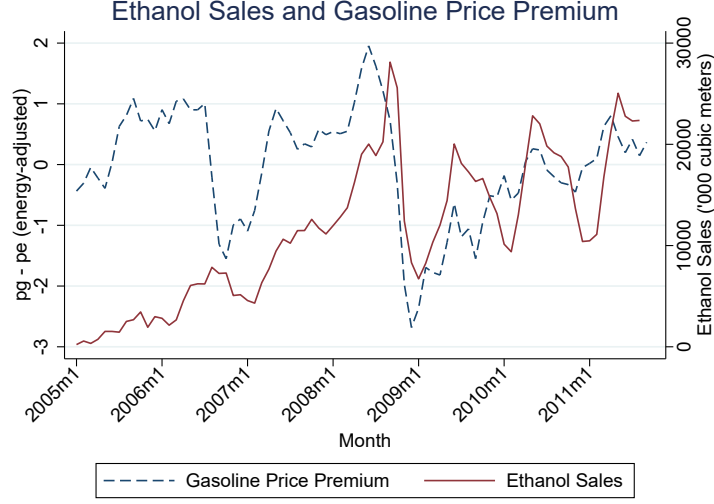


Figure 4: **Ethanol Sales and Gasoline Price Premium.** Ethanol sales and the gasoline price premium (energy-adjusted gasoline minus ethanol price; gasoline is 'cheap' when the premium is negative). Sales trend up with the expanding FFV fleet and show winter seasonality (E85 starts poorly in the cold), but also respond to the price premium. The calibration exploits the exogenous swing in the premium from the Fall 2008 oil-price collapse to back out the consumer-type shares.

The model distinguishes three consumer types. Ethanol-lovers (σ_e) and gasoline-lovers (σ_g) have sticky fuel choice; fuel arbitrageurs (σ_a) switch to whichever fuel offers the lowest energy-adjusted cost per kilometre.

The calibration yields shares of $(\sigma_e, \sigma_a, \sigma_g) = (0.421, 0.523, 0.056)$. The majority of FFV owners were price-sensitive arbitrageurs, consistent with the fuel optionality framework of Anderson (2012) and Salvo and Huse (2013).

Using these shares, I calculate the empirical aggregate share of lifetime VKT driven on gasoline: $\hat{\phi} = \sigma_a \pi + \sigma_g$, where π is the long-run probability that gasoline is cheaper than ethanol on an energy-adjusted basis. Evaluating π over the long-run (2005–2009) window at

³²Two caveats on this variation warrant note. The 2008 collapse was recession-driven and so potentially also reduced kilometres driven; because $\hat{\phi}$ is read off the *change* in ethanol volume between the two price regimes, a common vehicle-kilometres shock largely differences out, and I treat the calibrated gasoline share as an upper bound (Appendix D). And a fully econometric estimation of fuel choice requires a longer panel than the 2005–2009 window allows; I develop it in related work (Huse 2018), adopting here the transparent two-regime calibration that exploits the same 2008 reversal. For the same reason I do not model the vehicle-purchase decision structurally: the conversion carried no price premium of note and the rebate was a lump sum, so the purchase margin enters through the registration response of Section 6.7 and the welfare calculation conditions on the realised subsidised cohort.

the constant energy ratio $k \approx 0.70$ – the ratio of ethanol to gasoline fuel economy – gives $\pi = 0.58$ and a central $\hat{\phi} = 0.359$.³³ Subsidised FFV owners therefore drove 35.9 percent of their total kilometres on conventional gasoline, well above the 25 percent implied by the informal 75 percent ethanol benchmark; the welfare analysis below sets the utilisation parameter ϕ to this estimate, $\hat{\phi} = 0.359$.³⁴

A continuous-heterogeneity alternative corroborates the discrete-type calibration. Regressing the log-odds of the FFV fleet’s monthly ethanol share on the energy-adjusted price premium yields a strongly significant price response, a mean willingness to pay for ethanol indistinguishable from zero at energy-price parity, and wide dispersion – exactly the configuration a majority-arbitrageur market implies, and robust to calendar-month fixed-effects (Appendix D, Table A11). The regression pins down the price sensitivity and dispersion; the *level* of the implied gasoline share depends on a fleet-usage normalisation that aggregate data cannot identify, which is why I retain the transparent two-regime calibration.

Table A12 (Appendix D) quantifies the CO2 cost of the fuel choice failure. Combining the calibrated gasoline share $\hat{\phi} = 0.359$ with the deviation from the 75 percent ethanol benchmark, the excess CO2 damages from gasoline substitution range from EUR 0.62 mn to 6.11 mn depending on the carbon price and lifetime VKT scenario. Local pollutant effects are excluded from the cost-benefit accounting because the parallel-trends assumption fails for those outcomes.

However, this environmental damage represents only a partial accounting of the policy’s overall welfare cost. By choosing heavily taxed gasoline over tax-favoured ethanol, these drivers preserved Sweden’s pre-existing fuel tax base – the mechanism formalised as the Fiscal Loop Premium in Proposition 4 and quantified in the next subsection.

7.3 The Fiscal Loop Premium and Net Social Cost

The behavioural failure is also, in a second-best tax environment, an economy-wide fiscal offset. By driving the gamed cohort on heavily taxed gasoline rather than the intended ethanol, consumers preserved the pre-existing fuel-tax base ($\Delta q_f > 0$); where public funds carry a shadow premium ($\mu = \lambda - 1 > 0$, with λ the marginal cost of public funds), this preserved base acts as a Ramsey-like corrective that partially offsets (and, above a threshold

³³ $\hat{\phi}$ depends on the energy-adjustment convention (derived in the replication code): the constant long-run ratio $k = 0.70$ used here gives $\pi = 0.58$ and $\hat{\phi} = 0.36$; the seasonal pump blend of Figure 4 instead gives $\pi = 0.47$ and $\hat{\phi} = 0.30$; and the continuous log-odds route (Appendix D) implies $\hat{\phi} \approx 0.51$. I carry $\hat{\phi} \approx 0.36$ as central and report the welfare sensitivity across the $[0.30, 0.51]$ range below.

³⁴The calibration treats vehicle-kilometres as price-inelastic; Appendix D shows that correcting for price-elastic fuel demand shifts the aggregate gasoline share by under three percentage points, leaving the Fiscal Loop Premium and the welfare conclusions unchanged.

fossil share, fully offsets) the deadweight loss of the loophole. Unlike the classical double dividend, in which a well-designed environmental tax delivers both abatement and revenue (Bovenberg and de Mooij 1994; Goulder 1995), the recovery here arises directly from the policy’s *failure* (Proposition 4).

To quantify the Net Social Cost of the GCR, one must aggregate four components: the allocative opportunity cost (W_{loss}) from Proposition 3, the shadow cost of financing the subsidy payout itself, the gamed cohort’s own emissions from burning gasoline in place of ethanol, and the Fiscal Loop Premium from Proposition 4.³⁵ Since the magnitude of this fiscal premium depends on the share of lifetime kilometres driven on taxed gasoline ($\hat{\phi}$), I can bound the net social cost across the full theoretical domain of consumer behaviour, $\hat{\phi} \in [0, 1]$. Figure 5 displays this bounding exercise under the Central Scenario.

Gross damages have a fixed part – the environmental displacement cost plus the shadow cost of the rebate, EUR 29.1 mn under the Central Scenario, incurred whatever the cohort burns – and a part that rises with the gasoline share: the gamers’ own emissions from burning gasoline in place of ethanol, valued at the net lifecycle carbon content of the litres displaced (the dashed upper line). Against these the Fiscal Loop Premium, the shaded wedge, rises faster in $\hat{\phi}$, because at Swedish tax rates the fiscal value of a litre of gasoline, $\mu\tau_f$, exceeds its net carbon damage at $\tau_E = 40$; the Net Social Cost therefore slopes downward and crosses zero at $\hat{\phi} \approx 0.75$: the gamed rebate would have been self-financing only had the cohort driven about three-quarters of its kilometres on gasoline.

Table 3 aggregates the four components – which map onto Corollary 2 on two margins: the certified 62.2 gCO₂/km gap to the RFV threshold prices what a gamed vehicle displaces (W_{loss}), and the whole-tank litres an FFV on ethanol would have displaced price what its driver burns instead (the fuel-choice emissions cost and the Fiscal Loop Premium) – at the empirical calibration ($\hat{\phi} = 0.359$). The flawed design generated gross social costs of EUR 41.0 mn in the Central Scenario (EUR 88.8 mn in the High-Cost Scenario); because the government (unintentionally) hedged its environmental failure with standard fuel taxes, the Fiscal Loop Premium of EUR 25.8 mn offsets about three-fifths of it, leaving a Net Social Cost of EUR 15.2 mn (EUR 55.2 mn in the High-Cost Scenario). Both the Premium and the fuel-choice emissions cost scale with the fossil share, the Premium faster, so across the $[0.30, 0.51]$ range for ϕ the Central-Scenario net social cost runs from EUR 17.5 mn (at $\phi = 0.30$) to EUR 9.4 mn (at $\phi = 0.51$); the EUR 15.2 mn headline is the central $\phi = 0.36$ value.

³⁵ As the supplementary appropriations (tilläggsbudgetar) were funded through general taxation, the standard MCPF still applies to the entire 815 mn SEK cumulative envelope, see Section 2.3.

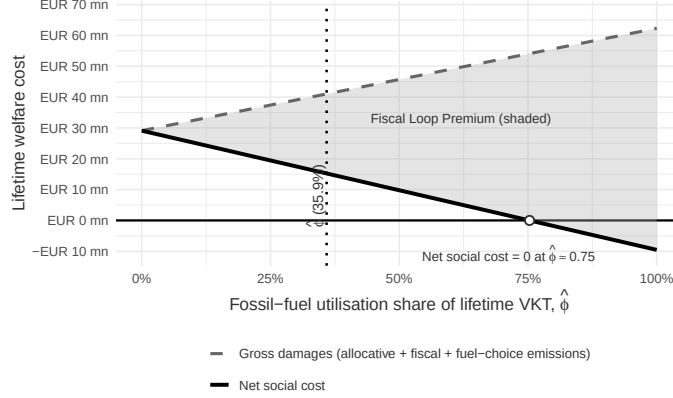


Figure 5: **Bounding the Fiscal Loop Premium.** The figure illustrates the bounds of the net social cost of the Green Car Rebate across the full domain of consumer fuel choice ($\hat{\phi}$) conditional on the central scenario. The dashed line is gross damages: the allocative opportunity cost of the premature exhaustion of the subsidy budget (Proposition 3) and the shadow cost of the rebate, EUR 29.1 mn at any $\hat{\phi}$, plus the gamed cohort's own emissions from burning gasoline in place of ethanol, which rise with $\hat{\phi}$. The solid line is the Net Social Cost, which nets out the fiscal value of the preserved gasoline tax base (Proposition 4). The shaded region – the Fiscal Loop Premium – is the deadweight loss recovered by the public treasury ($\tau_f \times \mu$ per litre) as consumers substitute towards the heavily taxed fossil fuel. The vertical dotted line denotes the empirical calibration ($\hat{\phi} = 35.9\%$), at which the Premium offsets about three-fifths of gross damages; the Net Social Cost reaches zero only at $\hat{\phi} \approx 0.75$.

Table 3: Net Social Cost of the Green Car Rebate Loophole

Welfare Component	Central Scenario	High-Cost Scenario
	($\tau_E = 40$ EUR, VKT=230k)	($\tau_E = 75$ EUR, VKT=300k)
1. Gross Damages & Fiscal Costs		
Shadow Cost of Rebate Financing	EUR 8.0 mn	EUR 8.0 mn
Allocative Opportunity Cost (W_{loss})	EUR 21.1 mn	EUR 51.7 mn
Fuel-choice emissions cost (gasoline in place of ethanol)	EUR 11.9 mn	EUR 29.1 mn
Total Gross Damages	EUR 41.0 mn	EUR 88.8 mn
2. Fiscal Recovery		
Fiscal Loop Premium ($\hat{\phi} = 35.9\%$)	(EUR 25.8 mn)	(EUR 33.6 mn)
Net Social Cost	EUR 15.2 mn	EUR 55.2 mn

Notes: This table aggregates the welfare impact of the GCR loophole at the empirically calibrated gasoline share ($\hat{\phi} = 35.9\%$). The Allocative Opportunity Cost (W_{loss}) is the carbon displacement cost of the budgetary exhaustion by the $N_G = 36,924$ gamed vehicles, measured on the 62.2 gCO₂/km certified gap to the RFV threshold. The fuel-choice emissions cost is the gamers' own CO₂ from burning gasoline in place of the intended ethanol, $N_G \hat{\phi} \Delta q_A \Delta c \tau_E$, with $\Delta q_A = \text{VKT}/13$ km/L the whole-tank litres an FFV on ethanol displaces and $\Delta c = 1,270.5$ gCO₂/L the net lifecycle carbon content of gasoline relative to ethanol (a 55 percent lifecycle saving). The pure financial transfer of the rebate to the gamed cohort (EUR 39.9 mn) is converted to a real resource cost using the marginal deadweight loss of taxation ($\mu = 0.2$), yielding the Shadow Cost of Rebate Financing. Symmetrically, the Fiscal Loop Premium is the deadweight loss *recovered* via the pre-existing gasoline tax ($\tau_f = 0.55$ EUR/litre) on the same litres, $N_G \mu \tau_f \hat{\phi} \Delta q_A$. Values in parentheses represent a welfare recovery.

Three implications follow. First, the asymmetric threshold – not the subsidy level – was the primary cause of the allocative failure, confirming the superiority of continuous instruments over binary step-functions (Weitzman 1974). Second, the dominance of intensive-margin gaming is a rational response to the discrete cost structure: when conversion costs under EUR 150 and physical abatement an order of magnitude more, attribute-based regulation systematically subsidises arbitrage. Third, the Fiscal Loop Premium is a property of Sweden’s high fuel tax: in lower-tax environments such as the United States the offset is far weaker and the net social cost correspondingly larger (Appendix F) – subsidising fuel optionality without enforcing utilisation carries welfare consequences that depend entirely on the underlying tax regime.

This mechanism operates at first-order scale today: a five-market PHEV calibration (Section 7.5, Appendix G) puts the annual Excess Fiscal Loop Premium, the fuel-tax revenue the type-approval rating assumed away, at EUR 202 mn.

7.4 Evaluating the Optimal Subsidy

With $\theta = 0.986$, $\phi = 0.359$, the whole-tank abatement an FFV on ethanol delivers ($\Delta q_A = \text{VKT}/13 \text{ km/L}$, valued at the net lifecycle carbon content of the litres displaced), and the pre-existing fuel tax in hand, I compute the welfare-maximising subsidy S^* of Proposition 4 directly and compare it to the actual rebate of EUR 1,081 (10,000 SEK). To show the verdict is robust to the behavioural parameter, I present S^* as a bounding exercise between the “pure gaming” benchmark of Ito and Saltee (2018), $\phi = 1$, and the empirically calibrated $\phi = 0.359$, holding the firm-side gaming rate fixed.

Table 4 reports the bounding calibration. Under the Central Scenario, the welfare-maximising rebate is EUR -71 at $\phi = 1$ (pure gaming) and EUR $-3,381$ at $\hat{\phi} = 0.359$ (empirical partial gaming), and runs from EUR $-3,686$ to EUR $-2,602$ across the $\hat{\phi} \in [0.30, 0.51]$ range: the GCR was a sizeable over-subsidy, and the welfare-maximising instrument was a vehicle *tax*. The negative value comes from a negative Benchmark subsidy, as the next paragraph sets out; the gaming parameters enter only through the factor $(1 - \theta\phi) \in [0, 1]$, which scales S^* but cannot flip its sign. S^* stays negative in every scenario, including the High-Cost Scenario ($\tau_E = 75, 300,000 \text{ km}$), where it is EUR -23 at $\phi = 1$ and EUR $-1,096$ at $\hat{\phi}$.

The two channels of over-subsidisation. Through the compact formulation (3), the first driver is the Benchmark subsidy, negative for carbon prices below EUR 86.6 per tonCO₂ even with zero gaming: genuine abatement destroys $\tau_f \Delta q_A$ of fuel-tax revenue per vehicle (EUR 9,731 over 230,000 km), and when this base-erosion penalty exceeds the scaled environmental benefit the Benchmark turns negative – the fiscal mirror image of the double dividend

Table 4: Evaluating the Optimal Subsidy Welfare Bounds

τ_E	VKT	Components of S^*			S^*
		Benchmark	Env. Penalty	Fiscal Loop	

Bound 1: Pure Behavioural Gaming ($\phi = 1.0$)					
10	230k	-8,607	1,109	9,598	-117
10	300k	-11,226	1,446	12,520	-153
40	230k	-5,235	4,434	9,598	-71
40	300k	-6,828	5,784	12,520	-93
75	230k	-1,301	8,315	9,598	-18
75	300k	-1,698	10,845	12,520	-23
Bound 2: Partial Behavioural Gaming ($\phi = 0.359$)					
10	230k	-8,607	398	3,446	-5,559
10	300k	-11,226	519	4,495	-7,251
40	230k	-5,235	1,592	3,446	-3,381
40	300k	-6,828	2,077	4,495	-4,410
75	230k	-1,301	2,985	3,446	-841
75	300k	-1,698	3,893	4,495	-1,096

Notes: EUR per vehicle. The welfare-maximising subsidy S^* is computed from equation (2) using $\theta = 0.986$ (the incumbent-conversion share of the loophole-zone AFV cohort), $\mu = 0.20$, and $\tau_f = 0.55$ EUR/L. Δq_A is the intended per-vehicle abatement of the target technology: ethanol substitution over the whole tank, $\Delta q_A = \text{VKT}/13 \text{ km/L}$ (17,692 L at 230,000 km), valued at the net lifecycle carbon content of the gasoline displaced, $\Delta c = 2,310 \times 0.55 = 1,270.5 \text{ gCO}_2/\text{L}$, so $\Delta E_A = 22.5 \text{ t}$ (230k) and 29.3 t (300k). The actual posted subsidy was EUR 1,081. The critical carbon price $\tau_E^{crit} = \mu\tau_f/\Delta c$ (where $S^* = 0$) is invariant to ϕ , θ and VKT and equals EUR 86.6 per tonne (EUR 47.6 if ethanol is treated as carbon-free, $\Delta c = 2,310 \text{ gCO}_2/\text{L}$); S^* is negative in every cell.

(Bovenberg and de Mooij 1994; Goulder and Parry 2008), and the Swedish calibration puts it below zero across the relevant range. The second driver is the effective abatement share $(1 - \theta\phi)$ scaling the Benchmark: 0.014 under pure gaming, 0.646 at the empirical ϕ ; both scale a negative Benchmark, so the over-subsidisation verdict is robust across the realistic parameter space.

The invariant critical carbon price. Because S^* scales the Benchmark by $(1 - \theta\phi)$, the critical carbon price τ_E^{crit} at which $S^* = 0$ (whenever $\theta\phi < 1$) is invariant to both θ and ϕ – and to vehicle lifetime – set by the jurisdiction’s fuel tax, excess burden, and the net carbon content of the litres the target technology displaces.³⁶ For Sweden $\tau_E^{crit} = 86.6$ EUR/tonCO₂, so the Fiscal Loop Premium dominates the Environmental Penalty in all three scenarios (per gamed vehicle at the Central Scenario, EUR 3,446 against EUR 1,592). This sits far above the EU ETS price during the GCR’s design and operation – below EUR 30 per tonne throughout 2005–2008 and near zero in 2007 – placing Sweden in the regime where any

³⁶Setting $S^* = 0$ in equation (2) with $\theta\phi < 1$ yields $\tau_E^{crit} = \mu\tau_f\Delta q_A/\Delta E_A = \mu\tau_f/\Delta c$, where Δc is the net carbon content per litre displaced. For ethanol in place of gasoline, $\Delta c = 2,310 \times 0.55 = 1,270.5 \text{ gCO}_2/\text{L}$ on the 55 percent lifecycle saving of Appendix B, so for Sweden ($\mu = 0.20$, $\tau_f = 0.55$ EUR/L) $\tau_E^{crit} = 86.6$ EUR/tonCO₂, independent of VKT. Treating ethanol as carbon-free ($\Delta c = 2,310 \text{ gCO}_2/\text{L}$) – the convention under which the policy was designed, and the relevant one for an efficient conventional car displacing gasoline outright – gives the special case $\tau_E^{crit} = 47.6$.

positive vehicle rebate was welfare-reducing, a constant policymakers can compute ex ante.³⁷

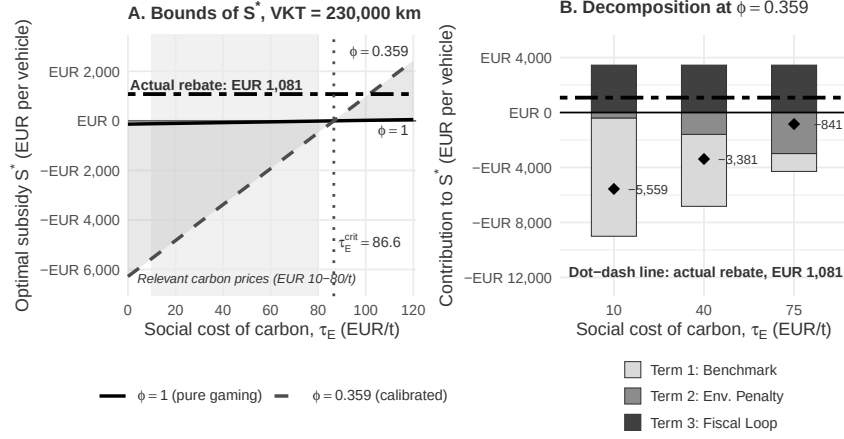


Figure 6: The Optimal Subsidy vs. Actual Policy Design. Panel A compares the welfare-maximising subsidy (S^* , solid line at $\phi = 1$, dashed at $\phi = 0.359$) against the actual Swedish Green Car Rebate (two-dash line) across carbon prices (τ_E). The actual policy over-subsidised the dual-fuel technology at every carbon price up to $\tau_E^{crit} = 86.6$, where $S^* = 0$ for every ϕ . Panel B decomposes S^* (black diamonds) into its structural determinants for a standard 230,000 km vehicle lifetime. The negative Benchmark (Term 1) and the environmental penalty from regulatory gaming (Term 2) depress the optimal subsidy; the perverse fiscal dividend of the preserved gasoline tax base (Term 3, EUR 3,446 per vehicle) offsets part of it. Evaluated at $\theta = 0.986$, $\mu = 0.2$, $\tau_f = 0.55$ EUR/litre, $\Delta q_A = \text{VKT}/13$ km/L and $\Delta c = 1,270.5$ gCO₂/L.

Figure 6 visualises the result: the actual rebate of EUR 1,081 sits above the optimal bounds across the entire empirically relevant range and up to τ_E^{crit} (Panel A), while Panel B shows the Fiscal Loop Premium partially offsetting the Environmental Penalty and the negative Benchmark, which together anchor the net below zero. To my knowledge this is the first empirical evaluation of an optimal corrective subsidy that jointly embeds structural gaming, behavioural utilisation, and pre-existing fiscal distortions – and the τ_E^{crit} formula is a simple ex ante diagnostic any jurisdiction can apply before committing to a vehicle subsidy.

7.5 The Global Validity of the Anatomy Proposition

The three Anatomy conditions are not specific to Swedish flex-fuel; they map directly onto the plug-in-hybrid subsidies that dominate today’s vehicle-policy debate, and both parameters retain measurable content. On the supply side, a PHEV clears the favourable company-car and fleet-CO₂ treatment triggered by a low certified rating (typically ≤ 50 gCO₂/km under WLTP) with a minimum-viable battery and an optimised test cycle – Assumption 2 in a

³⁷ τ_E^{crit} scales linearly in the marginal cost of public funds, so across the plausible range $\mu \in [0.10, 0.30]$ (roughly 0.15–0.30 across Europe; Bastani 2023; Kleven and Kreiner 2006) it spans EUR 43–130 per tonCO₂ and the GCR-era carbon price lies below it for *every* plausible μ : the negative-subsidy conclusion is robust to the MCPF. The Premium’s welfare value, $N_G \mu \tau_f \phi \Delta q_A$, also scales linearly in μ – roughly halved at $\mu = 0.10$ and raised by half at $\mu = 0.30$ – whereas Term 3 of S^* , $\theta \phi \tau_f \Delta q_A$, carries no μ : in subsidy units the fiscal offset is fixed by the tax rate and the litres alone.

different technology (Plötz et al. 2022).³⁸ The asymmetric threshold (Assumption 1) is here the gap between the type-approval rating and real-world emissions, and the binding budget (Assumption 3) generalises to fiscal caps, licence-plate quotas, and fleet-wide standards.

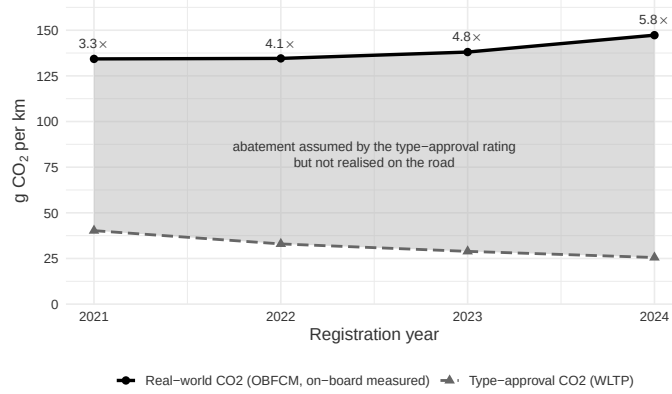


Figure 7: The Widening PHEV Gap: Real-World versus Type-Approval CO2. Fleet-weighted CO2 of plug-in hybrids registered in the EU-27, Norway and Iceland by registration year, from the EU on-board fuel-consumption monitoring (OBFCM) data published by the European Environment Agency under Regulation (EU) 2019/631 and Implementing Regulation (EU) 2021/392. Real-world emissions rise from 134 to 147 gCO₂/km across the 2021–2024 cohorts while the WLTP rating falls from 40 to 26; the ratio climbs from 3.3 to 5.8. The 2024 cohort is observed for a shorter period and is smaller (193,735 vehicles against 312,000–340,000 in each of the 2021–2023 cohorts), so its point is provisional. The figure covers petrol PHEVs; Table 5 pools petrol and diesel PHEVs, whose pooled real-world consumption is 6.19 L/100km against 6.04 for petrol PHEVs alone. Shaded: abatement assumed by the rating and not realised on the road.

On the demand side, that gap is now measured officially, and it is widening. Since 2021 the EU has collected, and the European Environment Agency now publishes, the on-board fuel-consumption readings of every newly registered car (European Environment Agency 2026); Figure 7 plots the fleet-weighted result for plug-in hybrids, whose real-world CO₂ climbs from 3.3 to 5.8 times the type-approval rating across the 2021–2024 cohorts – the certified number improving as the road outcome worsens. For a PHEV I define ϕ operationally as the ratio of real-world to charge-sustaining consumption, $\phi_{PHEV} = FC_{RW}/FC_{CS}$, both observed on board: the share of fuel, and hence of the fuel-tax base, that the engine accounts

³⁸The analogy is not exact. Unlike the fuel-line conversion, the battery is a real product attribute with a cost and a demand of its own, so a sub-50g PHEV is not a pure relabel and θ is best read as the share of the cohort’s certified abatement that is nominal rather than as a share of vehicles that abate nothing; this is why the calculation below is built to need no point identification of θ . The effective abatement share $1 - \theta\phi = (1 - \theta) \cdot 1 + \theta(1 - \phi)$ weights a genuine abater at one – its per-kilometre gain is realised however the car is driven, so no utilisation share is defined for it – and a gamed dual-fuel vehicle at its clean-fuel share. The one respect in which a PHEV departs from this is the battery’s mass: on engine kilometres a gamed PHEV consumes more than the conventional car it replaced if the battery’s mass outweighs the hybrid drivetrain’s recuperation, so its abatement is $1 - \phi(1 + \kappa)$ for a net penalty κ of either sign, and $1 - \theta\phi$ bounds the PHEV cohort’s effective share from above whenever $\kappa > 0$. Every result of Section 3 goes through with that share in place of $1 - \theta\phi$.

for.³⁹ It exceeds the kilometre share $1 - UF$ (UF the real-world utility factor) whenever charge-depleting operation burns fuel, as it does in blended driving – 0.75 against 0.67 in the pooled fleet – and it is the object the Premium needs; the Excess Premium below uses litres directly and is unaffected by the convention, which only the ϕ figures carry. Pooled over the 2021–2024 registration cohorts, the monitored PHEV fleet burns 6.19 litres per 100 km against a type-approval 1.42, a $4.4\times$ gap. The fleet ϕ of 0.75 is measured; the private/company split imposes the ratio in Plötz et al. (2022), whose company cars burn about 1.6 times the fuel of private ones, on each market’s fleet mean, holding that mean fixed, and puts ϕ near 0.56 for private owners and 0.90 for company cars – market totals in Table 5 do not depend on the split – against the 0.17 the rating itself implies on the same definition (FC_{TA}/FC_{CS} ; 0.22 in Sweden): the principal-agent friction at its sharpest, since the company-car driver bears no marginal fuel cost.

The preserved-base channel of Proposition 4 can then be quantified directly. Table 5 applies each market’s EEA consumption to its PHEV stock at 31 December 2023 (equation (15), Appendix G) at a uniform $\mu = 0.20$:⁴⁰ the annual Excess Fiscal Loop Premium, the fuel-tax revenue the type-approval rating assumed away, reaches EUR 17.6 mn for Sweden and **EUR 202 mn across Sweden, Germany, France, the Netherlands and Norway**, at EUR 41–129 per vehicle, and EUR 323 mn for the EU-27, Norway and Iceland together, 62 percent of it in these five markets. Measured instead against full electric operation ($\phi = 0$), the benchmark of Corollary 2, the Full Premium in the last column of the table values every real-world litre and is EUR 25 mn for Sweden, EUR 278 mn for the five markets and EUR 419 mn for all Europe; the Excess figure is the headline because it is the revenue the regulatory framework did not expect to collect. The calculation needs no point identification of the PHEV gaming share, which is subsumed into the fleet count N_j^{PHEV} , so the result is a statement about how subsidised PHEVs are *driven*; where θ is separately of interest, Germany’s 2026 split-eligibility subsidy offers a design-based route to it (Appendix G.2).

This is not a hypothetical extension. Regulators across China, Europe, and the United States are now tightening PHEV eligibility precisely because real-world emissions have failed to fall in line with type-approval ratings (Chu et al. 2025) – the observable signature of the utilisation failure analysed here, since these data measure ϕ rather than gaming. The diagnosis also identifies the remedy: a continuous instrument tied to real-world rather than

³⁹The monitoring data record fuel and distance separately in charge-depleting and charge-sustaining operation, so FC_{CS} is measured directly.

⁴⁰Stocks are Eurostat’s road-vehicle stock statistics for end-2023, compiled from the national registers, whose own figures agree with them to within 0.1 percent; company shares are measured on the national registry tables where published (Sweden, Germany, France) and assumed otherwise.

Table 5: Cross-Country Quantification of the Fiscal Loop Effect (EEA OBFCM real-world data)

Market	Segment	Stock (k)	FC_{TA}	FC_{RW}	ϕ	Excess L/yr	τ_f	Excess FLP /Veh (EUR)	Excess FLP (mn EUR)	Full FLP (mn EUR)
Sweden	Private	125.5	1.7	4.2	0.53	377	0.55	41	5	9
	Company	146.8	1.7	6.8	0.86	768	0.55	85	12	17
	Total	272.3							18	25
Germany	Private	415.7	1.8	4.9	0.58	461	0.65	60	25	40
	Company	506.0	1.8	7.8	0.93	900	0.65	117	59	77
	Total	921.8							84	116
France	Private	269.7	1.7	4.8	0.58	469	0.68	64	17	27
	Company	306.6	1.7	7.8	0.93	918	0.68	125	38	49
	Total	576.4							56	76
Netherlands	Private	87.0	1.7	4.4	0.54	406	0.79	64	6	9
	Company	176.7	1.7	7.1	0.87	814	0.79	129	23	30
	Total	263.7							28	39
Norway	Private	82.8	1.5	4.2	0.55	401	0.60	48	4	6
	Company	124.2	1.5	6.8	0.89	788	0.60	95	12	15
	Total	207.0							16	21
Grand Total		2241.2							202	278
All Europe (EU-27+NO+IS)	Private	1566.9	1.4	4.6	0.56	477	0.63	60	94	136
	Company	2013.4	1.4	7.4	0.90	903	0.63	114	229	283
	Total	3580.3							323	419

Notes: The *Excess FLP* is the annual fuel-tax revenue the type-approval rating assumed away: N times μ , τ_f and the excess litres burned per vehicle-year, $(FC_{RW} - FC_{TA}) VKT/100$, at $\mu = 0.20$ and $VKT = 15,000$ km. The *Full FLP* is the same revenue measured against full electric operation ($\phi = 0$), the benchmark of Corollary 2, and so values all real-world litres, $FC_{RW} VKT/100$. The text headlines the Excess FLP; the per-vehicle column is the Excess FLP. N (*thousands*) is the *plug-in hybrid passenger-car stock at 31 December 2023*, from Eurostat’s road-vehicle stock statistics, compiled from the national registers, whose own published figures agree with it to within 0.1 per cent; all Europe is the EU-27 plus Norway and Iceland. FC_{RW} and FC_{TA} (L/100km) are *fleet-weighted EEA on-board monitoring (OBFCM) figures for PHEVs registered 2021–2024*, published under Regulation (EU) 2019/631 and Implementing Regulation (EU) 2021/392; ϕ is the ratio of real-world to *measured* charge-sustaining consumption in the same data (the gap ratio FC_{RW}/FC_{TA} of an earlier version is omitted for width). The OBFCM data carry no owner field, so the private/company split of FC_{RW} applies the ratio in Plötz et al. (2022) to the EEA fleet mean, holding that mean fixed. Company shares are *measured* on national registry tables for Sweden (53.9 per cent), Germany (54.9) and France (53.2) and *assumed* for the Netherlands (67.0) and Norway (60.0); market totals are linear in N and independent of the split. The all-Europe row contains the five markets (62.6 per cent of its stock, 62.3 per cent of its Premium) and is excluded from the grand total.

certified outcomes eliminates the supply-side channel by construction (Proposition 6), while the demand-side channel must be addressed on the utilisation margin itself – through charging infrastructure, company-car tax design, or usage-based rather than purchase-based support.

8 Validation: Gaming Under Three Regimes

The Anatomy Proposition makes sharp out-of-sample predictions: removing any one of the three conditions should prevent the gaming response from arising. Sweden ran this experiment. The GCR was followed by two further national policies that varied the instrument design while holding the market, manufacturers, and consumers approximately constant: the Super Green Car Rebate (SGCR, 2012–2017), a binary rebate of up to SEK 40,000 for vehicles emitting at most 50 gCO₂/km *symmetrically across fuel types*, and the Bonus-Malus feebate (2018–2022), a continuous schedule pairing a bonus below 60 gCO₂/km with a tax penalty above 95 gCO₂/km. The SGCR is the intermediate case. It retains Assumption 1 in its rating–road form – a certified 50 gCO₂/km is reachable with a minimum-viable battery, whatever the car then burns on the road – but removes the fuel-type asymmetry, and it nominally removes the low-cost compliance technology (Assumption 2), since reaching the rating requires a physical battery; its single threshold at 50 gCO₂/km is the symmetric notch of Remark 1, so the response it invites is Ito–Sallee bunching in a dual-fuel setting rather than categorical relabelling. It serves here as the bridge to the instrument the framework prescribes. That instrument is the Bonus-Malus, which removes the categorical component of the threshold by construction while the rating–road gap remains, and so gives Proposition 6 a real-world test of categorical gaming. The escalation across the three regimes is thus: categorical gaming under the GCR; certified-attribute gaming routed through the company-car channel under the SGCR; categorical gaming eliminated under the Bonus-Malus, with the utilisation failure remaining. Each regime is confronted with the same empirical strategy as the GCR analysis: distributional plots of the supply response, followed by DiD regressions (specifications and full tables in Appendix H).

8.1 The Super Green Car Rebate: Gaming Adapts

With Assumption 1 read as the rating–road asymmetry, Proposition 5 predicts that gaming under the SGCR migrates from the fuel class to the certified rating itself, and the distributions bear this out: post-policy, 95 percent of plug-in hybrid (PHEV) registrations carry a type-approval value at or below 50 gCO₂/km, spread over 35–50 g in roughly equal thirds rather than at a single value, with a thin tail into the high twenties (Outlander 44, V60 D6 48, XC90 T8 49, 330e 44.5, Passat GTE 37, Kia Optima/Ceed 29–33 gCO₂/km) – heavy SUVs and large sedans from Volkswagen, Mitsubishi, Volvo, BMW, and KIA, engineered with minimum-viable battery packs to drive the NEDC-weighted type-approval value under the threshold (Figure A2, Appendix H). Manufacturers had pivoted from the GCR’s fuel-line conversion to a higher-cost analogue of the same categorical targeting.

To identify which incentive sustained this targeting, I exploit a mid-regime shock: on 1 January 2016 the direct PHEV rebate was halved to SEK 20,000 while the BEV rebate was left untouched and the comparison-car adjustment of the company-car benefit value (*förmånsvärde*) was unchanged at the 2016 break. In the split-era DiD (Appendix H, equation (16) and Table A18) the PHEV emissions response is large and statistically indistinguishable across the 2016 break ($\delta_1^P = -114.4$ vs. $\delta_2^P = -109.2$ gCO₂/km for the PHEV variants of eligible families, both $p < 0.01$), even though two of the three incentives to target the threshold – the direct rebate and the EU supercredit multiplier – weakened simultaneously at that boundary.⁴¹ The PHEV rating response and the registration response did not weaken after the 2016 halving (the change in δ^P across the break is -5.2 gCO₂/km with a 95 percent interval of $[-17.9, 7.6]$, about ± 13 gCO₂/km), consistent with the rebate not being the binding incentive.⁴² The SGCR’s fiscal envelope, finally, was finite in form but accommodating in practice: Assumption 3 held within each fiscal year but did not bind at the programme level, so the allocative-displacement outcome (iii) of Proposition 5 is not activated.⁴³

The incentive that did *not* change at the 2016 boundary is the *förmånsvärde* comparison-car adjustment, which strips the electrification price premium out of the company-car tax base every year and remained in force for new registrations until 30 June 2022, when SFS 2022:479

⁴¹ Eligibility in equation (16) is a *model-level* attribute: a family qualifies through any sub-50 gCO₂/km variant, so the eligible group is dominated by those families’ conventional (ICE) variants, which sit far above it (registration-weighted means of 166, 143 and 129 gCO₂/km pre-policy, in Era 1 and in Era 2 on the register series). Within these families the conventional variants show no drift: $\delta_1^E = +3.2$ gCO₂/km ($p < 0.10$) and $\delta_2^E = -8.7$ ($p < 0.01$), small and of opposite signs. Eligibility does not nest the PHEV indicator – 133 of the 161 PHEV variant-years belong to an eligible family – so the specification carries an $\text{Elig} \times \text{PHEV} \times \text{era}$ interaction ($+25$ and $+29$ gCO₂/km, $p < 0.05$), and the δ_k^P quoted in the text are the eligible-family PHEV responses, the sum of the double and triple interactions (Table A18, last rows). PHEV registrations, meanwhile, surged in both eras (log-point responses of $+1.99$ and $+2.22$) while BEV registrations did not respond: the SGCR’s take-up effect was confined to threshold-targeting PHEVs. The eligible families’ conventional variants also registered more – $+0.144$ log points in Era 1 and $+1.11$ in Era 2 (Table A18, column $\ln(\text{Reg})$) – which I read as portfolio composition, the sub-50g variant sitting in families whose conventional lineups were growing, rather than as a prediction of the propositions.

⁴² Hennlock (2019) attributes about one in three PHEV registrations over 2012–2015 to the SGCR and finds that the 2016 halving saved roughly SEK 450 mn with little effect on uptake. The two findings concern different margins: a third of *registrations* attributed to the rebate is compatible with the rebate having no effect on *where the ratings sit*.

⁴³ The appropriation ran out before year-end in 2012, 2014, 2015 and 2016 – the ordinance pays the premium “in so far as funds are available” and “in turn by the date of registration” (Regeringen 2011, §7) – and each time Transportstyrelsen queued eligible buyers until the Riksdag raised the appropriation: SEK 115 mn added to the 2015 budget against the government’s proposal (Miljö- och jordbruksutskottet 2014), SEK 132 mn and SEK 180 mn in the 2015 and 2016 autumn amending budgets (Regeringen 2015, 2016), about SEK 1.7 bn cumulatively against the SEK 200 mn planned for 2012–2014 (Riksrevisionen 2020, pp. 58–59). Unlike the GCR, the cost never forced termination: the rebate was extended year by year until the Bonus-Malus replaced it in July 2018; the queue meant delay for buyers, not exclusion.

replaced it with fixed reductions (SEK 350,000 for battery-electric and SEK 140,000 for plug-in hybrid cars, capped at half the list price). Its capitalised value over a three-year corporate lease plausibly exceeds the incremental cost of a minimum-viable battery – functionally restoring the low-cost compliance condition (Assumption 2) for the corporate fleet market that the battery requirement had nominally removed. Registration data by owner category (Table A19, Appendix H.1) confirm that this is where the response landed: **95 percent of SGCR-era PHEV registrations (2013–2017) went to companies rather than private buyers**, against 78 percent for battery-electric cars and 64 percent for conventional vehicles.⁴⁴ Battery-electric cars received the same rebate and the same *förmånsvärde* relief, so the PHEV–BEV difference does not identify the tax channel on its own; it identifies the *product* – a threshold-targeting variant of an incumbent model family – and the company channel is where such a product sells. The two are complements: the tax code made the certified rating valuable to the fleet buyer, and the incumbent families supplied the variant that met it. Gaming adapted under the SGCR, migrating from the fuel-line to the tax code. This is the same principal-agent channel that drives ϕ towards one in the contemporary PHEV markets of Section 7.5: the decision-maker who books the vehicle does not bear its running cost.

8.2 The Bonus-Malus Feebate: Gaming Eliminated

The Bonus-Malus is the instrument Proposition 6 analyses, enacted: a continuous schedule declining from SEK 60,000 at 0 gCO₂/km by SEK 833 per gram to a SEK 10,000 floor at the 60g threshold, paired with an escalating tax on vehicles above 95 gCO₂/km, with the 60–95g middle zone as an untreated control group. What the theory prescribes is that pricing emissions continuously moves buyers rather than labels, and that is what the data show. Relative to the 60–95 g control group, bonus-eligible registrations rose roughly 5.6-fold and malus-zone registrations fell by about 33 percent – the first significant *negative* demand response to high emissions in any of the three regimes; the EU 95 g fleet target and the WLTP re-rating are confounds shared by all bins, which the difference-in-differences nets out only insofar as they hit the bins alike. Ownership broadened, though only partly for policy reasons (Table A19): the PHEV company share fell from 95 percent under the SGCR to 69 percent by 2022, yet PHEVs remain the most company-concentrated segment – against 66 percent in the bonus zone, 62 percent in the malus zone and 55 percent for battery-electric cars (about half by 2022) – and the BEV share fell too, from 78 to 55 percent, so part of the broadening is secular. Where the SGCR routed a compliance benefit through the corporate

⁴⁴Owner category (private person versus company) comes from Statistics Sweden’s (SCB) new-registration records by registrant type, merged to the vehicle-characteristics panel. Shares are registration-weighted and pooled over 2013–2017; the PHEV company share climbs from 76 percent in 2012 to 96 percent by 2016.

tax base, the continuous schedule priced emissions for every buyer.

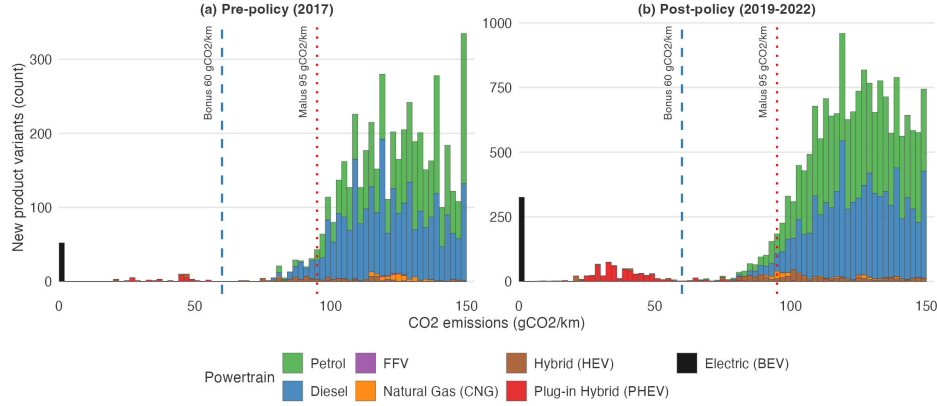


Figure 8: **CO2 Emission Distributions Pre- and Post-Feebate.** CO2 emissions of new product variants emitting up to 150 gCO2/km: **Panel (a)** pre-policy (2017) and **Panel (b)** post-policy (2019–2022). The dashed blue line marks the 60 gCO2/km bonus threshold; the dotted red line the 95 gCO2/km malus threshold. CO2 is the register’s type-approval value (ADAC/EEA-matched where the register is silent); plug-in hybrids from matched type-approval values. Panel (b) shows mass shifting to zero- and low-emission powertrains.

The supply side moved with it, as Figure 8 shows. A dual-threshold DiD (Appendix H, equation (17) and Table A20) yields a bonus-arm coefficient of $\delta_B = -63.2$ gCO2/km and a malus-arm coefficient of $\delta_M = +47.5$ gCO2/km (both $p < 0.01$), and three features are consistent with extensive-margin substitution rather than categorical gaming. First, the bonus coefficient is the same to within 0.3 gCO2/km across the full-sample, incumbent-only, and incumbent-eligible specifications ($-63.2, -63.5, -63.4$): legacy automakers integrated BEV and PHEV variants into existing model families rather than relabelling anything. Second, the malus coefficient is compositional – manufacturers discontinued marginal models just above 95g while retaining the price-insensitive upper tail, so the zone average rises as its bottom erodes. Third, it survives harmonising all emissions to NEDC across the WLTP transition, and holds with the plug-in hybrids on the WLTP rating the schedule itself used from 2020 ($\delta_B = -57.4, \delta_M = +50.7$), so it is not an artefact of the re-basing of the certified rating on which the malus is levied.⁴⁵

The schedule is not a pure feebate: the SEK 10,000 floor leaves a residual notch at 60 gCO2/km. It went unexploited.⁴⁶ The categorical gaming that was near-complete under the

⁴⁵Whether the 2020 re-basing of that rating to WLTP improved its ranking of real-world emissions is a separate question, taken up in the companion paper (Huse 2026): the base’s level rose by a fifth while its ranking of true emissions was unchanged. The feebate’s elimination of categorical gaming is therefore a statement about the compliance margin alone; the Bonus-Malus era’s record on real emissions is a separate matter.

⁴⁶A McCrary-style density test on the type-approval values finds no excess density below 60g: on the NEDC-harmonised rating the estimated discontinuity is $T = +0.8$ ($p = 0.42$); on the WLTP rating it is $+2.3$ ($p = 0.02$) with the positive sign, the opposite of notch targeting, and a test restricted to plug-in hybrid

Table 6: Empirical Results and Welfare Implications Across Three Swedish Policy Regimes

Construct	GCR (2007–09)	Super GCR (2012–17)	"Bonus-Malus" (2018–22)
<i>Panel A: Empirical Results</i>			
Strategy	DiD + bootstrap + fuel-choice calibration	Split-era DiD + log-reg. + event study	Dual-threshold DiD + event study + log-reg.
Distribution	Rightward shift; 73% of AFV mass in $(\hat{e}, 220]$	PHEV platforms rated 35–50 gCO ₂ /km	Leftward shift; extensive BEV/PHEV entry
Supply DiD	+14.2*** gCO ₂ /km (int.-margin gaming)	PHEV plunge stable across subsidy cut (−114.4*** to −109.2***); eligible families' ICE lineups flat (+3.2*, −8.7***)	$\delta_B = -63.2^{***}$, $\delta_M = +47.5^{***}$ (robust to WLTP harmonisation; extensive-margin exit)
Demand	FFV sales surge; $\phi = 0.359$	PHEV reg. surge (ln Reg +1.99***, +2.22*** by era); BEV reg. flat	Bonus reg. +460%***; Malus reg. −33%***
θ (Gaming)	$\theta = 0.986$ (incumbent-conversion share of the loophole-zone cohort, §7.1)	$\theta > 0$ (PHEV threshold targeting)	Categorical $\theta \approx 0$ (residual notch unexploited)
ϕ (Fossil Fuel Use)	$\phi = 0.359$ (§7.2)	High but not separately calibrated (test-cycle PHEVs)	$\phi = 0.53$ private / 0.86 company, Swedish PHEVs 2021–24 (EEA OBFCM, Table 5)
$(1 - \theta\phi)$	0.646	< 1 (not separately quantified)	Categorical $\theta \approx 0$; $(1 - \theta\phi)$ not separately quantified
<i>Panel B: GCR-budget feebate counterfactual (Appendix H.3)</i>			
Net Soc. Cost, $\tau_E = 40$	EUR 15.2 mn	N/A	EUR 7.5 mn (feebate dominates)
Net Soc. Cost, $\tau_E = 75$	EUR 55.2 mn	N/A	EUR 6.8 mn (feebate dominates)
Verdict	Cascade activated. 4 failure modes materialize (Prop. 5)	Cascade partially activated. Binary notch + corporate tax channel preserved structural gaming for PHEVs.	Cascade largely neutralised. Cont. design eliminates categorical arbitrage; residual 60g notch unexploited. Confirms Prop. 6 for categorical θ ; the utilisation failure (ϕ) remains (Table 5)

Notes: This table maps three Swedish dual-fuel policies onto the framework of Section 3; the condition-by-condition mapping (Anatomy conditions and predictions) is Table A17 in the Online Appendix. Panel A: DiD results from Tables 1, A18, A20; θ , ϕ from Sections 7.1–7.2. Panel B: welfare results from Section 7.3 and the feebate counterfactual of Appendix H.3; these are net social cost figures (carbon benefit netted at the stated τ_E) and are distinct from the allocative deadweight range cited in the text. The Bonus-Malus column of Panel B is the calibrated GCR-budget counterfactual on the 2007–09 cohort, not an evaluation of the 2018–22 policy; the Bonus-Malus ϕ in Panel A is the EEA OBFCM measurement for Swedish PHEVs registered 2021–24 (Section 7.5). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Policy parameters from Transportstyrelsen and Prop. 2021/22:91.

GCR and adapted under the SGCR is eliminated under the continuous design, $\theta_{cat} \rightarrow 0$; the utilisation failure remains, and Table 5 prices it for the feebate-era Swedish PHEV fleet. The welfare comparison (Appendix H.3) is the calibrated GCR-budget counterfactual on the 2007–09 cohort rather than an evaluation of the 2018–22 policy: there the feebate dominates the gamed rebate at both carbon prices – EUR 7.5 mn against EUR 15.2 mn in net social cost

variants finds nothing ($T = +0.9$, $p = 0.37$). The 58–60g band holds 162 PHEV registrations over 2019–22 on the WLTP basis (0.7 percent of PHEV registrations fall in 55–60g); the only mass near the notch on the NEDC-correlated rating is two platforms rated before the WLTP switch, the BMW 330e/530e at 57g and the Volvo XC90 T8 at 59g (Appendix H).

in the Central Scenario and EUR 6.8 mn against EUR 55.2 mn in the High-Cost Scenario – the feebate dominating at every carbon price above about EUR 31 per tonne (Corollary A3).

8.3 Synthesis: Three Regimes, One Framework

Table 6 maps the three regimes onto the framework, and Table A17 (Appendix H) gives the condition-by-condition mapping of the Anatomy assumptions to each design.

The progression completes the paper’s argument. The Anatomy conditions identify the structural causes of failure ex ante; the optimal subsidy formula prices the failure (Section 7.4); and the three-regime validation shows the same market responding to instrument design as the design conditions predict once Assumption 1 is read as the rating–road asymmetry. The theory is identified on the GCR; the SGCR and the Bonus-Malus test its design conditions within one market; the PHEV section measures the utilisation parameter at fleet scale and prices its fiscal consequence, with the gaming share left to designs such as Germany’s split-eligibility subsidy (Appendix G.2). The limit is equally plain: three regimes are one country and one tax code, and the Bonus-Malus coincides with the EU 95 g fleet target.⁴⁷

Conclusion

This paper develops a framework for dual-fuel policy design that separates two failure channels: structural gaming by manufacturers (θ) and behavioural fuel arbitrage by consumers (ϕ). The channels enter multiplicatively through the effective abatement share ($1 - \theta\phi$), so a subsidy can fail on either margin and policy design must address both. The Premium is large enough to change the arithmetic of every dual-fuel subsidy in a fuel-taxing jurisdiction and not large enough to justify one: the design conclusion is the feebate, and the ex-ante diagnostic is the critical carbon price.

The 2007-2009 Swedish Green Car Rebate activated all three Anatomy conditions. The supply-side DiD estimates a causal increase of 14.2 gCO₂/km in treated fleet emissions, the bootstrap puts the allocative displacement cost at EUR 21-52 mn, and the fuel-choice calibration shows 35.9 percent of driving in the gamed cohort running on gasoline. Measured against this environment, the welfare-maximising subsidy is negative for carbon prices below EUR 87 per tonCO₂ (47.6 if ethanol is treated as carbon-free) – and the welfare accounting

⁴⁷One caveat sharpens rather than undercuts the argument. The feebate was designed to be self-financing, so it carried no fixed ex ante appropriation that gaming could exhaust in the GCR’s manner. In practice it still met a fiscal envelope – malus revenue fell short of bonus cost from 2020, payouts were suspended in August 2021 pending a supplementary appropriation, and the bonus was abolished in November 2022 (Regeringskansliet 2022) – but the source of the pressure was the volume of low-emission registrations: the substitution the framework predicts a well-designed instrument should generate. The PHEV share of bonus outlays is not observed in my data.

surfaces the Fiscal Loop Premium, the fiscal mirror image of the double dividend, whereby gaming preserves the fuel tax base that genuine abatement would erode.

The three-regime validation (Section 8) shows the framework predicting out of sample – gaming adapting through the company-car tax channel under the Super Green Car Rebate and disappearing under the Bonus-Malus feebate, in the same market, with the same manufacturers and consumers. Calibrated to contemporary European PHEV markets, the mechanism generates an annual Excess Fiscal Loop Premium – the fuel-tax revenue the type-approval rating assumed away – of EUR 202 mn across five jurisdictions, roughly seven-tenths of it from company cars.

The policy lessons are threefold. Instrument re-design is the first-order intervention: a continuous, technology-neutral feebate removes the firm-side channel by construction. It is not, however, sufficient – the feebate eliminates categorical θ but leaves ϕ untouched, so fuel prices, charging infrastructure, and company car taxation remain necessary complements. Finally, the critical carbon price τ_E^{crit} serves as an ex ante diagnostic: any jurisdiction can compute it from its fuel tax, its MCPF, and the net carbon content of the fuel its target technology displaces, and thereby learn whether a vehicle subsidy is welfare-reducing before enacting it.

I leave two extensions for future work. Estimating θ and ϕ jointly from variation in subsidy amounts would recover the endogenous gaming response of Remark A4. And applying the framework to fleet-wide emission standards – where the budget is the manufacturer’s CO2 cap rather than a fiscal appropriation – would carry the Anatomy conditions into the regulatory setting that matters most for transport decarbonisation.

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Online Appendix to: Fast, Furious, and Dirty: Gaming, Fuel Choice Behaviour, and the Welfare Cost of Dual-Fuel Subsidies

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A Framework Details and Market Overview

A.1 Gaming Mechanisms Across Alternative-Fuel Technologies

Table A1 sets out the two framework parameters for three technologies chosen to span the mechanism space (Section 3.7 of the main text); the catalogue below fills in the fuller range.

Table A1: The framework across dual-fuel technologies

Technology	θ : gaming mechanism	ϕ : fossil-utilisation margin	Evidence on magnitudes
Flex-fuel (GCR)	Fuel-type reclassification at $\approx$ EUR 150 (Assumption 2)	Share of km driven on gasoline	$\theta = 0.986$, $\phi = 0.359$
Plug-in hybrid (PHEV)	Minimum-battery / test-cycle optimisation to clear a range or gCO ₂ threshold	Engine share of fuel, FC_{RW}/FC_{CS} (above 1 – utility factor when charge-depleting driving burns fuel)	$\phi \approx 0.6$ (private) $\rightarrow 1$ (company-car); ^a $\theta > 0$, not point-identified ^b
Diesel (defeat-device)	Emissions-control shading under monitoring	n/a – single-fuel, θ -channel only	$\theta > 0$ ^c

Notes: θ is always the share gaming the certified attribute; ϕ the share of real-world use on the fossil fuel. GCR estimates are from this paper. The diesel row is a single-fuel contrast in which the ϕ -channel is absent, isolating the pure θ mechanism. ^aPlötz et al. (2022). ^bNo clean point estimate of θ exists, but bunching below the 50 gCO₂/km EU super-credit threshold and continuous test-cycle optimisation (Reynaert 2021) establish $\theta > 0$, near-complete in company-car fleets. ^cAlé-Chilet et al. (2026); Reynaert and Salée (2021).

The firm-side gaming channel formalised in Proposition 5 arises across a range of dual-fuel and alternative-fuel regulations, with the specific technical implementation varying by technology.

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Flex-fuel vehicles (FFVs). The canonical case analysed in this paper: manufacturers convert gasoline models to ethanol (typically E85) compatibility at marginal cost (EUR 150 per vehicle) without re-designing the combustion system for optimal ethanol performance. The Swedish GCR offered a EUR 1,081 subsidy for such vehicles, and 98.6 percent of the induced cohort were gamed conversions (Section 7.1).

Plug-in hybrid electric vehicles (PHEVs). The contemporary case, in which a minimum-viable battery clears the type-approval threshold while the vehicle is driven on its engine, is developed in Section 7.5 and Appendix G.

Continuous test-cycle optimisation. Reynaert (2021) documents that European manufacturers optimised engine control software to minimise emissions under the specific NEDC test conditions, achieving approximately 30 percent of apparent CO₂ reductions through test-cycle calibration rather than physical abatement. This is a continuous analogue of the discrete gaming channel analysed here: rather than reclassifying vehicles into a favoured category, firms optimise along the continuous emissions dimension for the specific conditions under which emissions are measured. The two channels can operate simultaneously: a manufacturer can convert a model to FFV specification (discrete) and optimise its NEDC/WLTP calibration (continuous) in the same production decision.

These examples share the gaming structure of this paper: an asymmetric regulatory threshold (Assumption 1), a cheap technical modification achieving categorical reclassification (Assumption 2), and a regulatory test protocol that fails to capture the separable consumer-side utilisation decision (parameterised by ϕ in Proposition 4). Whether each becomes a full *welfare* failure depends additionally on the budget regime (Assumption 3) and the pre-existing fuel tax. The Swedish GCR case stands out empirically because it combines all these features with both registration and fuel sales data, enabling the joint identification of θ and ϕ . The broader class of gaming mechanisms, however, is a general feature of attribute-based environmental regulation under dual-technology vehicles.

Table A2 collects the notation and the calibrated values used throughout the paper.

A.2 Market Overview: Selected Summary Statistics

Table A3 reports summary statistics of the variables used in the empirical analysis.

Table A4 reports mean CO₂ emissions – over time and across fuels – in the Swedish market.¹ Emissions fell over the sample period for the market as a whole and for gasoline and diesel

¹The full version of the table, adding standard errors of the mean, medians and interquartile ranges for each segment-year cell, is omitted for space; it is produced by the replication code.

Table A2: Notation and Parameter Reference

Symbol	Definition	Value / source
<i>Firm-side (supply) channel</i>		
θ	Gaming share: fraction of subsidised vehicles qualifying via reclassification rather than abatement	0.986 (GCR, strict incumbent-conversion share of the loophole-zone cohort, §7.1)
c^G, c^A	Cost of gaming (fuel-type conversion) vs. physical abatement	$c^G \approx \text{EUR } 150$; $c^A \gg c^G$
N_G	Number of gamed vehicles ($= \theta \bar{N}$)	36,924 (GCR)
<i>Consumer-side (demand) channel</i>		
ϕ	Fossil-fuel utilisation share: fraction of km driven on fossil fuel (FFV); FC_{RW}/FC_{CS} , the engine's share of fuel (PHEV)	0.359 (GCR); 0.56/0.90 private/company PHEV (EEA OBFCM)
ϕ^{bm}	Regulatory-assumed fossil share (type-approval benchmark)	0.17 (PHEV, FC_{TA}/FC_{CS} , all Europe; 0.22 Sweden); 0 (FFV)
$(1 - \theta\phi)$	Effective abatement share: compound dilution from both channels	0.646 (GCR)
<i>Fiscal and environmental parameters</i>		
μ	Excess burden of taxation; $\mu \equiv \lambda - 1$, λ the marginal cost of public funds	0.20
τ_f	Pre-existing volumetric fuel (gasoline) tax	EUR 0.55/L (Sweden)
τ_E	Social cost of carbon	EUR 40/t (central), 75/t (high)
τ_E^{crit}	Critical carbon price, $\mu\tau_f/\Delta c$: below it the optimal subsidy is negative	EUR 86.6/t (47.6 if ethanol is carbon-free)
$\Delta q_A, \Delta E_A$	Intended per-vehicle abatement of the target technology: whole-tank litres displaced, VKT/13 km/L, and $\Delta E_A = \Delta c \Delta q_A$	$\Delta c = 1,270.5$ gCO ₂ /L (net lifecycle); horizon set by VKT
$\bar{e}^{RFV}, \bar{e}^{AFV}$	Eligibility thresholds (conventional vs. alternative fuel)	120 / 220 gCO ₂ /km
$\bar{e}_G^{AFV}$	Gamers' <i>certified</i> (type-approval) emissions	182.2 gCO ₂ /km
S	Unit purchase subsidy	SEK 10,000 = EUR 1,081
VKT	Lifetime vehicle kilometres travelled	230k (central), 300k (high)

Notes: SEK converted at 9.25 SEK/EUR (footnote 4). The two failure channels are independent: θ is governed by the Anatomy conditions (Assumptions 1–3), ϕ by the consumer fuel-choice environment. Displacement (Proposition 3) is evaluated at certified emissions $\bar{e}_G^{AFV}$ and carries no ϕ ; ϕ enters only the fuel-tax channels (Fiscal Loop Premium and the optimal-subsidy environmental penalty).

Table A3: Summary Statistics of Selected variables

	N	Mean	SD	P25	P50	P75
CO2 Emissions (g/km)	9372	201.55	54.70	162.00	191.00	229.00
NOx Emissions (mg/km)	7902	86.74	105.42	19.00	36.22	130.14
CO Emissions (mg/km)	8107	305.43	204.25	151.00	285.00	430.00
Horsepower (HP)	9354	175.29	85.31	119.68	149.60	209.44
Weight (kg)	9161	1577.64	323.39	1385.00	1550.00	1720.00
HPW (HP/kg)	9142	0.11	0.04	0.08	0.10	0.12
Engine Size (cc)	9352	2325.85	952.90	1794.00	1997.00	2720.00
AFV (DV)	9384	0.02	0.15	0.00	0.00	0.00
RFV (DV)	9384	0.98	0.15	1.00	1.00	1.00

Note: The table shows number of observations (N), means, standard deviations, and quartiles for selected variables used in the DD specifications.

vehicles, but rose for FFVs and for gasoline/electric vehicles. Among vehicles emitting no more than 120 gCO₂/km (“low-emission vehicles”) the trend runs the other way – upward overall and for gasoline and diesel alike – consistent with bunching below that threshold; no FFV marketed during the sample period emitted at or below 120 gCO₂/km.

Table A4: Mean CO₂ Emissions by Vehicle Type (gCO₂/km)

Fuel	2005	2006	2007	2008	2009
All	210.4	205.6	199.5	198.8	191.3
All $\leq$ 120 g	106.8	113.6	114.4	113.7	114.1
Gasoline	218.3	215.4	213.0	212.4	206.0
Gasoline $\leq$ 120 g	115.3	112.1	111.1	112.1	113.1
Diesel	188.1	183.0	172.2	174.8	168.3
Diesel $\leq$ 120 g	101.3	114.8	115.8	114.6	115.2
FFV	185.3	185.4	184.4	194.2	195.1
FFV $\leq$ 120 g	No models available				
Gasoline/CNG	198.0	164.4	150.4	147.6	156.9
Gasoline/Electric	104.0	147.8	147.8	161.8	173.3

Notes: Mean engine CO₂ emissions (gCO₂/km) by fuel segment and year. For a given year, a model is a combination of brand-model-fuel. Standard errors of the mean, medians and interquartile ranges for each cell are produced by the replication code.

B Mathematical Proofs

B.1 Compliance Cost Dominance

Proof of Proposition 1. Since both strategies yield identical regulatory eligibility and hence identical revenue, the manufacturer’s problem reduces to minimising compliance cost. The

cost of gaming, c^G , is constant.

Case (i). [Low fixed abatement cost, $F_A < c^G$ (including the continuous case $F_A = 0$).] Since $\lim_{e_i \rightarrow \bar{e}^{RFV+}} c^A(e_i, \bar{e}^{RFV}) = F_A < c^G$ and, by assumption, $c^A(\bar{e}^{AFV}, \bar{e}^{RFV}) > c^G$, with c^A strictly increasing on $(\bar{e}^{RFV}, \bar{e}^{AFV}]$, the Intermediate Value Theorem guarantees at least one crossing and strict monotonicity its uniqueness. At the unique $\hat{e} \in (\bar{e}^{RFV}, \bar{e}^{AFV})$ defined by $c^A(\hat{e}, \bar{e}^{RFV}) = c^G$: $c^A(e_i, \bar{e}^{RFV}) < c^G$ for $e_i \in (\bar{e}^{RFV}, \hat{e})$, so abatement strictly dominates; and $c^A(e_i, \bar{e}^{RFV}) > c^G$ for $e_i \in (\hat{e}, \bar{e}^{AFV}]$, so gaming strictly dominates. The continuous case $F_A = 0$ is the boundary, with $c^A(\bar{e}^{RFV}, \bar{e}^{RFV}) = 0 < c^G$.

Case (ii). [Large fixed abatement cost, $F_A \geq c^G$.] Since $c^A(e_i, \bar{e}^{RFV}) \geq F_A \geq c^G$ for all $e_i \in (\bar{e}^{RFV}, \bar{e}^{AFV}]$, gaming strictly dominates everywhere in the interval, yielding the corner solution $\hat{e} = \bar{e}^{RFV}$.

In all cases, firms indifferent at $\hat{e}$ are assigned to gaming without loss of generality. $\square$

Remark A1 (Above-threshold vehicles). Manufacturers with e_i marginally above $\bar{e}^{AFV}$ face a standard single-threshold bunching incentive (Sallee and Slemrod 2012): a small adjustment (in this case, below 220 gCO₂/km) unlocks the subsidy. The regression discontinuity confirms this bunching (Section 6.2), but it is second-order – boundary bunching accounts for under 10 percent of the allocative loss (Section 7.1). Propositions 1–3 therefore treat classical bunching as secondary to the dominant gaming channel, slightly understating the total distortion (Remark 1).

B.2 The Distributional Shift

Proof of Proposition 2. Let F_0 here denote the pre-policy distribution of vehicles within the AFV segment and N_0 denote the pre-policy AFV count.

Pre-policy, let $p_0 \equiv \Pr_{F_0}[e \in (\hat{e}, \bar{e}^{AFV})]$ denote the pre-policy probability mass in the upper loophole interval. Post-policy, any manufacturer with an incumbent RFV model emitting $e_i > \hat{e}$ finds it strictly profitable to introduce an AFV variant at its *original, unreduced* baseline emissions level $e_i \in (\hat{e}, \bar{e}^{AFV}]$. Since c^A is strictly increasing in e_i , the net gain from gaming, $c^A(e_i, \bar{e}^{RFV}) - c^G$, is also strictly increasing in emissions e_i , as are the incentives to game, making it more likely.

Let $G(e)$ denote the CDF of the $N_G > 0$ converted models, with support strictly on $(\hat{e}, \bar{e}^{AFV}]$, so $\Pr_G[e \in (\hat{e}, \bar{e}^{AFV})] = 1$. The post-policy distribution is the convex combination:

$$F_1(e) = \frac{N_0}{N_0 + N_G} F_0(e) + \frac{N_G}{N_0 + N_G} G(e) \quad (1)$$

The post-policy mass in $(\hat{e}, \bar{e}^{AFV}]$ is therefore:

$$\begin{aligned}
p_1 &\equiv \Pr_{F_1}[e \in (\hat{e}, \bar{e}^{AFV}]] \\
&= \frac{N_0}{N_0 + N_G} p_0 + \frac{N_G}{N_0 + N_G} \cdot 1 \\
&> \frac{N_0}{N_0 + N_G} p_0 + \frac{N_G}{N_0 + N_G} p_0 = p_0
\end{aligned} \tag{2}$$

where the strict inequality follows from $p_0 < 1$ – maintained as a condition of the proposition and consistent with the empirical distribution in Figure A1 – and $N_G > 0$, which holds since $\hat{e} < \bar{e}^{AFV}$ and the loophole interval is non-degenerate. $\square$

B.3 Allocative Welfare Loss Under Budget Exhaustion

Proof of Proposition 3. The budget B finances exactly $\bar{N} = B/S$ subsidy slots. Since the budget binds, every slot captured by a gamed vehicle – one emitting at its original baseline $e_i > \bar{e}^{RFV}$ – directly displaces a slot that would otherwise have financed a genuinely efficient RFV emitting at or below $\bar{e}^{RFV}$. The lifetime CO2 differential per displaced vehicle is $(\bar{e}_G^{AFV} - \bar{e}^{RFV}) \times VKT/10^6$ tonnes. Aggregating over the N_G gamed vehicles and monetising at the social cost of carbon τ yields equation (1) in the main text.

The loss arises entirely from the reallocation of a fixed public budget from abatement-inducing to arbitrage-enabling uses. No additional public expenditure is incurred and no abatement is achieved; the entire welfare cost reflects foregone emission reductions relative to the within-budget efficient allocation. $\square$

B.4 Second-Best Optimal Subsidy Under Asymmetric Design

Proof of Proposition 4. I proceed in five steps.

Step 1: The welfare objective.

The regulator chooses the subsidy S to maximise expected social welfare. Whatever the incidence split – consumers retain an effective price reduction ρS , manufacturers capture $(1 - \rho)S$ in margin – the government’s fiscal expense is S per subsidised vehicle, so the net social cost of financing it through distortionary taxation is the excess burden $\mu S = (\lambda - 1)S$. Each subsidised vehicle of type $k \in \{A, G\}$ reduces emissions by ΔE_k – delivering a social benefit $\tau_E \Delta E_k$ – and lowers the fuel tax base by Δq_k , imposing a fiscal externality of $\mu \tau_f \Delta q_k$ per vehicle. The welfare objective is:

$$\mathcal{W}(S) = \tau_E \mathbb{E}[\Delta E] \cdot Q(\rho S) - \mu S \cdot Q(\rho S) - \mu \tau_f \mathbb{E}[\Delta q] \cdot Q(\rho S) \quad (3)$$

The expectation is taken over a vehicle drawn at random from the subsidised cohort – a gamer with probability θ , a genuine abater with probability $1-\theta$. Abaters realise $(\Delta q_A, \Delta E_A)$ in full; gamers realise only $(1-\phi)$ of these reductions, so $\Delta E_G = (1-\phi)\Delta E_A$ and $\Delta q_G = (1-\phi)\Delta q_A$. The cohort's expected reductions are therefore:

$$\mathbb{E}[\Delta E] = (1-\theta)\Delta E_A + \theta(1-\phi)\Delta E_A = (1-\theta\phi)\Delta E_A, \quad (4)$$

$$\mathbb{E}[\Delta q] = (1-\theta)\Delta q_A + \theta(1-\phi)\Delta q_A = (1-\theta\phi)\Delta q_A \quad (5)$$

Step 2: The first-order condition. Differentiating $\mathcal{W}(S)$ with respect to S via the chain rule:

$$\frac{d\mathcal{W}}{dS} = \underbrace{[\tau_E \mathbb{E}[\Delta E] - \mu S - \mu \tau_f \mathbb{E}[\Delta q]]}_{\text{net social value of a marginal adoption}} \rho Q'(\rho S) - \underbrace{\mu Q(\rho S)}_{\text{excess burden on inframarginal adopters}} = 0 \quad (6)$$

Dividing through by $\rho Q'(\rho S) > 0$:

$$\tau_E \mathbb{E}[\Delta E] - \mu S - \mu \tau_f \mathbb{E}[\Delta q] = \frac{\mu}{\rho} \cdot \frac{Q(\rho S)}{Q'(\rho S)} \quad (7)$$

Step 3: Elastic demand at the margin. In a differentiated-products market with a large number of vehicle varieties, demand is strongly own-price elastic – Reynaert (2021) estimates a discrete-choice demand system for the European car market with a large negative price coefficient – so the marginal term $Q(\rho S)/Q'(\rho S) \rightarrow 0$. The first-order condition (7) reduces to:

$$\tau_E \mathbb{E}[\Delta E] = \mu S + \mu \tau_f \mathbb{E}[\Delta q] \quad (8)$$

Step 4: Solving for S^* . Solving (8) for S :

$$S^* = \frac{\tau_E \mathbb{E}[\Delta E]}{\mu} - \tau_f \mathbb{E}[\Delta q] \quad (9)$$

Step 5: Substituting the cohort mix. Substituting (4) into (9):

$$\begin{aligned}
S^* &= \frac{\tau_E(1 - \theta\phi)\Delta E_A}{\mu} - \tau_f(1 - \theta\phi)\Delta q_A \\
&= (1 - \theta\phi) \left[\frac{\tau_E\Delta E_A}{\mu} - \tau_f\Delta q_A \right] \\
&= \left[\frac{\tau_E\Delta E_A}{\mu} - \tau_f\Delta q_A \right] - \theta\phi \frac{\tau_E\Delta E_A}{\mu} + \theta\phi \tau_f\Delta q_A
\end{aligned} \tag{10}$$

which establishes both (3) and (2). $\square$

Remark A2 (Connecting ABR, Double-Dividend, and Optimal Taxation). Each term in equation (2) maps to a distinct strand of the literature.

Term 1 – Benchmark second-best subsidy. With no gaming ($\theta\phi = 0$), every subsidised vehicle genuinely abates. The regulator’s problem reduces to: how large a subsidy can be justified given that public funds are costly to raise? The answer has two parts. On the benefit side, each abating vehicle reduces emissions by ΔE_A , generating social value $\tau_E\Delta E_A$. Because the regulator must tolerate μ units of deadweight loss for every unit of subsidy spent, the environmental benefit must be scaled by $1/\mu$ to express it in subsidy-equivalent units, yielding $\tau_E\Delta E_A/\mu$. On the cost side, genuine abatement reduces fuel consumption by Δq_A , which destroys $\tau_f\Delta q_A$ of fuel tax revenue that must eventually be replaced through other distortionary taxes. The optimal subsidy is therefore discounted by $\tau_f\Delta q_A$ to account for this fiscal leakage. This benchmark is the partial-equilibrium counterpart of the second-best environmental subsidy of Parry (1998).² The economic content is identical: in both, pre-existing distortions push the optimal subsidy strictly below its first-best Pigouvian level.

Term 2 – Environmental Penalty. Introducing gaming ($\theta > 0$) and fractional fossil-fuel utilisation ($\phi > 0$), each gamer – a share θ of the cohort – delivers only a fraction $(1 - \phi)$ of the emissions reduction promised by abatement. Averaging over abaters (share $1 - \theta$) and gamers (share θ), the expected reduction across the cohort falls from ΔE_A to $(1 - \theta\phi)\Delta E_A$. The optimal response is to reduce S^* by $\theta\phi \tau_E\Delta E_A/\mu$, that is, scaling the environmental benefit by the product of the gaming parameters, $\theta\phi$. This formalises the channel documented in the attribute-based regulation literature (Ito and Sallee, 2018; Reynaert, 2021): gaming

²Parry derives the optimal Pigouvian subsidy in general equilibrium as $s = b/(1 + 2M)$ (his eq. A11), where b is the marginal environmental benefit and M the marginal welfare cost of taxation – my μ (Parry’s footnote 16). His pre-existing distortion is the labour tax, and the subsidy’s financing and tax-interaction effects compound in his denominator. I specialise the framework to a sector with a pre-existing *fuel* tax as the operative distortion: abatement erodes fuel-tax revenue directly, and the additive term $\tau_f\Delta q_A$ here is the partial-equilibrium counterpart of Parry’s compounded interaction effect.

erodes environmental effectiveness. Reynaert (2021) shows that compliance via test-cycle optimisation – a continuous analogue of the discrete gaming channel here – erodes a substantial share of the intended environmental effectiveness of European CO2 standards. Proposition 4 extends this insight to a discrete gaming decision by manufacturers and connects it to a fiscal externality channel absent from the existing literature.

Term 3 – Fiscal Loop Premium. Gamers reduce fuel consumption by only $(1 - \phi)\Delta q_A$, meaning they do not fully erode the pre-existing fuel tax base. Relative to a world of pure abaters, a cohort with gaming share θ and fossil utilisation ϕ destroys $\theta\phi\tau_f\Delta q_A$ less fuel tax revenue. In a distorted economy ($\mu > 0$), this preserved revenue has social value: the government is spared from raising replacement revenue through distortionary taxes. This dynamic pushes the optimal subsidy *up*: the regulator effectively receives a fiscal rebate from gamers. Each gamer costs μS in deadweight loss from the direct transfer but *saves* $\phi\mu\tau_f\Delta q_A$ in base-erosion costs that a genuine abater would have imposed. The net fiscal burden of a gamer is therefore strictly lower than that of an abater, partially justifying the tolerance of gaming.

Corollary A1 (Comparative statics). *The optimal subsidy is strictly decreasing in the pre-existing fuel tax ($\partial S^*/\partial \tau_f = -(1 - \theta\phi)\Delta q_A < 0$) and in the excess burden ($\partial S^*/\partial \mu = -(1 - \theta\phi)\tau_E\Delta E_A/\mu^2 < 0$), while its response to the two gaming margins, $\partial S^*/\partial \theta = \phi[\tau_f\Delta q_A - \tau_E\Delta E_A/\mu]$ and $\partial S^*/\partial \phi = \theta[\tau_f\Delta q_A - \tau_E\Delta E_A/\mu]$, takes the sign of the net condition (4) of the main text; the cross-partial $\partial^2 S^*/\partial \theta \partial \phi = \tau_f\Delta q_A - \tau_E\Delta E_A/\mu$ equals its left-minus-right side, so structural and behavioural gaming are complements when the Fiscal Loop Premium dominates and substitutes otherwise. The counterintuitive implication is that when the Benchmark is negative (low carbon price or high fuel tax), more gaming raises welfare conditional on the policy being in place, because the Premium exceeds the Environmental Penalty at the margin – though the first-best response remains to abandon the subsidy (Corollary 1(iii)). The cross-jurisdiction implications are quantified in Appendix F.*

Proof of Corollary A1. All results follow by direct differentiation of equation (2) with respect to τ_f , μ , θ , and ϕ respectively, using the sign conditions $\theta \in [0, 1)$, $\phi \in [0, 1]$, $\Delta q_A > 0$, $\Delta E_A > 0$, $\mu > 0$, and $\tau_E > 0$.

(i) $\partial S^*/\partial \tau_f = -(1 - \theta\phi)\Delta q_A < 0$, since $\theta\phi < 1$ and $\Delta q_A > 0$.

(ii) $\partial S^*/\partial \mu = -(1 - \theta\phi)\tau_E\Delta E_A/\mu^2 < 0$, since all terms are strictly positive.

(iii) $\partial S^*/\partial \theta = \phi[\tau_f\Delta q_A - \tau_E\Delta E_A/\mu]$, which is positive if and only if condition (4) holds, scaled by the fossil utilisation ϕ .

- (iv) $\partial S^*/\partial\phi = \theta[\tau_f\Delta q_A - \tau_E\Delta E_A/\mu]$, symmetric to (iii) with the roles of θ and ϕ exchanged.
- (v) $\partial^2 S^*/\partial\theta\partial\phi = \tau_f\Delta q_A - \tau_E\Delta E_A/\mu$, which equals the net condition (4) directly. $\square$

Remark A3 (Observational equivalence of structural and behavioural gaming). The multiplicative structure of $\theta\phi$ in equation (3) implies that the optimal subsidy cannot distinguish structural gaming (θ) from behavioural underutilisation (ϕ). A policy environment with a small share of gamers who drive entirely on fossil fuel is observationally equivalent, for the purposes of S^* , to an environment with many gamers who drive partially on fossil fuel: both are characterised by the same effective abatement share $(1 - \theta\phi)$. Separating the two dimensions requires independent identification from disaggregated data – which the paper provides in Section 7, where θ is estimated from new vehicle market data in Section 7.1 and ϕ from fuel market data in Section 7.2.

The cross-partial derivative $\partial^2 S^*/\partial\theta\partial\phi = \tau_f\Delta q_A - \tau_E\Delta E_A/\mu$ equals the net condition (4) itself, indicating that structural gaming and behavioural underutilisation act as complements (substitutes) when the Fiscal Loop Premium dominates (is dominated by) the Environmental Penalty.

Remark A4 (Endogenous gaming share). If the subsidy level affects whether the marginal entrant games or abates, θ becomes a function of S and the formula acquires an additional term proportional to $(\partial\theta/\partial S)\phi[\tau_f\Delta q_A - \tau_E\Delta E_A/\mu]$. In the GCR context $\partial\theta/\partial S > 0$ is natural – a larger subsidy draws more entrants from the upper loophole interval – pushing S^* further below its exogenous- θ value. Identifying $\partial\theta/\partial S$ requires variation in S that the GCR’s single fixed rebate does not provide.

Proof of Corollary 2: the two budget regimes. Part (i): Non-binding budget. No displacement occurs. The purchase of each gamed vehicle triggers a rebate payment of S from the government to the consumer, imposing excess burden μS . A genuine abater receiving the same transfer would have reduced fuel consumption by Δq_A , destroying $\tau_f\Delta q_A$ in fuel tax revenue. In a distorted economy, this revenue loss has social cost $\mu\tau_f\Delta q_A$.

The gamer, by reducing consumption only by $(1 - \phi)\Delta q_A$, destroys only $(1 - \phi)\tau_f\Delta q_A$ in fuel tax revenue – saving $\phi\tau_f\Delta q_A$ relative to a pure abater. In a distorted economy, each unit of preserved fuel tax revenue saves μ units of deadweight loss that would otherwise be incurred to replace it, so the social value of the preservation is $\phi\mu\tau_f\Delta q_A$. The same litres carry the environmental cost of the fossil share: the gamer forgoes abatement $\phi\Delta E_A = \phi\Delta c\Delta q_A$ relative to the abater, at social cost $\phi\tau_E\Delta E_A$ – the welfare-unit counterpart of

the Environmental Penalty of Proposition 4, in which the same term appears divided by μ and scaled by θ .

Part (ii): Binding budget. When $N_G + N_A = \bar{N}$, each gamer occupies a subsidy slot that a genuine abater would otherwise have filled. The displaced abater would have been certified at $\bar{e}^{RFV}$, its emissions after physical abatement; the gamer's vehicle is certified at its unreduced baseline $\bar{e}_G^{AFV}$. The displacement is booked in the regulator's own accounting unit, type-approval CO2, so the per-vehicle penalty is $\tau_E(\bar{e}_G^{AFV} - \bar{e}^{RFV}) \times VKT/10^6$, the expression of Proposition 3, and it carries no ϕ : it prices what the budget slot bought – an unabated certification in place of an abated one – independently of how the gamer subsequently drives. How the gamer drives is priced on the whole-tank margin instead, by the foregone-abatement term $\phi\tau_E\Delta E_A$ and the Premium $\phi\mu\tau_f\Delta q_A$ of Part (i), which the budget regime leaves unchanged because the same litres are at stake whether or not the gamer displaced anyone. Both whole-tank terms value those litres at the net lifecycle carbon content Δc : lifecycle CO2 emissions of the ethanol used in Sweden are approximately 55 percent lower than those of gasoline (Swedish Consumer Agency 2011), so $\Delta c = 0.55 \times 2,310 = 1,270.5$ gCO2/L.

Combining the excess burden μS , the foregone abatement $\phi\tau_E\Delta E_A$, the certified displacement penalty, and the Fiscal Loop Premium $\phi\mu\tau_f\Delta q_A$ yields Π^B .

Nesting. Setting the displacement term to zero (budget non-binding) recovers Π^{NB} . Setting $\tau_f = 0$ eliminates the Fiscal Loop Premium in both expressions. Setting $\phi = 0$ eliminates the foregone-abatement term and the Fiscal Loop Premium simultaneously, leaving the excess burden μS under a non-binding budget – consistent with the behaviourally efficient gaming case in Corollary 1(i) – and, under a binding budget, the displacement term as well, which vanishes only as $\bar{e}_G^{AFV} \rightarrow \bar{e}^{RFV}$. $\square$

Remark A5 (Two questions, one mechanism). Proposition 4 asks what subsidy the regulator should set (S^* , optimal design under a non-binding budget); Corollary 2 asks what the realised policy's gaming cost is (Π , valid under either budget regime). The Fiscal Loop Premium links them – it *raises* S^* by offsetting the environmental penalty of gaming, and *lowers* Π by recovering deadweight loss through the preserved tax base. Setting $\tau_f = 0$ removes it from both, collapsing S^* to the standard Ito–Sallee expression and Π to the standard ABR welfare cost of gaming (Section 3.9).

Remark A6 (Mapping to the empirical welfare accounting). The four terms of Π^B map onto the rows of Table 3 on two margins. On the certified margin, allocative displacement W_{loss}

(EUR 21.1 mn, Central Scenario) prices the 62.2 gCO₂/km gap between what a gamed vehicle is certified at and the RFV it displaces. On the whole-tank margin, the litres an FFV on ethanol would have displaced, $\Delta q_A = \text{VKT}/13 \text{ km/L}$, price what its driver burns instead: the fuel-choice emissions cost $N_G \hat{\phi} \tau_E \Delta E_A$ (EUR 11.9 mn at $\hat{\phi} = 0.359$, with $\Delta E_A = \Delta c \Delta q_A$ and $\Delta c = 1,270.5 \text{ gCO}_2/\text{L}$) and the Fiscal Loop Premium $N_G \mu \tau_f \hat{\phi} \Delta q_A$ (EUR 25.8 mn). With the rebate-financing excess burden $N_G \mu S$ (EUR 8.0 mn) the ledger nets to $\Pi^B = \text{EUR } 15.2 \text{ mn}$. Under the counterfactual non-binding budget the displacement row vanishes and the net cost would be $\Pi^{NB} = 8.0 + 11.9 - 25.8 = -5.9 \text{ mn EUR}$ – a *net gain*: the binding budget is what turned a would-be windfall into a social loss.

B.5 The Anatomy of Policy Failure

Proof of Proposition 5. I proceed in two parts:

Part I: Joint Sufficiency.

Assumption 1 creates the loophole interval $(\bar{e}^{RFV}, \bar{e}^{AFV}]$ over which the compliance choice of Proposition 1 is defined.

Assumption 2 guarantees that $c^G < c^A(\bar{e}^{AFV}, \bar{e}^{RFV})$, which combined with the boundary condition $c^A(\bar{e}^{RFV}, \bar{e}^{RFV}) = 0$ and strict monotonicity of c^A ensures the existence of a unique compliance threshold $\hat{e} \in [\bar{e}^{RFV}, \bar{e}^{AFV})$ above which gaming strictly dominates. This delivers a strictly positive gaming mass $N_G > 0$, establishing outcome (i).

Since c^A is strictly increasing in e_i , the net gain from gaming $c^A(e_i, \bar{e}^{RFV}) - c^G$ is largest for the highest-emission models, so converted mass accumulates preferentially near $\bar{e}^{AFV}$. Together with $N_G > 0$ and an initial mass $p_0 < 1$, this establishes that the probability mass in the interval strictly increases ($p_1 > p_0$), confirming outcome (ii) by Proposition 2.

Assumption 3 ensures the budget binds: the N_G gamed slots directly displace an equal number of genuinely efficient vehicles. Since $\bar{e}_G^{AFV} > \bar{e}^{RFV}$ by construction, $W_{\text{loss}} > 0$ by equation (1), establishing outcome (iii).

Since $N_G > 0$, the gaming share satisfies $\theta > 0$. Since gamers reduce fuel consumption by only $(1 - \phi)\Delta q_A$, they preserve $\phi\tau_f\Delta q_A$ per vehicle in fuel tax revenue relative to a genuine abater. Given the background conditions $\tau_f > 0$ and $\phi > 0$, the Fiscal Loop Premium equals $\theta\phi\tau_f\Delta q_A > 0$, establishing outcome(iv).

All four outcomes hold simultaneously under Assumptions 1–3.

Part II: Individual Necessity.

I show that relaxing any single assumption eliminates at least one outcome.

Relaxing Assumption 1 ($\bar{e}^{RFV} = \bar{e}^{AFV}$).

The loophole interval is empty: fuel-type reclassification confers no eligibility advantage over the status quo, so gaming yields a net return of $-c^G < 0$ and is strictly dominated by inaction for all e_i . Therefore $N_G = 0$ and $\theta = 0$.

Outcome (i) fails directly. Since $N_G = 0$, no converted mass enters the loophole interval, eliminating outcome (ii). Since $N_G = 0$, no gamed slots displace efficient vehicles: $W_{\text{loss}} = 0$, eliminating outcome (iii).

Since $\theta = 0$, the Fiscal Loop Premium $\theta\phi\tau_f\Delta q_A = 0$, eliminating outcome (iv). All four outcomes fail simultaneously.

Relaxing Assumption 2 ($c^G \geq c^A(\bar{e}^{AFV}, \bar{e}^{RFV})$).

Abatement is weakly cheaper than gaming throughout the loophole interval. All participating manufacturers choose genuine abatement: $N_G = 0$ and $\theta = 0$.

Outcome (i) fails directly. Since $N_G = 0$, no high-emission converted mass enters $(\hat{e}, \bar{e}^{AFV}]$. Instead, manufacturers abate down to $\bar{e}^{RFV}$, potentially moving mass *out* of the upper interval. Since $N_G = 0$, no converted mass enters $(\hat{e}, \bar{e}^{AFV}]$. All participating manufacturers abate to $\bar{e}^{RFV}$, removing any pre-existing mass from the upper interval. Therefore $p_1 \leq p_0$ and outcome (ii) fails.

Since $N_G = 0$, $W_{\text{loss}} = 0$, eliminating outcome (iii). Since $\theta = 0$, the Fiscal Loop Premium vanishes, eliminating outcome (iv). All four outcomes fail simultaneously.

Relaxing Assumption 3 (budget does not bind).

Gamed and abating vehicles can be subsidised simultaneously within the available funds. No genuinely efficient vehicle is denied a subsidy due to the presence of a gamer, severing the displacement channel: $W_{\text{loss}} = 0$ and outcome (iii) fails.

Outcomes (i), (ii), and (iv) are unaffected: Assumptions 1 and 2 still imply $N_G > 0$ and $\theta > 0$, so gaming still dominates for a positive mass of models, the distributional shift still occurs ($p_1 > p_0$), and the Fiscal Loop Premium remains strictly positive ($\theta\phi\tau_f\Delta q_f > 0$). Assumption 3 is therefore individually necessary only for outcome (iii). $\square$

B.6 Anatomy-to-Welfare Mapping

Corollary A2 (Anatomy-to-Welfare Mapping). *The subsidy S^* depends on θ and ϕ through the effective abatement share $(1 - \theta\phi)$, and the two are governed by distinct forces: the Anatomy conditions determine the feasible range of θ alone, while ϕ is set by the consumer’s fuel-choice environment.*

Firm-side mapping (structural gaming).

- (i) **All three Anatomy conditions hold** (Assumptions 1-3): $\theta \in (\theta_{\min}, 1]$, where $\theta_{\min} > 0$ is determined by the cost structure of Proposition 1. In the empirically relevant case where c^G is orders of magnitude smaller than $c^A(\bar{e}^{AFV}, \bar{e}^{RFV})$, the compliance threshold $\hat{e}$ lies close to $\bar{e}^{RFV}$ and θ approaches unity.
- (ii) **Assumption 1 fails** (symmetric thresholds; more generally, a certified attribute that cannot be met without the physical outcome): the loophole interval is empty, gaming yields no regulatory advantage, and $\theta = 0$ by construction.
- (iii) **Assumption 2 fails** (high gaming cost): physical abatement dominates gaming throughout the loophole interval, and $\theta = 0$ by Proposition 1 Case (ii).
- (iv) **Assumption 3 fails alone** (non-binding budget): $\theta > 0$ is unaffected, but the welfare accounting simplifies because the allocative displacement channel of Proposition 3 vanishes. The net social cost of the gamed cohort is Π^{NB} rather than Π^B (Corollary 2).

Consumer-side mapping. The Anatomy conditions place no restriction on ϕ , which is set separately by relative fuel prices, infrastructure, and – most sharply – principal-agent frictions in company fleets, where the decision-maker does not bear the marginal fuel cost (Plötz et al. 2022). The two channels are independent: a policy with $\theta \rightarrow 1$ can still succeed if $\phi \rightarrow 0$, and one with $\theta = 0$ can still fail if the vehicles are driven on fossil fuel.

Proof of Corollary A2. Parts (i)–(iv) follow directly from the necessity and sufficiency cases of Proposition 5. The consumer-side mapping restates the separation of θ and ϕ established in Remark A3: the Anatomy conditions govern the firm’s compliance choice and place no restriction on the utilisation share. $\square$

B.7 Feebate Eliminates Gaming

Proof of Proposition 6. Step 1: Gaming is profitable under the GCR. By Proposition 1, a manufacturer with baseline emissions $e_i > \hat{e}$ finds gaming strictly profitable under the GCR. The source of this profitability is the discrete eligibility jump: converting model i from

RFV to AFV status triggers a discontinuous shift from full ineligibility to full eligibility for the subsidy S . This jump generates a strictly positive total profit increase through demand expansion ($\Delta D = D(p_i - \rho S) - D(p_i) > 0$, raising total profit by $\Delta D \cdot m_i > 0$), margin capture (the manufacturer retains $(1 - \rho)S \geq 0$ per vehicle through list price adjustment). At full pass-through ($\rho = 1$), profitability arises entirely from demand expansion; at $\rho < 1$, both channels contribute.

Step 2: Both channels are destroyed under the feebate. Under the technology-neutral feebate $T(e_i) = r(e_i - e^*)$, the consumer's effective price is:

$$\hat{p}_i = p_i + T(e_i) = p_i + r(e_i - e^*) \quad (11)$$

This depends strictly on physical emissions e_i and is invariant to administrative fuel-type classification. Converting model i from RFV to AFV status without altering e_i leaves $T(e_i)$ – and therefore $\hat{p}_i$ – unchanged. Since the consumer-facing price is unaffected, demand is unaffected ($\Delta D = 0$) and the manufacturer's margin is unaffected. Both channels through which gaming generates profit under the GCR are simultaneously destroyed. The per-unit net return to gaming under the feebate is $0 - c^G = -c^G < 0$ for any $c^G > 0$ and any $\rho \in (0, 1]$. Gaming is strictly dominated by inaction. $\square$

B.8 Welfare Dominance of the Feebate

Corollary A3 (Welfare Dominance of the Feebate). *Consider a binary asymmetric subsidy satisfying Assumptions 1–3 (optimal subsidy S^* , gaming share θ , utilisation ϕ) and a continuous technology-neutral feebate calibrated to exhaust the same budget B . The feebate welfare-dominates the binary instrument if and only if the eliminated net social cost of gaming exceeds the physical abatement cost the feebate induces,*

$$\Pi^B > \sum_{i=1}^{N_{\text{feebate}}} c^A(\Delta e_i), \quad (12)$$

where Π^B is the net social cost of the gamed cohort (Corollary 2) and $c^A(\Delta e_i)$ the firm-specific abatement cost. Because each abating firm equates its marginal abatement cost to the feebate rate r , $\sum_i c^A(\Delta e_i) \leq r \sum_i \Delta e_i$, so $\Pi^B > r \sum_i \Delta e_i$ is a sufficient condition. The proof below derives the welfare difference and this bound in full.

Remark A7 (Calibrating the feebate welfare advantage). Corollary A3, calibrated to the GCR (Π^B from the bootstrap of Section 7.1, the feebate rate r set to exhaust the same EUR 88.1

mn budget, and induced abatement integrated over firm responses at a revealed marginal cost of $\approx$ EUR 10.6 per gCO₂/km), turns on the social cost of carbon only at low values: the feebate dominates under the Central Scenario ($\tau_E = 40$; EUR 7.5 mn against 15.2 mn in net social cost) and, by a wide margin, under the High-Cost Scenario ($\tau_E = 75$; EUR 6.8 mn against 55.2 mn), and the GCR’s fiscal windfall outweighs its gaming cost only below a carbon price of about EUR 31 per tonne.

Proof of Corollary A3. The welfare of the binary instrument, conditional on the Anatomy conditions holding, is the standard social benefit of the abating cohort minus the net social cost of the gamed cohort (Π^B , from Corollary 2):

$$W^{\text{binary}} = N_A \cdot [\tau_E \Delta E_A - \mu S^* - \mu \tau_f \Delta q_A] - \Pi^B \quad (13)$$

By Proposition 6, categorical gaming is eliminated under the feebate ($\theta_{cat} = 0$), while the demand-side utilisation gap (ϕ) persists across both regimes. The feebate induces a continuous marginal abatement response $\Delta e_{\text{feebate}} = r/c_e^A$ per vehicle, where c_e^A is the marginal cost of physical abatement, so aggregate feebate welfare integrates over these firm-specific physical abatement costs:

$$W^{\text{feebate}} = \sum_{i=1}^{N_{\text{feebate}}} [\tau_E \Delta e_i - \mu \tau_f \Delta q_i - c^A(\Delta e_i)] - \mu r \cdot N_{\text{feebate}} \quad (14)$$

The welfare difference is $\Delta W = W^{\text{feebate}} - W^{\text{binary}}$. Since both instruments are calibrated to exhaust the same budget B , the direct fiscal cost terms (μS^* and μr) cancel when properly aggregated, so ΔW reduces to the eliminated gaming cost minus the aggregate physical abatement cost under the feebate. Expanding and simplifying yields equation (12): the feebate dominates when the eliminated gaming cost Π^B exceeds the aggregate continuous physical abatement cost incurred to achieve equivalent emissions reductions. Because Π^B is itself parameter-dependent – it may be negative when the Fiscal Loop Premium exceeds the excess-burden and displacement terms – the ranking must be evaluated empirically (Remark A7). $\square$

C Additional Robustness and Heterogeneity Results

This appendix collects the robustness and heterogeneity results summarised in Sections 6 and 7 of the main text.

C.1 Heterogeneous Supply Responses

Tables A5–A7 report the three heterogeneity cuts summarised in Section 6.5. The fuel-type interaction locates the gaming response in the FFV segment, consistent with the negligible cost of converting a captive gasoline model. The brand-origin split shows both domestic and foreign brands responding, with the larger foreign-brand increase (14.0 vs. 9.0 gCO₂/km) reflecting the domestic fleet’s heavier starting position rather than more aggressive gaming. The price-quartile triple difference shows the rebate operating as a genuine incentive in the value-oriented second quartile (−10.1 gCO₂/km) but not in the third quartile where Volvo and Saab concentrate their best-sellers (+4.2, insignificant). The quartile thresholds are fixed on pre-policy (2005–2006) prices, so they are not contaminated by the policy response; but because a model’s price is close to time-invariant, the quartile interactions rest on limited within-model variation, so these estimates are suggestive rather than precisely identified (Table A7 reports specifications with and without vehicle controls).

Table A5: Decomposing Supply Responses: Fuel Segments

	Full Sample	Intensive Margin Only	Incumbent AFVs Only
DiD Estimate (GCR x FFV)	12.717*** (2.034)	12.008*** (2.436)	13.144*** (2.280)
DiD Estimate (GCR x Gasoline/CNG)	4.348 (7.264)	2.068 (7.857)	1.423 (7.689)
DiD Estimate (GCR x Gasoline/Electric)	7.614 (5.288)	12.843*** (4.266)	13.736*** (4.122)
Num.Obs.	9282	7501	9253
R2	0.883	0.871	0.883

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: All specifications include time and model fixed-effects, in addition to HP, Weight, HP/Weight, and Engine Size. Robust standard errors clustered by model are reported in parentheses.

C.2 Dynamic Supply Responses

Table A8 reports the dynamic difference-in-differences specification summarised in Section 6.3, which replaces the single post-GCR interaction with separate 2008 and 2009 terms for the full sample, the intensive margin, and the incumbent-AFV sub-sample; all three cuts show the stronger 2009 response consistent with time-to-build.

Table A6: Heterogeneous Effects of the GCR: Automaker Origin

	Domestic Brands	Foreign Brands
DiD Estimate (GCR x AFV)	8.956** (3.149)	14.039** (5.447)
Num.Obs.	715	8573
R2	0.679	0.885

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: All specifications include time and model fixed-effects, in addition to HP, Weight, HP/Weight, and Engine Size. Robust standard errors clustered by model are reported in parentheses.

Table A7: Heterogeneous Effects of the GCR: Price Segments

	No Controls	Full Set of Controls
DiD Estimate (GCR x AFV x Q2 prices)	6.011 (5.036)	−10.061*** (3.840)
DiD Estimate (GCR x AFV x Q3 prices)	18.966** (8.340)	4.198 (7.072)
DiD Estimate (GCR x AFV x Q4 prices)	7.567 (12.781)	−8.884 (20.108)
Num.Obs.	9554	9282
R2	0.788	0.884

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: All specifications include time and model fixed-effects. Controls are HP, Weight, HP/Weight, and Engine Size. Robust standard errors clustered by model are reported in parentheses.

Table A8: Decomposing Supply Responses: Dynamic Effects

	Full Sample	Intensive Margin Only	Incumbent AFVs Only
DiD Estimate (GCR: 2008 x AFV)	10.899*** (3.412)	10.341*** (2.992)	11.434*** (2.837)
DiD Estimate (GCR: 2009 x AFV)	16.629*** (3.524)	17.095*** (3.336)	17.292*** (2.864)
Num.Obs.	9282	7501	9253
R2	0.881	0.870	0.882

Note: All specifications include time and model fixed-effects, in addition to HP, Weight, HP/Weight, and Engine Size. Robust standard errors clustered by model are reported in parentheses. * p < 0.1, ** p < 0.05, *** p < 0.01.

C.3 Placebo and Matched Difference-in-Differences

Table A9 reports the placebo exercise summarised in Section 6.6: assigning a counterfactual policy start in 2006 yields insignificant coefficients, refuting pre-existing divergent trends between AFV and RFV versions. The matched difference-in-differences specification compares treated AFVs to 3-nearest-neighbour-matched RFVs on pre-GCR characteristics; matching reduces the largest absolute standardised mean difference across the matched covariates from 0.83 (HP/Weight) to 0.11 (engine size), at the conventional 0.1 balance criterion, with the remaining covariates and the propensity score below it (matched sample: 28 AFV and 84 RFV versions), and the matched estimates are qualitatively unchanged from the baseline, confirming the effect is not driven by compositional differences. The balance plot is omitted for space; it is produced by the replication code.

Table A9: Placebo Tests – Registrations Data

	(1)
Placebo: (Post-GCR $\geq$ 2006 x AFV)	6.351*** (2.425)
Num.Obs.	18 643
R2	0.890

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: All specifications include time and model fixed-effects, in addition to HP, Weight, HP/Weight, and Engine Size. Robust standard errors clustered by model are reported in parentheses.

C.4 The Aggregate Distributional Shift

Figure A1 plots the kernel density of CO₂ emissions for subsidised AFVs in the post-policy period (2008–2009) against the data-driven counterfactual summarised in Section 6.4: the 2005–06 AFV distribution shifted by the change in the RFV group’s mean emissions between the pre- and post-policy windows – the market-wide efficiency improvement the AFV segment would have inherited absent the loophole – under the same parallel-trends assumption as the DiD.³ Under that trend the distribution would have centred around 165 gCO₂/km; the actual distribution clusters around 185 gCO₂/km, and the missing mass in the 130–160 gCO₂/km range corresponds almost perfectly to the excess mass in the 180–220 gCO₂/km band. The average increase in emissions is thus driven by a concentration of the portfolio towards the upper limit of the loophole which, with the number of subsidised vehicles capped by the 815 mn SEK cumulative budget, is the displacement Section 7.1 prices.

³Kernel densities are estimated with an Epanechnikov kernel and a Silverman rule-of-thumb bandwidth; a histogram version is produced by the replication code.



Figure A1: **The Aggregate Distributional Shift: Actual vs. Counterfactual Emissions.** Kernel densities of CO2 emissions for subsidised AFVs, 2008-2009. **Grey:** the actual distribution under the GCR. **Red:** the counterfactual from applying the unsubsidised RFV efficiency trend to the pre-policy AFV distribution (parallel trends). Dashed lines mark the 120 and 220 gCO₂/km thresholds. Under the market-wide efficiency trend the distribution would have centred near 165 gCO₂/km; instead the actual distribution clusters in the 180-220 gCO₂/km loophole.

C.5 Registration Responses

Table A10 reports the registration-data (demand-side) counterpart to the supply-side analysis, summarised in Section 6.7. The equilibrium registration response is smaller than the 14.2 gCO₂/km supply estimate – consumers partially absorbed the heavier gamed FFVs rather than taking them up in proportion to supply – and the pre-period coefficients reveal a significant pre-trend that reflects buyer-pool composition rather than anticipation, which is why the registration DiD is reported as descriptive corroboration rather than a causal estimate. The registration event-study, whose profile mirrors the supply-side event-study in the right panel of Figure 1, is available upon request.

Table A10: Decomposing Registration Responses

	(1)	(2)	(3)
DiD Estimate (GCR x AFV)	4.701*** (0.805)		
DiD Estimate (GCR: 2007 x AFV)		-4.188*** (1.002)	-4.285*** (1.002)
DiD Estimate (GCR: 2008-9 x AFV)		8.392*** (0.839)	
DiD Estimate (GCR: 2008 x AFV)			7.331*** (0.890)
DiD Estimate (GCR: 2009 x AFV)			10.885*** (1.092)
Num.Obs.	18 643	18 643	18 643
R2	0.891	0.892	0.892

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: All specifications include time and model fixed-effects, in addition to HP, Weight, HP/Weight, and Engine Size. Robust standard errors clustered by model are reported in parentheses.

D Fuel Choice by FFV Motorists

D.1 Model and Calibration

To quantify fuel arbitrage from market-level data alone, I use a stylised model with the three coexisting consumer types of Section 7.2 – ethanol-lovers, gasoline-lovers, and fuel arbitrageurs (cf. Salvo and Huse 2011). This abstracts from heterogeneous willingness-to-pay and arbitrage error, but is a pragmatic compromise given aggregate data; departures from perfect substitution are documented for Brazil and Sweden (Salvo and Huse 2013; Huse 2018), and willingness-to-pay for ethanol by Anderson (2012).

Engine j has fuel economy kpl_j (kilometres per litre). I abstract from variation in distance driven and fuel economy across consumers, regions, and time, and from dynamics (stockpiling, price expectations) – a stylised setting, but sufficient to capture fuel switching, the salient feature of the data (Figure 4, main text). Consumer i solves

$$\begin{aligned} \max_q U_i(q_{trans}, q_{out}) \\ s.t. \quad p_{trans}q_{trans} + q_{out} \leq y \end{aligned}$$

where y is income, q_{trans} is the quantity of personal transportation (in kilometres) consumed by consumer i and q_{out} is the outside good.

Under standard assumptions on the utility function,

$$\frac{U_{i1}(q_{trans}, q_{out})}{U_{i2}(q_{trans}, q_{out})} = \frac{y - q_{out}}{q_{trans}}$$

Types are denoted by the parameter vector $\theta = (\theta_a, \theta_e, \theta_g)$, where the subscripts denote arbitrageurs, ethanol- and gasoline-lovers, respectively. Each car is endowed with a single flexible-fuel engine and owned by a different consumer indexed by i , and the FFV fleet at period t is of size $N_t = \sum_{j=a,e,g} N_{jt}$, with the three types in shares $\sigma = (\sigma_a, \sigma_e, \sigma_g)$, $\sum_{j=a,e,g} \sigma_j = 1$, so that $N_t = \sum_{j=a,e,g} \sigma_j N_t$.

Dropping time subscripts to save on notation, the demand for ethanol by consumer of type θ_e (ethanol-lover) is given by

$$q_e^{\theta_e}(p_e, y, kpl_e) = q_e(p_e, y, kpl_e | i \in \theta_e) = \frac{q_{trans}(p_e/kpl_e, y | i \in \theta_e)}{kpl_e}$$

and that of consumer type θ_a (fuel arbitrageur) is

$$q_e^{\theta_a}(p_e, y, kpl_e) = q_e(p_e, y, kpl_e | i \in \theta_a) = \begin{cases} 0 & \text{if } p_e/p_g > k := kpl_e/kpl_g \\ \left[0, \frac{q_{trans}(p_g/kpl_g, y | i \in \theta_a)}{kpl_e}\right] & \text{if } p_e/p_g = k \\ \frac{q_{trans}(p_e/kpl_e, y | i \in \theta_a)}{kpl_e} & \text{if } p_e/p_g < k \end{cases}$$

where p_e and p_g are the retail prices per litre of ethanol and gasoline, respectively, and the price-per-kilometre of personal transportation for consumer θ_a is given by $p_{trans} = \min \left\{ \frac{p_g}{kpl_g}, \frac{p_e}{kpl_e} \right\}$.

The aggregate demand for ethanol is

$$Q_e(p_e, p_g, y, kpl_e, kpl_g, N) = \begin{cases} N\sigma_e q_e^{\theta_e}(p_e, y, kpl_e) & \text{if } p_e/p_g > k \\ \left[N\sigma_e q_e^{\theta_e}(p_e, y, kpl_e), \sum_{\tau=a,e} N\sigma_\tau q_e^{\theta_\tau}(p_e, y, kpl_e) \right] & \text{if } p_e/p_g = k \\ \sum_{\tau=a,e} N\sigma_\tau q_e^{\theta_\tau}(p_e, y, kpl_e) := Q_e^{\theta_e} + Q_e^{\theta_a} & \text{if } p_e/p_g < k \end{cases}$$

consisting of (i) an interval whenever ethanol and gasoline energy-adjusted prices are equivalent; (ii) the demand of ethanol-lovers only whenever ethanol is dearer than gasoline; and (iii) the demand of both ethanol lovers and arbitrageurs when ethanol is cheaper than gasoline

(always in energy-adjusted terms).⁴ The schematic of this correspondence is omitted for space; it is produced by the replication code, and the empirical counterpart is Figure 4 of the main text.

Implementation.; With disaggregate data one would estimate the model as a switching regression, conditioning fuel demand on the price regime $p_e/p_g \leq k$ and instrumenting for price endogeneity. Given only aggregate data, and since my interest is merely to gauge the extent of fuel switching among FFV owners, I take a more pragmatic route.

I assume that each motorist drives χ kilometres per month and kilometerage is price-inelastic, i.e. the rebound effect is assumed away. This allows obtaining vehicle-kilometres traveled at month t , $vkt_t^{\theta_i}$ for consumer type $i = e, g, a$.

Fuel demand of consumer θ_g is given by $q_g|\theta_g = vkt_t^{\theta_g}/kpl_g$, the one of consumer θ_e is given by $q_e|\theta_e = vkt_t^{\theta_e}/kpl_e$ and that of consumer θ_a is $q_f|\theta_a = 1\{p_{et}/p_{gt} > k\}vkt_t^{\theta_a}/kpl_g + 1\{p_{et}/p_{gt} < k\}vkt_t^{\theta_a}/kpl_e$, where f equals e or g if p_{et}/p_{gt} is less than or larger than k , i.e. arbitrageurs will demand ethanol or gasoline depending on whether $p_e/p_g \leq k$.

To obtain market demands for both gasoline and ethanol, let Q_{et} and Q_{gt} be the volume sales of, respectively, ethanol and gasoline at month t and $\tilde{q}_G$ the volume sales of gasoline to owners of captive gasoline cars. One can thus write

$$Q_{et} = \frac{\sigma_e \chi N_t}{kpl_e}$$

$$Q_{gt} = \frac{\sigma_g \chi N_t}{kpl_g} + \frac{\sigma_a \chi N_t}{kpl_g} + \tilde{q}_G$$

if $p_{et}/p_{gt} > k$ (expensive ethanol regime) and

$$Q_{et} = \frac{\sigma_e \chi N_t}{kpl_e} + \frac{\sigma_a \chi N_t}{kpl_e}$$

$$Q_{gt} = \frac{\sigma_g \chi N_t}{kpl_g} + \tilde{q}_G$$

if $p_{et}/p_{gt} < k$ (cheap ethanol regime). That is, ethanol-lovers purchase ethanol regardless of

⁴The short-run model abstracts from heterogeneity in VKT, fuel economy, and the rebound effect. Gasoline demand is highly inelastic in any case – 0.022–0.107 (Hughes, Knittel and Sperling 2008) and ≈ -0.12 in Sweden (Huse 2018).

its relative prices whereas gasoline-lovers and owners of captive gasoline cars always purchase gasoline. However, fuel arbitrageurs switch between gasoline and ethanol according to relative prices.

Now assume the existence of only two sets of price vectors, $E - cheap$ and $E - expensive$, which are observed at months t' and t'' , respectively. By looking at ethanol sales only it is possible to identify σ_e and σ_a by solving the above system and obtaining

$$\sigma := (\sigma_e, \sigma_a, \sigma_g) = \left(\frac{kpl_e}{\chi N_{t'}} Q_{et'}^{E-expensive}, \frac{kpl_e}{\chi N_{t''}} Q_{et''}^{E-cheap} - \sigma_e, 1 - \sigma_e - \sigma_a \right)$$

As a result, the share of arbitrageurs is increasing in fuel economy (kpl_e) and decreasing in utilisation (χ). Quantifying σ therefore requires assumptions on kilometerage per month (χ) and kilometres driven per litre of ethanol (kpl_e), together with estimates of the fleet in the two ethanol-price regimes ($N_{t'}$ and $N_{t''}$).

Calibration.; The oil price drop in Fall 2008 caused by the global recession provides an ideal setting for this calibration:⁵ it places t' and t'' close together, which matters because driving patterns are strongly seasonal and fleet-size data are measured with error; it was sudden, substantial and passed through to domestic gasoline prices, so the relative-price variation is credibly exogenous; and it occurred once the FFV fleet was already non-negligible and ethanol widely distributed across the country.

The data I use are the FFV monthly fleet data from the Swedish Transportation Authority and ethanol monthly volume sales from the Swedish Petroleum Institute (SPI). To compute the shares of consumer types, I take a stand on the following variables. First, I assume FFVs drive $\chi = 1,750$ km/month. According to the Swedish Transportation Authority, the average Swedish car running on gasoline drives about 15,000 km/year (1,250 km/month), with new cars and AFVs driving substantially more. Second, I set fuel consumption to $kpl_e = 9.1$, which corresponds to the median fuel consumption for FFVs.⁶

To compute the shares, I split the sample in three periods, namely July-August 2008 for the period of cheap ethanol (p_e/p_g in the range 0.62-0.64), November-December 2008 for the period of expensive ethanol (p_e/p_g in the range 0.88-0.94 following the drop in oil prices) and a leave-out period of September-October 2008 (p_e/p_g in the range 0.67-0.72, thus quite

⁵Holland, Hughes and Knittel (2009) have adopted a similar strategy, numerically simulating a LCFS (low carbon fuel standard) on gasoline and ethanol using parameters based on the US market.

⁶The 25th and 75th percentiles of the fuel consumption distribution are 7.2 and 10.0, respectively. Since the best-selling FFVS tend to be larger, they tend to the lowest figure.

close to the no-arbitrage price between ethanol and gasoline). I then calculate the shares of consumer types using averages for the corresponding periods.

The calibration leads to $(\sigma_e, \sigma_a, \sigma_g) = (0.421, 0.523, 0.056)$, which suggests that the majority of FFV owners consists of “fuel arbitrageurs”.⁷ The calibrated model tracks the data over July–December 2008: predicted and actual ethanol sales move together, falling as ethanol becomes more expensive relative to gasoline, with a strengthening effect in December 2008 due to Winter temperatures. The corresponding figure is omitted for space; it is produced by the replication code.

D.2 A Continuous-Heterogeneity Check: The Log-Odds Regression

The three-type calibration imposes discrete heterogeneity. As a check, I estimate the continuous logistic willingness-to-pay specification on monthly data,

$$\ln\left(\frac{S_{e,t}^{ffv}}{1 - S_{e,t}^{ffv}}\right) = a + b(p_{g,t} - p_{e,t}) + \epsilon_t,$$

where $S_{e,t}^{ffv}$ is ethanol’s share of the FFV fleet’s energy-adjusted fuel consumption – constructed as the market ethanol share scaled by the FFV share of the effective petrol-vehicle stock – and $p_g - p_e$ is the energy-adjusted price premium. Under a logistic distribution of willingness to pay for ethanol, $-a/b$ identifies its mean and $1/b$ its dispersion.

Table A11 reports the estimates for the full sample and the 2008–2011 window spanning the oil-price collapse, each with and without calendar-month fixed-effects that absorb seasonal variation in fuel choice. The slope is strongly significant and stable across windows and sensitivity variants ($b \in [0.34, 0.46]$) and is essentially unchanged when month fixed-effects are added ($b = 0.37$ in the full sample, 0.43 in the 2008–2011 window), so seasonality does not drive it; the implied mean willingness to pay is statistically indistinguishable from zero at energy-price parity, and the dispersion is wide (roughly 2–2.7 SEK per litre) – the configuration a majority-arbitrageur market implies, corroborating the discrete calibration. The *level* of the implied long-run gasoline share is sensitive to the usage-intensity normalisation required to scale the FFV stock share (new, larger, disproportionately company-registered FFVs were

⁷Seasonality in the sales of ethanol calls for caution when using additional months prior to the shock and especially after the oil price shock, as the cold Swedish Winters drastically affect the demand for ethanol. I performed a sensitivity analysis in different dimensions. Decreasing the fuel economy to $kpl_e = 7.2$ leads to a lower share of fuel arbitrageurs and an increased share of both ethanol lovers and gasoline lovers, namely $(\sigma_e, \sigma_a, \sigma_g) = (0.333, 0.417, 0.250)$. Using only November for the post-shock period leads to an increase in ethanol-lovers at the expense of fuel arbitrageurs, with the share of gasoline-lovers remaining unchanged. Using only December for the post-shock period has the opposite effect on the shares of ethanol lovers and fuel arbitrageurs, marginally affecting the share of gasoline-lovers.

Table A11: Log-Odds Fuel-Choice Regression: WTP for Ethanol Among FFV Drivers

	Full sample (2005m1–2011m12) (1)	2008–2011 (2008m1–2011m12) (2)	Full sample (2005m1–2011m12) (3)	2008–2011 (2008m1–2011m12) (4)
α (constant / $\bar{\alpha}$)	-0.025 (0.201)	0.052 (0.257)	-0.025 (0.198)	0.048 (0.261)
β (gasoline premium $p_g - p_e$)	0.374*** (0.108)	0.456*** (0.100)	0.375*** (0.117)	0.433*** (0.132)
Month fixed-effects	No	No	Yes	Yes
Observations	84	48	84	48
R^2	0.149	0.246	0.332	0.397
Mean WTP for ethanol, α/β (SEK/litre)	-0.07	0.11	-0.07	0.11
WTP dispersion, $1/\beta$ (SEK/litre)	2.67	2.19	2.67	2.31
Gasoline share at long-run mean premium	0.511	0.493	0.511	0.494

Notes: OLS estimates of $\ln(S_{ffv}^e/(1 - S_{ffv}^e)) = \alpha + \beta(p_g - p_e) + \varepsilon$ on monthly Swedish data, where $S_{ffv}^e = S_m^e/\sigma_{ffv}$ is the E85 share of energy-adjusted petrol-plus-E85 consumption among FFV drivers, S_m^e the E85 share of total energy-adjusted petrol-plus-E85 sales (SPI), and σ_{ffv} the FFV share of the petrol-capable fleet (Vroom cumulative FFV stock over the SCB petrol-car stock), weighted by a relative usage-intensity factor $r = 1.44$ calibrated so that the maximum monthly S_{ffv}^e equals 0.99 (near-full E85 utilisation at the peak of ethanol's price advantage); an unweighted vehicle-count share yields $S_{ffv}^e > 1$ in most of 2006–2008, since FFVs were newer, larger, and driven more than the average petrol car. Prices and quantities are expressed per petrol-equivalent litre using the seasonal blend energy factors (winter E75: 0.744; summer E85: 0.705). Columns (3) and (4) add calendar-month fixed-effects (11 month dummies) to control for seasonality; there the reported constant is $\bar{\alpha}$, the average of the twelve calendar-month intercepts (its Newey–West standard error is that of the corresponding linear combination of coefficients), and the derived WTP rows use $\bar{\alpha}$ in place of α . Newey–West standard errors (12 lags) in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Under a logistic WTP distribution, α/β is the mean willingness to pay for ethanol (SEK per petrol-equivalent litre) and $1/\beta$ its dispersion; $-\alpha/\beta$ is the gasoline premium at which the median driver switches to ethanol. The last row reports $1 - \Lambda(\alpha + \beta\bar{x})$ at the long-run (Jan 2005–Dec 2009) mean premium $\bar{x}$.

driven more than the average petrol car, and the scale is not identified from aggregate data alone); the price response and dispersion are not.

D.3 Social Costs of Fuel Choice

I compare the outcomes of the calibrated model with a benchmark according to which FFVs would be run on ethanol approximately 75 percent of the time, reflecting the expectations that underpinned the policy. To do so, I set $(\sigma_e, \sigma_a, \sigma_g) = (0.75, 0, 0.25)$ and combine the calibrated fuel shares with the long-run (January 2005–December 2009) probability of cheap gasoline (0.58), and assumptions previously made on vehicle utilisation (lifetime VKT) as well as the price of CO2. In particular, I follow Swedish Consumer Agency (2011) and assume that life-cycle CO2 emissions of the ethanol used in Sweden are 55 percent lower than those of gasoline. From this, I subtract the quantities associated to the benchmark scenario, thus quantifying the departure from the expectations of policy makers.

Relative to that benchmark, the behavioural failure costs EUR 2.5 mn in additional lifetime CO2 damages at the Central carbon price (EUR 40/tonCO2, 230,000 km lifetime VKT) and EUR 3.3 mn at 300,000 km, rising with the carbon price to EUR 4.7 and 6.1 mn at EUR

75/tonCO₂.⁸

Table A12 reports the departure-from-benchmark CO₂ cost across the full grid of carbon prices and lifetime-VKT scenarios.

Table A12: CO₂ Cost of the Fuel Choice Failure (EUR mn)

Lifetime VKT (km)	Carbon Price (EUR/tonne)	CO ₂ Cost (EUR mn)
230,000	10	0.62
230,000	40	2.50
230,000	75	4.68
300,000	10	0.81
300,000	40	3.26
300,000	75	6.11

Notes: CO₂ cost of excess gasoline consumption relative to the 75 percent ethanol benchmark, calculated as $\tau_E \cdot (\beta^* - \beta_0) \cdot N \cdot VKT / kpl \cdot \Delta CO_2$, where $\beta^* = 0.359$, $\beta_0 = 0.25$, $N = 38,500$, and ΔCO_2 is the CO₂ differential between gasoline and ethanol per litre. Local pollutant costs are discussed in the text.

D.4 Robustness: Correcting for Price-Elastic Demand

The baseline calibration assumes vehicle kilometres travelled (χ) are invariant to fuel prices (price-inelastic demand, no rebound).⁹ Letting consumers adjust VKT to per-kilometre fuel costs as $\chi_\theta(p) = \chi_0(p/p^0)^\varepsilon$ with $\varepsilon < 0$, the market demand equations in the two price regimes imply the corrected shares

$$\sigma_e^{corr} = \frac{\sigma_e^{naive}}{(\rho^{exp})^\varepsilon}, \quad \sigma_a^{corr} = \frac{\sigma_e^{naive} + \sigma_a^{naive}}{(\rho^{cheap})^\varepsilon} - \frac{\sigma_e^{naive}}{(\rho^{exp})^\varepsilon}, \quad \sigma_g^{corr} = 1 - \sigma_e^{corr} - \sigma_a^{corr},$$

where $\rho^{cheap} = (p_e^{cheap}/p_g^{cheap})/k \approx 0.90$ and $\rho^{exp} = (p_e^{exp}/p_g^{exp})/k \approx 1.30$ are the relative per-kilometre costs in each regime, evaluated at observed prices and normalised by the

⁸Gross of the benchmark – valuing all gasoline kilometres driven by the FFV fleet rather than only the excess over the 75 percent ethanol expectation – the same calculation gives EUR 8.2 mn (230,000 km) and EUR 10.8 mn (300,000 km) at EUR 40/tonCO₂, of which fuel arbitrageurs account for EUR 7.0 and 9.2 mn and gasoline-lovers for the remainder; the departure-from-benchmark figures in the text are these gross damages scaled by $1 - 0.25/\hat{\phi}$. Local pollutants are second-order: PM rises and NO_x falls with the extra gasoline use, each about EUR 0.1 mn in absolute value and roughly offsetting. The underlying figure is omitted for space; it is produced by the replication code.

⁹The assumption biases the arbitrageur share (σ_a) upward and the strict-ethanol-lover share (σ_e) downward, because the surge in ethanol sales during the cheap-ethanol regime reflects both extensive-margin switching (arbitrageurs moving to ethanol) and intensive-margin rebound (existing ethanol users driving more); both act in the same direction, so the baseline shares are an upper bound on the behavioural failure. The stability of $\hat{\phi}$ under the correction reflects an offset: the falling arbitrageur share is compensated by a rising share of gasoline-lovers, who contribute fully rather than partially (58 percent) to fossil fuel consumption.

no-arbitrage ratio $k \approx 0.70$. Table A13 reports the corrected shares across elasticities from $\varepsilon = -0.12$ (the gasoline own-price elasticity estimated by Huse 2018) to $\varepsilon = -0.50$ (a conservative upper bound for the highly substitutable ethanol demand): the arbitrageur share falls from 0.523 in the baseline to 0.416 at the most elastic bound, with the strict ethanol- and gasoline-lover shares rising correspondingly, but the aggregate gasoline share $\hat{\phi}$ drops by only one percentage point (from 35.5 to 34.5 percent). The fiscal Loop Effect multiplier therefore stays within ± 10 percent of its baseline value and the welfare conclusions of Section 6.6 are robust to the price-inelastic-demand assumption, with the baseline a slightly conservative upper bound that alters the net social cost by at most EUR 2.0 mn.

Table A13: Corrected Consumer Type Shares Under Price-Elastic Demand

VKT Elasticity (ε)	ρ^{cheap} adj.	ρ^{exp} adj.	σ_e^{corr}	σ_a^{corr}	σ_g^{corr}	β^* (Gasoline)	$\Delta\beta$	Loop Effect Multiplier
0 (Baseline)	1.000	1.000	0.421	0.523	0.052	0.355	0.105	1.000
-0.12	1.013	0.969	0.434	0.498	0.068	0.357	0.107	1.019
-0.20	1.021	0.949	0.444	0.481	0.075	0.354	0.104	0.990
-0.30	1.032	0.924	0.456	0.459	0.085	0.351	0.101	0.962
-0.40	1.043	0.900	0.468	0.437	0.095	0.348	0.098	0.933
-0.50	1.054	0.877	0.480	0.416	0.104	0.345	0.095	0.905

Notes: $\rho^{cheap} = (0.63/0.70)^{-\varepsilon}$; $\rho^{exp} = (0.91/0.70)^{-\varepsilon}$. Baseline shares are from the main calibration. The aggregate gasoline share is $\beta^* = (\sigma_a^{corr} \times 0.58) + \sigma_g^{corr}$. $\Delta\beta = \beta^* - 0.25$ represents the excess gasoline share above the policy's 75 percent ethanol benchmark. The Loop Effect multiplier is the ratio of $\Delta\beta^{corr}$ to $\Delta\beta^{baseline}$. Elasticity estimates are anchored to Huse (2018).

E Sensitivity of the Fiscal Loop Effect to the Ethanol Benchmark

The Fiscal Loop Premium of the main text is measured against a genuine abater ($\phi = 0$): it values every litre of gasoline the gamed cohort burned in place of ethanol. An alternative convention, used in this and the next section, measures the windfall against the policy's own baseline expectation – the tax revenue generated by the excess gasoline consumption beyond that expectation – which makes the resulting net social cost mechanically linked to the benchmark ethanol utilisation rate ($\hat{\phi}_0$) that anchored the policy's implicit expectation; the figures below are therefore benchmark-relative and smaller than the main-text ledger, not restatements of it.

While no formal utilisation target was codified in the GCR legislation, Swedish policy documents and transport authorities (e.g., Trafikverket, 2011) routinely evaluated FFVs using an assumption of 70 to 80 percent renewable fuel usage. To ensure the conclusions are not driven by a knife-edge assumption, Table A14 reports the sensitivity of the Loop Effect across benchmarks ranging from 60 to 90 percent, holding the calibrated actual gasoline share fixed

at $\hat{\phi} = 0.359$.

Table A14: Sensitivity of the Fiscal Loop Effect to the Ethanol Utilization Benchmark

Benchmark (β_0)	Expected Petrol	Excess Petrol ($\Delta\beta$)	Gross Windfall		Welfare Value		Net Social Cost	
			Low VKT	High VKT	Low VKT	High VKT	Low VKT	High VKT
60%	40.0%	-4.1%	-16.0	-20.8	-3.2	-4.2	13.3	33.3
65%	35.0%	+0.9%	3.5	4.6	0.7	0.9	9.4	28.2
70%	30.0%	+5.9%	23.0	30.0	4.6	6.0	5.5	23.1
75%	25.0%	+10.9%	42.5	55.4	8.5	11.1	1.6	18.0
80%	20.0%	+15.9%	61.9	80.8	12.4	16.2	-2.3	12.9
85%	15.0%	+20.9%	81.4	106.2	16.3	21.2	-6.2	7.9
90%	10.0%	+25.9%	100.9	131.6	20.2	26.3	-10.1	2.8

Notes: All monetary values are in EUR millions. "Low VKT" assumes lifetime vehicle kilometers traveled of 230,000 km; "High VKT" assumes 300,000 km. The gross fiscal windfall is calculated as $N \times (V/kpl) \times \Delta\beta \times \tau_G$, where $N = 38,500$ vehicles, $kpl = 12.5$ km/liter, and $\tau_G = \text{EUR } 0.55/\text{liter}$. The welfare value applies the MCPF premium of 0.2. Net social cost = Cost of public funds (EUR 8.3 mn) + Unintended social costs (EUR 1.8 mn for Low VKT, EUR 20.8 mn for High VKT) - Welfare value of fiscal windfall. Negative net social costs indicate net welfare gains. The calibrated actual gasoline share is $\beta^* = 0.359$, held fixed across all rows.

The sign of the windfall is benchmark-dependent – below an assumed utilisation of 64.1 percent it becomes a shortfall – but across the historically plausible 70–80 percent range the net social cost stays in roughly EUR -2.3 to 23.1 mn: the policy remains a net loss under nearly all scenarios while the Loop Effect offsets a sizeable share of the gross damages.

F Generalisability of the Loop Effect Across Tax Regimes

Corollary A1 establishes that the optimal subsidy S^* is strictly decreasing in the pre-existing fuel tax τ_f and that the sign of $\partial S^*/\partial\theta$ depends on whether $\tau_f\Delta q_f \gtrless \tau_E\Delta E_f/\mu$. This appendix quantifies both comparative statics numerically across OECD tax regimes, holding the Swedish fleet parameters and behavioural failure rates fixed – an illustrative calibration of the theoretical predictions rather than a cross-country empirical estimate, since it applies the GCR's estimated θ , $\hat{\phi}$, and Δq_A to alternative tax environments. The benchmark-relative gross fiscal windfall (FW) of the preceding section generalises as:

$$FW = N \times \frac{VKT}{kpl} \times \Delta\hat{\phi} \times (\tau_G - \tau_{alt})$$

where τ_G is the tax rate on gasoline, τ_{alt} the tax rate on the alternative fuel, and $\Delta\hat{\phi}$ the unexpected excess gasoline share driven by consumer arbitrage. Table A15 applies the formula to alternative OECD tax regimes at approximate 2008 rates (IEA, 2008), with Sweden – largely tax-exempt ethanol ($\tau_{alt} \approx 0$) against heavily taxed gasoline ($\tau_G \approx \text{EUR } 0.55/L$) – as the maximal-differential benchmark.

Table A15: The Loop Effect Across Tax Regimes: Sensitivity to Fuel Tax Differentials

Country/ Scenario	Gas. Tax (EUR/L)	Alt. Fuel Tax (EUR/L)	Diff. (EUR/L)	Gross Windfall (EUR mn)	Welfare Value (EUR mn)	Net Social Cost (Low VKT, EUR mn)
SWE	0.55	0.00	0.55	42.5	8.5	1.6
NLD	0.72	0.20	0.52	40.2	8.0	2.1
DEU	0.65	0.15	0.50	38.6	7.7	2.4
UK	0.58	0.10	0.48	37.1	7.4	2.7
FRA	0.61	0.18	0.43	33.2	6.6	3.5
EU avg.	0.48	0.12	0.36	27.8	5.6	4.5
USA	0.20	0.05	0.15	11.6	2.3	7.8
$\tau_f = 0$	0.00	0.00	0.00	0.0	0.0	10.1

Notes: Country codes: SWE Sweden, NLD Netherlands, DEU Germany, UK United Kingdom, FRA France, USA United States; “EU avg.” is the EU average and $\tau_f = 0$ denotes the zero-fuel-tax scenario. Fuel-tax rates are approximate 2008 rates (IEA, 2008); all other inputs are the Swedish GCR calibration held fixed across regimes (the GCR fleet, its $\hat{\phi}$ and Δq_A), so the table is an illustrative comparative static rather than a cross-country estimate. The gross windfall is benchmark-relative, as in Table A14: the tax revenue on the excess gasoline share $\Delta\hat{\phi}$ beyond the 75 percent ethanol expectation, valued at the gasoline–alternative-fuel tax differential; the welfare value applies the excess burden $\mu = 0.20$; net social cost is at 230,000 km lifetime VKT.

The Loop Effect is not specific to Sweden: high-tax European regimes (Germany, the Netherlands, the UK) would generate windfalls exceeding EUR 35 mn under identical behavioural assumptions, whereas the United States, with far lower fuel taxes and a lower excess burden, recovers roughly one-quarter of Sweden’s. Identical behavioural failures therefore impose substantially higher net social costs where the fiscal insurance of high fuel taxes is absent.

G The Contemporary Analogue: PHEVs and the Global Validity of the Anatomy Proposition

G.1 The PHEV Mechanism and the Principal-Agent Friction

The PHEV setting activates both failure margins. The effective asymmetry here runs between the test-cycle emissions that determine favourable (e.g. sub-50 gCO₂/km) tax treatment and the real-world emissions set by driver behaviour, where under the GCR it ran between vehicle categories; the consumer-side channel ϕ is directly measurable from real-world fuel-consumption data (Grigolon et al. 2023; Plötz et al. 2022), and since 2021 from the EU’s on-board fuel-consumption monitoring (OBFCM) readings (EEA 2026). The channel operates for *any* PHEV driven on its engine – private owners already run at $\phi \approx 0.56$ – and a principal-agent friction *amplifies* it in company cars, where the employer captures the subsidy while the employee-driver bears no marginal fuel cost, pushing ϕ towards one. I therefore disaggregate by the private/company margin, which sharpens the failure rather than creating it.

I calibrate the contemporary Fiscal Loop Premium (FLP) on the EEA OBFCM data for

plug-in hybrids registered 2021–2024, which give each market’s fleet-weighted real-world consumption (FC_{RW}), the type-approval figure, and the charge-sustaining consumption that defines $\phi = FC_{RW}/FC_{CS}$ (Section 7.5). Fleet-wide, PHEVs in the EU-27, Norway and Iceland burn 6.19 L/100km on the road against a type-approval 1.42 – a gap of $4.4\times$ that widens by registration cohort, from $3.3\times$ in 2021 to $5.8\times$ in 2024. The OBFCM data carry no owner field, so the private/company split comes from Plötz et al. (2022, Table A3), which reports observed PHEV consumption separately by country (Germany versus Rest of Europe) and user group: private owners, who internalise fuel costs, at 4.2–4.5 L/100km, and company cars, whose employee-driver faces zero marginal fuel cost because fuel is typically expensed, at 6.8–7.2 L/100km. The two Plötz figures are rescaled by a common market-specific factor so that their stock-weighted mean equals the EEA fleet mean for that market; the market total is then the EEA-based Premium whatever the split, and the segment rows keep the Plötz company/private ratio of about 1.6.

The principal-agent interpretation is supported by the regression analysis in Plötz et al. (2022, Tables C.1–C.6): conditional on system power and vehicle segment, company-car status raises log real-world fuel consumption by 0.45 to 0.57 – roughly 56 to 77 percent more fuel than comparable private vehicles. This specification does not fully absorb model-level heterogeneity (trim, electric range, or model choice within a segment), but a gap of this size within a segment is far too large to be compositional, and matches the principal-agent mechanism in which the employee-driver faces zero marginal fuel cost.

Summing the per-vehicle Premium of Corollary 2 over jurisdiction j ’s fleet and expressing the fuel differential in observable consumption terms gives the annual *Excess* Fiscal Loop Premium – the revenue the regulatory framework implicitly assumed would not exist:

$$\text{Excess } FLP_j = N_j^{PHEV} \cdot \mu_j \cdot \tau_{f,j} \cdot (FC_{RW,j} - FC_{TA,j}) \cdot \frac{VKT_j}{100} \quad (15)$$

where $FC_{RW,j}$ and $FC_{TA,j}$ are real-world and type-approval fuel consumption (litres/100km) and $\tau_{f,j}$ the volumetric fuel tax. Section 7.5 of the main text reports the evaluation for Sweden, Germany, France, the Netherlands and Norway (Table 5), with N_j^{PHEV} the PHEV passenger-car stock in each national registry at 31 December 2023, $\mu = 0.20$ and a VKT of 15,000 km throughout. Sweden illustrates the arithmetic: 272,342 PHEVs, 53.9 percent company-held (Trafikanalys), at a real-world 5.62 L/100km (EEA OBFCM) split 4.2/6.8 against a type-approval 1.7 and $\tau_f = 0.55$ EUR/litre burn 377 and 768 excess litres per vehicle-year, EUR 41 and 85 per vehicle, EUR 5.2 plus 12.4 mn, or EUR 17.6 mn a year. Two features of the table are worth drawing out. Company cars represent 53–67 percent of the

PHEV stock but generate roughly seven-tenths of the windfall (in Sweden, 54 percent of the stock and 70 percent of the EUR 17.6 mn), because their utilisation gap ($4.0\times$ type-approval in Sweden, against $2.5\times$ for private owners) compounds their stock share. And the per-vehicle Premium ranges from EUR 41 (Sweden, private, $\tau_f = 0.55$) to EUR 129 (Netherlands, company, $\tau_f = 0.79$) – the jurisdiction-dependence of Corollary A1: the tax systems most generous to PHEVs are precisely those where preserved fuel-tax revenue is worth most.¹⁰

Two technical notes complete the derivation. First, the operational definition $\phi_{PHEV} = FC_{RW}/FC_{CS}$ uses the charge-sustaining consumption measured on board in the OBFCM data rather than a type-approval figure, so it is insulated from test-cycle optimisation of the engine-mode rating (Reynaert 2021); it is the engine’s share of fuel, and hence of the fuel-tax base, which is the object the Premium needs. It exceeds the kilometre share $1 - UF$ whenever charge-depleting operation burns fuel, since $FC_{RW}/FC_{CS} = (1 - UF) + UF \cdot FC_{CD}/FC_{CS}$: in the pooled 2021–2024 fleet the two read 0.75 and 0.67. The Excess Premium of equation (15) uses litres directly and is unaffected by the convention; only the reported ϕ carry it. The convention $FC_{ICE} = FC_{TA}/0.25$ of an earlier version of the table, which imposes the utility-factor complement of about 0.25 conventionally assigned to a PHEV of roughly 50 km electric range, returns $\phi > 1$ for company cars at the EEA real-world levels and is discarded. Second, equation (15) measures the fiscal windfall relative to the type-approval benchmark – whose implied fossil share on the same definition is $FC_{TA}/FC_{CS} = 1.415/8.248 = 0.17$ for all Europe and $1.70/7.89 = 0.22$ for Sweden – rather than to full electric operation ($\phi = 0$). The full Fiscal Loop Premium of Corollary 2 uses $FC_{RW,j}$ directly (the $\phi = 0$ counterfactual) and is reported in the last column of Table 5: EUR 25 mn for Sweden, EUR 278 mn for the five markets and EUR 419 mn for all Europe against full electric operation, 1.3–1.4 times the Excess figures. The “Excess” formulation isolates the revenue the regulatory framework *implicitly assumed would not exist*, and is the quantity the text headlines. Read through the main-text Premium $\theta\phi\tau_f\Delta q_A$, with $\Delta q_A = FC_{CS} - FC_{TA}$ the abatement the rating claims, the Excess formula implies $\theta\phi = (FC_{RW} - FC_{TA})/(FC_{CS} - FC_{TA})$, the share of the claimed abatement not realised on the road, which on the Swedish inputs of Table 5 is 0.41 for private owners and 0.83 for company cars; the discrete gaming share θ is here subsumed into the continuous utilisation share ϕ and the fleet count N^{PHEV} (which plays the role of $\theta \cdot N$): every PHEV underutilises by degree ϕ rather than gaming as a discrete category.

¹⁰At the US fuel tax of approximately USD 0.12/litre and $\mu = 0.15$ (Bastani, 2023), the roughly 1.8 mn US PHEV fleet yields only about EUR 10 mn – about five percent of the five-market aggregate despite a fleet 80 percent as large – almost entirely explained by the fuel-tax differential.

G.2 Institutional Mapping by Jurisdiction

The Anatomy conditions map onto contemporary alternative-fuel policies once the “binding budget” (Assumption 3) is generalised to fiscal caps, physical quotas, and fleet-wide constraints. Table A16 maps four contemporary settings onto the three conditions; the German split eligibility test is the empirical basis for the gameable/not-gameable conditional in Table A1.

Table A16: **The Anatomy Conditions Across Contemporary Jurisdictions**

Setting	Eligibility test, budget, and Anatomy status
Germany (2026)	The reintroduced EUR 3 bn private-buyer subsidy uses a split test: a PHEV qualifies via an all-electric range of ≥ 80 km <i>or</i> certified emissions of ≤ 60 gCO ₂ /km. The 80 km arm demands a 22–25 kWh battery and largely closes the low-cost-compliance channel (Assumption 2); the 60 gCO ₂ /km arm is the familiar type-approval loophole, clearable with a modest battery and favourable calibration. Vehicles entering through that door satisfy all three conditions, and at $\phi_{\text{private}} \approx 0.58$ (EEA on-board data for Germany, Section 7.5) the effective abatement share falls to $(1 - \theta\phi) \approx 0.42$.
China (megacities)	NEV licence-plate quotas are a physical-budget instance of Assumption 3. Several cities (Shanghai from 2023, Beijing throughout) withdrew preferential PHEV plates in response to observed gaming – Corollary A2(ii), $\theta \rightarrow 0$ under symmetric treatment – while permissive cities and the national dual-credit system still activate it.
United States (IRA, 2022–2025)	Up to USD 7,500 with a 7 kWh battery threshold (Assumption 1) but <i>uncapped</i> funding, so Assumption 3 failed: no allocative crowd-out arose, and the credit ended by political termination rather than budget exhaustion.
Fleet CO ₂ and CAFE standards	PHEV super-credits based on type-approval values direct the compliance margin to the certified rather than the realised value (Remark 3); correcting type-approval testing to real-world ϕ would realign it with physical outcomes.

H Validation Details: The SGCR, the Bonus-Malus, and the Feebate Counterfactual

This appendix reports the specifications, full regression tables, and secondary diagnostics behind the three-regime validation of Section 8. Table A17 gives the condition-by-condition mapping of the Anatomy assumptions to each regime, the companion to the results matrix in the main text.

H.1 The Split-Era SGCR Specification

The SGCR (*Supermiljöbilspremie*) offered a purchase rebate for vehicles emitting at most 50 gCO₂/km (NEDC), initially technology-neutral at SEK 40,000 for BEVs and PHEVs alike. Eligible vehicles also received a substantial reduction in the taxable benefit value (*förmånsvärde*) for company-car drivers, five years of vehicle-tax exemption, and free municipal

Table A17: Anatomy Conditions and Predictions Across Three Swedish Policy Regimes

Construct	GCR (2007–09)	Super GCR (2012–17)	”Bonus-Malus” (2018–22)
Mechanism	Asym. binary subsidy (10k SEK)	Symm. binary (SEK 40k, 2012–15); tiered (BEV: 40k; PHEV: 20k, 2016–17)	Cont. schedule (SEK 60k at 0 gCO ₂ /km declining SEK 833/g to a SEK 10k floor at 60g, then 0; cap raised to SEK 70k in 2021)
Threshold	120 (RFV) vs. 220 gCO ₂ /km (AFV)	50 gCO ₂ /km (all fuel types)	Bonus ≤ 60 vs malus ≥ 95 gCO ₂ /km
A1 Asym.	Holds. Loophole (120, 220] gCO ₂ /km	Holds (rating–road form); fuel-type asymmetry removed. Symm. notch at 50 gCO ₂ /km (Remark 1); mild BEV/PHEV tiering from 2016	Categorical component violated; rating–road gap remains. Cont. below 60 gCO ₂ /km; residual SEK 10k notch at 60g, empirically unexploited
A2 Cheap c^G	Holds. FFV $\leq$ EUR 150 vs. c^A EUR 3.6–22k (central 8.8k)	Violated (Private); Holds (Corporate). Capitalized <i>förmånsvärde</i> reduction (comparison-car adjustment plus capped 40%) exceeds incremental battery cost, functionally restoring cheap compliance (A2 restored for the corporate channel only).	Moot. Cont. schedule offers no categorical reclassification target; gaming transfer ≈ 0 (Prop. 6)
A3 Binding	Holds (political economy). Budget exhausted; triggered early termination June 2009	Holds within-year; accommodated ex post. Appropriation exhausted and payouts queued in 2012, 2014, 2015, 2016 (Förordning 2011:1590 §7); topped up SEK 115 + 132 + 180 mn and extended four times; no early termination, so outcome (iii) not activated	Does not bind via gaming. Self-financing by design; later deficits (2020+) and the 2022 phase-out reflect the volume of low-emission registrations; PHEV share of outlays not observed
Prop. 5	All 4 failures activate	PHEV threshold-targeting via corporate tax channel, stable across the 2016 rebate cut; eligible families’ ICE lineups flat; budget accommodated, so outcome (iii) not activated.	Categorical $\theta \approx 0$; ext.-margin substitution; residual notch unexploited; utilisation failure (ϕ) remains

Notes: Condition-by-condition companion to Table 6 (main text). A1–A3 refer to Assumptions 1–3. Policy parameters from Transportstyrelsen and Prop. 2021/22:91.

parking.¹¹ The sub-50g focal points are over-determined: during 2012–2015 a sub-50 gCO₂/km

¹¹The rebate was formally capped at a share of the price difference relative to the nearest comparable conventional vehicle (35 percent for BEVs, capped at SEK 40,000; 17.5 percent for PHEVs, capped at SEK 20,000), so for the relatively expensive eligible models the binding amount was the cap. The *förmånsvärde* reduction operated in two stacked steps: the benefit value of a plug-in or gas vehicle was first set down to that of the nearest comparable conventional car, stripping the entire electrification price premium out of the annual tax base, and the resulting value was then reduced by a further 40 percent, capped at SEK 16,000 per year (SEK 10,000 from 2017). This transitional provision ran independently of the direct rebate and expired only at the end of 2020 (SFS 2016:1055), whereas the comparison-car step survived until the July 2022 reform; the 40 percent step thus spanned the entire SGCR period and the early feebate years. Of the two steps, the comparison-car adjustment is the heavier lever. The only *förmånsvärde* change in the sample window is the 1 January 2017 cut in the cap on the supplementary 40 percent reduction from SEK 16,000 to SEK 10,000 (SFS 2016:1055), a reduction of at most SEK 6,000 a year that falls inside the second era and leaves the comparison-car adjustment untouched. The legal basis is 61 kap. 8 a § inkomstskattelagen (1999:1229), as amended by SFS 2011:1271, 2013:960, 2016:1055 and 2017:1212.

type-approval value was rewarded simultaneously by the SGCR threshold, the *förmånsvärde* reduction, and the EU fleet-CO2 supercredit scheme.¹²

I estimate the fully saturated split-era difference-in-differences

$$\begin{aligned}
y_{it} = & \sum_{k \in \{1,2\}} \delta_k^E (\text{Era}_k \times \text{Elig}_{it}) + \sum_{k \in \{1,2\}} \delta_k^P (\text{Era}_k \times \text{PHEV}_{it}) \\
& + \sum_{k \in \{1,2\}} \delta_k^B (\text{Era}_k \times \text{BEV}_{it}) + \sum_{k \in \{1,2\}} \delta_k^{EP} (\text{Era}_k \times \text{Elig}_{it} \times \text{PHEV}_{it}) \\
& + \delta_2^{\text{era}} \text{Era}_2 + \delta^{\text{elig}} \text{Elig}_{it} + \delta^{\text{phev}} \text{PHEV}_{it} + \delta^{\text{bev}} \text{BEV}_{it} + \gamma' x_{it} + \alpha_m + \lambda_t + \varepsilon_{it}
\end{aligned} \tag{16}$$

where Era 1 covers the high-subsidy period (2012–2015) and Era 2 the halved-subsidy period (2016–2017). Eligibility is defined at the *model* level: $\text{Elig}_{it} = 1$ for every variant of a model family that offers at least one variant at or below 50 gCO₂/km in the post-period – eligibility is thus defined on post-period outcomes, and δ_k^E describes the families that came to offer a qualifying variant rather than a group fixed before the policy – so it attaches mostly to those families’ conventional (ICE) variants (registration-weighted means of 166, 143 and 129 gCO₂/km pre-policy, in Era 1 and in Era 2 on the register series), whereas PHEV_{it} and BEV_{it} flag the powertrain of the individual variant. Accordingly δ_k^E , δ_k^P , and δ_k^B isolate the era- k emissions response of, respectively, eligible models’ conventional variants, PHEVs in non-eligible families, and BEVs, each relative to the non-eligible conventional-ICE base, and $\delta_k^P + \delta_k^{EP}$ is the response of the PHEV variants of eligible families, the quantity Section 8.1 reports.¹³ Standard errors are clustered at the model level.

Table A19 reports the registrant-type shares cited in Sections 8.1 and 8.2: the company share of registrations by powertrain and by feebate zone, and the PHEV and BEV shares by year across the two regimes.

¹²Under the supercredit scheme a car emitting at most 50 gCO₂/km counted as 3.5 vehicles in 2012–2013, 2.5 in 2014, and 1.5 in 2015 towards a manufacturer’s fleet average, falling to one from 2016 (Regulation (EC) No 443/2009, Art. 5). Because it operated on manufacturers’ EU-wide fleet averages, Swedish registration data cannot separate it from the domestic tax channel; it plausibly shaped *which* sub-50g models existed to be sold, EU-wide, rather than why they sold disproportionately in Sweden.

¹³The powertrain and eligibility main effects are time-invariant within model and hence absorbed by α_m , and the era main effect by λ_t ; only the era-powertrain interactions are separately identified. 133 of the 161 PHEV variant-years belong to an eligible model family; the 28 that do not (Porsche Panamera/Cayenne S E-Hybrid, Mercedes S500e, BMW X5 40e, rated above 50 gCO₂/km) identify the eligible-PHEV triple interaction (+25.3 and +28.8 gCO₂/km, $p < 0.05$), so the eligible-family PHEV response reported in the text is the sum of the double and triple interactions (Table A18, last rows); every BEV variant belongs to an eligible family, so the BEV triple is not identified. The outcome is the register-first CO₂ series described in the notes to Table A18: the register’s type-approval value, else the ADAC/EEA value matched at year, make, fuel and rated power, with variant-years lacking both dropped.

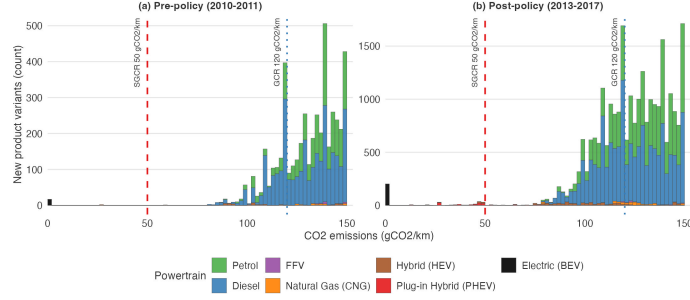


Figure A2: **CO2 Emission Distributions Pre- and Post-SGCR.** CO2 emissions of new product variants emitting up to 150 gCO₂/km: **Panel (a)** pre-policy (2010–2011) and **Panel (b)** post-policy (2013–2017). The dotted blue line marks the GCR’s former 120 gCO₂/km threshold for reference; the dashed red line the SGCR’s 50 gCO₂/km eligibility threshold. CO₂ is the register’s type-approval value (ADAC/EEA-matched where the register is silent); plug-in hybrids from matched type-approval values. Panel (b) shows PHEV variants rated between 25 and 50 gCO₂/km, at or below the threshold, with no accumulation at a single value.

Table A18 reports the results discussed in Section 8.1.¹⁴

H.2 The Dual-Threshold Feebate Specification

The continuous Bonus-Malus schedule requires separating the two treatment arms:

$$y_{it} = \delta_B(\text{Post}_t \times \text{Bonus}_{it}) + \delta_M(\text{Post}_t \times \text{Malus}_{it}) + \gamma'x_{it} + \alpha_m + \lambda_t + \varepsilon_{it} \quad (17)$$

where $\text{Bonus}_i = 1$ if $e_i \leq 60$ gCO₂/km and $\text{Malus}_i = 1$ if $e_i \geq 95$ gCO₂/km; the 60–95 gCO₂/km middle zone – facing neither bonus nor malus – is the omitted control group.¹⁵

¹⁴Beyond the headline coefficients, two further patterns stand out. Sales-weighted emissions fall for both PHEV and BEV models (Column 3), with the BEV effect larger – BEV abatement is real but thin in volume. In contrast, PHEV entry generated a large registration response (Column 4) while BEV registrations barely move: the volume is where the test-cycle-gamed vehicles are. The event-study specification (year-specific interactions relative to 2011, the omitted base year; coefficients omitted for space and produced by the replication code) adds a pre-trend placebo and confirms stability: the Elig. $\times$ 2010 coefficient is -2.4 (SE 2.2), indistinguishable from zero; the eligible-model coefficients lie between -10.0 and $+3.8$ gCO₂/km across 2012–2017, and the PHEV coefficients for non-eligible families between -119.1 and -154.3 gCO₂/km across 2013–2017 (all $p < 0.01$), with eligible-family triple interactions of $+11.9$ to $+45.0$ gCO₂/km (between -108.7 and -118.4 when eligibility is assigned so that every PHEV family qualifies); the BEV coefficients are significant and stable at -111 to -140 gCO₂/km throughout 2010–2017, consistent with the near-zero emissions of BEVs irrespective of the policy.

¹⁵Both coefficients are, in the first instance, compositional: each compares an emissions-defined treatment bin to the middle-zone control, so the intensive-versus-extensive decomposition comes from comparing the full sample to the incumbent-only and incumbent-eligible specifications, the same logic applied to the GCR. The bins are held fixed on the NEDC-harmonised rating throughout, although from 1 April 2021 the malus threshold moved to 90 gCO₂/km on the WLTP basis (at SEK 107 and 132 per gram) and the bonus cap to SEK 70,000. Among the 2021–22 variants for which both ratings are observed, 16 variants (80 registrations) fall in the NEDC 95 g malus bin but below the WLTP 90 g line, and 129 variants (2,784 registrations) sit below the NEDC 95 g line but at or above WLTP 90 g, against 11,956 variants (216,417 registrations) in the

Table A18: Decomposing SGCR Responses: The Company Car Tax Loophole

	Full Sample	Int. Margin	Sales-weighted	ln(Reg)
Elig. $\times$ 2012-15	3.169* (1.788)	3.112** (1.520)	-3.523* (2.033)	0.144*** (0.043)
Elig. $\times$ 2016-17	-8.661*** (3.178)	-9.077*** (3.034)	-9.302*** (3.086)	1.110*** (0.134)
PHEV $\times$ 2012-15	-139.669*** (8.068)	-139.174*** (8.567)	-125.502*** (3.598)	0.986** (0.411)
PHEV $\times$ 2016-17	-138.001*** (11.628)	-151.284*** (11.556)	-137.882*** (6.820)	1.858*** (0.307)
BEV $\times$ 2012-15	-131.779*** (8.460)	-121.796*** (8.843)	-113.342*** (8.325)	0.356 (0.261)
BEV $\times$ 2016-17	-113.334*** (7.528)	-118.083*** (8.179)	-119.901*** (3.058)	0.046 (0.404)
Elig. $\times$ PHEV $\times$ 2012-15	25.263** (10.918)	16.907* (10.237)	37.388*** (10.937)	0.999 (0.667)
Elig. $\times$ PHEV $\times$ 2016-17	28.778** (12.069)	36.689*** (13.521)	45.278*** (6.713)	0.360 (0.535)
Elig.-family PHEV $\times$ 2012-15	-114.406*** (7.455)	-122.267*** (5.911)	-88.114*** (10.499)	1.986*** (0.523)
Elig.-family PHEV $\times$ 2016-17	-109.224*** (5.233)	-114.596*** (7.816)	-92.604*** (2.738)	2.219*** (0.429)
Num.Obs.	96 129	86 668	96 129	105 002
R2	0.695	0.728	0.819	0.273

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: Specifications estimate unweighted supply-side variant adjustments in Columns 1-2 and sales-weighted responses in Column 3. The dependent variable is CO2 emissions, except in Column 4 where it is ln(Registrations). CO2 is the vehicle register's type-approval value; where the register carries zero, the ADAC/EEA value matched at year $\times$ make $\times$ fuel $\times$ kW (NEDC through 2020; WLTP $\times$ 0.85 for conventional and 0.75 for hybrid variants in 2021-22); plug-in hybrids from matched type-approval values; variant-years without a value are dropped (1.7 percent of registrations), which is why Column 4, which needs no CO2 value, has more observations. Eligibility is defined on this series at the model level, so PHEV $\times$ era is the response of PHEV variants in non-eligible families and the eligible-family PHEV response is the sum of PHEV $\times$ era and Elig. $\times$ PHEV $\times$ era, reported in the last four rows with its standard error. Sample: 2010-2017; Era 1 is 2012-2015 and Era 2 2016-2017. Controls: hp, weight and hp/weight. All specifications include year and model fixed-effects. Standard errors clustered at the model level.

Table A20 reports the results discussed in Section 8.2.¹⁶ Both tables are robust to the construction of the CO2 series.¹⁷

malus bin: the reclassification touches about one percent of the bin, at its boundary.

¹⁶The event-study specification (year-specific interactions relative to 2017, the omitted base year; coefficients omitted for space and produced by the replication code) is estimated on 2017–2022 and so retains the 2018 NEDC-to-WLTP transition year that the pooled specifications of Table A20 drop (54,606 against 45,024 observations); the difference is the 2018 cohort, whose coefficient the event study needs. It shows the supply-side response materialised immediately in 2018 and held through 2022, with the bonus arm between -61.5 and -77.2 and the malus arm between +40.8 and +51.8 gCO2/km across years (all $p < 0.01$): an immediate technological bifurcation rather than gradual adjustment. The sales-weighted regression (Column 4, -62.1, $p < 0.01$) confirms the fleet-composition shift.

¹⁷Full tables are produced by the replication code. On an EEA-first series (the ADAC/EEA product-line match taking precedence over the register): eligible-family $\delta_1^P = -132.9$, $\delta_2^P = -142.3$; $\delta_B = -70.2$, $\delta_M = +48.6$; bonus registrations +1.56 and malus -0.66 log points (4.8-fold, -49 percent). With every PHEV family

Table A19: Company Share of New Registrations by Powertrain and Regime

<i>Panel A: SGCR era, registrations 2013–2017 (percent company)</i>				
Plug-in hybrid (PHEV)	94.9			
Battery-electric (BEV)	77.9			
Conventional (petrol/diesel)	63.7			
PHEV by year	2012: 75.7	2013: 88.4	2014: 93.3	
	2015: 95.5	2016: 96.3	2017: 94.9	
<i>Panel B: Bonus-Malus era, registrations 2019–2022 (percent company)</i>				
Plug-in hybrid (PHEV)	75.3			
Conventional (petrol/diesel)	61.1			
Battery-electric (BEV)	55.1			
Bonus zone (≤ 60 gCO ₂ /km)	66.0			
Middle zone (60–95 gCO ₂ /km)	52.9			
Malus zone (≥ 95 gCO ₂ /km)	62.2			
PHEV by year	2018: 91.3	2019: 87.9	2020: 81.2	
	2021: 72.1	2022: 68.5		
BEV by year	2019: 70.7	2020: 66.4	2021: 54.5	2022: 49.8

Source: Swedish new-registration records by registrant type (Statistics Sweden), merged to the vehicle panel. Shares are registration-weighted; “company” is the SCB registrant category for legal persons. Zones in Panel B are defined on the NEDC-harmonised rating used in equation (17). Produced by the replication code.

Table A20: Decomposing Bonus-Malus Responses

	Full Sample	Int. Margin	Incumb. Elig.	Sales-wtd.	Ln(Reg)
Feebate x Bonus	−63.153*** (5.062)	−63.473*** (5.386)	−63.361*** (5.252)	−62.110*** (3.992)	1.722*** (0.259)
Feebate x Malus	47.476*** (4.448)	47.294*** (4.718)	47.482*** (4.478)	37.413*** (4.044)	−0.395*** (0.151)
Num.Obs.	45 024	42 552	44 932	45 024	45 024
R2	0.699	0.694	0.695	0.892	0.207

* p < 0.1, ** p < 0.05, *** p < 0.01

Note: Specifications estimate unweighted supply-side variant adjustments in Columns 1–3 and sales-weighted responses in Column 4. The dependent variable is CO₂ emissions, except in Column 5 where it is ln(Registrations). CO₂ is the vehicle register’s type-approval value; where the register carries zero, the ADAC/EEA value matched at year × make × fuel × kW (NEDC through 2020; WLTP × 0.85 for conventional and 0.75 for hybrid variants in 2021–22); plug-in hybrids from matched type-approval NEDC values, WLTP × 0.45 where only WLTP is observed (2020–22); variant-years without a value are dropped (1.7 percent of registrations). Bonus and malus bins are defined on this NEDC-harmonised series. Sample: 2017 (pre) and 2019–2022 (post); the 2018 transition year is retained only by the event-study specification. Controls: hp, weight and hp/weight. All specifications include year and model fixed-effects. Standard errors clustered at the model level.

The malus arm decomposed. Splitting the malus segment at the statutory schedule kinks (SEK 82/gram from 95–140 gCO₂/km, SEK 107/gram above 140) into 95–140, 140–170, and above-170 sub-ranges and re-estimating separately confirms the compositional interpretation of δ_M : the feebate induced exit of marginal malus-zone models rather than re-engineering of mature ICE technology, leaving the price-insensitive upper tail intact.¹⁸

The residual notch. The SEK 10,000 bonus floor leaves a discrete notch at 60 gCO₂/km which – interacting with binary thresholds elsewhere in the tax code, such as the *förmånsvärde* reduction – could in principle preserve categorical gaming. A McCrary-style density test on the type-approval values does not reject in the direction of bunching: on the NEDC-harmonised rating the estimated discontinuity at 60 gCO₂/km is $T = +0.8$ ($p = 0.42$); on the WLTP rating the schedule used from 2020 it is $+2.3$ ($p = 0.02$) with the positive sign, more density just above 60g than below, and a test restricted to plug-in hybrid variants finds nothing ($T = +0.9$, $p = 0.37$). Registration-weighted, plug-in hybrid mass sits in three groups near 31, 38 and 46 gCO₂/km on the WLTP rating (32, 41 and 44g on the NEDC-correlated rating) and is all but absent above 53g; the 58–60g band holds 162 registrations over 2019–22, 0.7 percent of PHEV registrations fall in 55–60g on the WLTP basis, and the 2.4 percent that do so on the NEDC-correlated basis are two platforms rated before the WLTP switch, the BMW 330e/530e at 57g and the Volvo XC90 T8 at 59g (density plots produced by the replication code). Had the 60g notch been the operative incentive, mass would concentrate at 58–59 gCO₂/km; the location of the mass is itself evidence the notch went unexploited.

assigned eligible (no triple interaction): $\delta_1^P = -118.9$, $\delta_2^P = -111.9$ (difference -7.0 , $[-17.8, 3.8]$); $\delta_1^E = +3.1$, $\delta_2^E = -9.1$; registrations $+1.87$, $+2.20$ (PHEV) and $+0.146$, $+1.04$ (Elig). With 2020–22 plug-in hybrids on the WLTP rating the schedule itself used: $\delta_B = -57.4$ (-57.1 , -57.3 across the three samples), $\delta_M = +50.7$; bonus $+1.76$ and malus -0.41 log points (5.8-fold, -34 percent); malus brackets $+34.3$, $+56.7$, $+97.1$ with registrations -0.29 ($p < 0.05$), -0.52 , -0.69 . With an engine-displacement control (94 percent of variant-years): $\delta^P = -112.7$, -105.6 ; $\delta_B = -57.5$, $\delta_M = +47.4$.

¹⁸The supply-side coefficient rises monotonically with the bracket midpoint ($+31.9$, $+54.3$, $+94.7$, all $p < 0.01$), sales-weighted counterparts behave identically, and registrations fall across all three brackets (-0.28 , -0.51 , -0.68 log points), though the effect in the lowest bracket is significant only at the 10 percent level. The feebate’s introduction coincided with the EU transition from NEDC to WLTP, which Sweden adopted as its tax basis in 2020 and which raised reported ICE emissions by roughly 20 percent absent any engineering change. All emissions are harmonised to NEDC in three tiers: the vehicle register’s type-approval value where recorded; otherwise the ADAC/EEA type-approval value matched at year, make, fuel and rated power (NEDC through 2020); and, for 2021–22 variants for which only a WLTP value is observed, a WLTP-to-NEDC back-cast with powertrain-specific factors (0.85 for conventional engines, 0.75 for hybrids, 1 for battery-electric cars). Plug-in hybrids take matched type-approval NEDC values (register, EEA monitoring data, ADAC) at year, make, model and rated power – 95–100 percent of PHEV registrations in 2013–21 and 75 percent in 2022 – with the remainder carried within variant or, for under 0.5 percent, back-cast from WLTP at 0.45; variant-years with no value on any tier are dropped. This channel is therefore removed by construction and the positive malus coefficient survives harmonisation.

H.3 The Feebate Counterfactual: Calibrated Welfare Comparison

Corollary A3 establishes that a continuous feebate welfare-dominates the binary GCR whenever the eliminated gaming cost Π^B exceeds the induced abatement cost; Section 8.2 of the main text shows the corresponding instrument in actual operation, and this subsection calibrates the comparison to the Swedish context using the parameters estimated in Sections 6 and 7. Where the closest previously studied analogue, the French bonus-malus (Durrmeyer and Samano 2018; Durrmeyer 2022), compares a feebate to no feebate, the present exercise sets two instruments against each other in the *same* jurisdiction and under an identical fiscal budget.

Consider a linear feebate schedule $T(e_i) = r(e_i - e^*)$ with pivot e^* set at the pre-GCR (2005–2006) sales-weighted average fleet emissions, $e^* \approx 184$ gCO₂/km, and the rate calibrated to exhaust the GCR’s actual budget of EUR 88.1 mn over counterfactual baseline demand, yielding $r^* \approx 15$ EUR per gCO₂/km. Figure A3 contrasts the two schedules: the GCR’s thresholds create the loophole zone, which the continuous schedule eliminates by construction (Proposition 6).

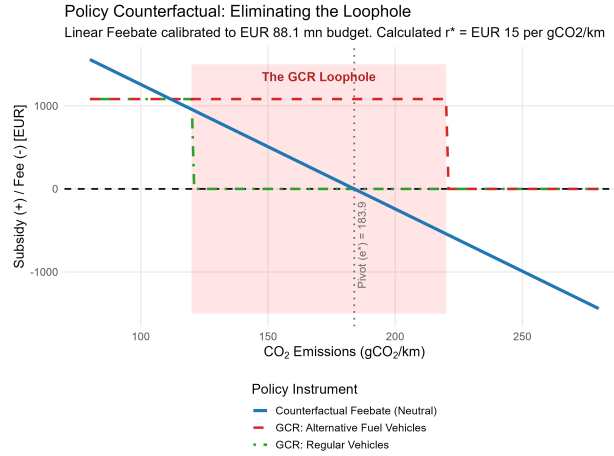


Figure A3: **Policy Counterfactual: GCR vs. Technology-Neutral Feebate.** The binary incentive structure of the Green Car Rebate (dashed and dot-dash lines) against a simulated continuous feebate schedule (solid line) calibrated to the same total fiscal budget. Shaded area: the regulatory loophole zone in which vehicles emitting 120–220 gCO₂/km received the full subsidy if classified as AFVs. Under the feebate the transfer depends strictly on emissions relative to the market pivot ($e^* \approx 184$ gCO₂/km).

The feebate rate induces a per-vehicle abatement response of approximately r^*/MAC , where the marginal abatement cost is bounded below by revealed preference: since a EUR 150 conversion cost allowed manufacturers to bypass 14.2 gCO₂/km of physical abatement, physical abatement must cost at least $150/14.2 \approx 10.6$ EUR per gCO₂/km, implying per-

vehicle abatement of roughly 1.4 gCO₂/km.¹⁹

Table A21: **Welfare Comparison: GCR versus Technology-Neutral Feebate**

Welfare Component	Central Scenario		High-Cost Scenario	
	GCR (Actual)	Feebate	GCR (Actual)	Feebate
Shadow Cost of Subsidy Financing	8.0	8.0	8.0	8.0
Allocative Opportunity Cost (W_{loss})	21.1	0	51.7	0
Fuel-choice emissions cost (gasoline in place of ethanol)	11.9	0	29.1	0
Fiscal Loop Premium (Windfall)	(25.8)	0	(33.6)	0
Genuine Abatement Benefit	0	(0.5)	0	(1.2)
Net Social Cost	15.2	7.5	55.2	6.8

Notes: All values in EUR millions. The Feebate is calibrated to the exact same total budget as the GCR. To maintain comparability, the Shadow Cost of Subsidy Financing isolates the EUR 39.9 mn allocated to the $N_G = 36,924$ gamed units, evaluated at a marginal deadweight loss of taxation of $\mu = 0.2$. The Central Scenario assumes $\tau_E = 40$ EUR/ton and VKT = 230,000 km; the High-Cost Scenario assumes $\tau_E = 75$ EUR/ton and VKT = 300,000 km. The fuel-choice emissions cost is the gamed cohort's own CO₂ from burning gasoline in place of ethanol, $N_G \hat{\phi} \Delta q_A \Delta c \tau_E$ at $\hat{\phi} = 0.359$, $\Delta q_A = \text{VKT}/13$ km/L and the net lifecycle $\Delta c = 1,270.5$ gCO₂/L (Table 3). Under the continuous feebate, financial rewards are based strictly on rated physical emissions, so the loophole's allocative displacement, its fuel-choice emissions cost and the associated Fiscal Loop Premium drop to zero. The Genuine Abatement Benefit credits the feebate's induced abatement of 1.4 gCO₂/km per vehicle only on the 38,531 AFVs the GCR subsidised, a conservative lower bound: market-wide it would be several times larger, which only strengthens the ranking. Values in parentheses represent a welfare surplus/recovery that reduces the Net Social Cost. The carbon price at which the feebate's net social cost falls below the GCR's is EUR 31 per tonne (the root of the two columns, invariant to VKT); it is EUR 27 at $\hat{\phi} = 0.30$ and EUR 38 at $\hat{\phi} = 0.51$, EUR 24 if ethanol is treated as carbon-free, and EUR 48 without the fuel-choice emissions row.

Table A21 reports the welfare decomposition across the Central Scenario ($\tau_E = 40$ EUR/tonCO₂, $\text{VKT} = 230,000$ km) and the High-Cost Scenario ($\tau_E = 75$, $\text{VKT} = 300,000$ km). The ranking runs as Remark A7 states: the feebate yields the lower net social cost under the Central Scenario (EUR 7.5 mn vs. 15.2 mn) and decisively under the High-Cost Scenario (EUR 6.8 mn vs. 55.2 mn). The GCR's fiscal dividend (EUR 25.8 mn) still exceeds its allocative loss (EUR 21.1 mn) at the Central carbon price, but once the gamed cohort's own fuel-choice emissions (EUR 11.9 mn) are on the GCR side of the ledger the dividend no longer decides the ranking: the two net social costs cross at a carbon price of about EUR 31 per tonne (table note), and the GCR wins only below it. Contemporary EU ETS prices, intermittently above EUR 75 since 2021, place the comparison far inside the feebate-dominant regime.²⁰

¹⁹Because the bound reflects the cost at which firms *chose* to circumvent rather than abate, the true engineering MAC is likely steeper, making 1.4 gCO₂/km an upper bound on the feebate's abatement induction.

²⁰Two further findings map onto the framework. By Proposition 6 the feebate eliminates categorical gaming ($\theta_{\text{cat}} = 0$), zeroing the allocative displacement cost, the fuel-choice emissions cost and the Fiscal Loop Premium of the loophole cohort. Its advantage is also allocative rather than abatement-inducing: spreading EUR 88.1 mn across the market yields a weak marginal signal, so the monetised benefit of new physical abatement is modest (EUR 0.5–1.2 mn) and the welfare gain comes almost entirely from eliminating the displacement channel.