# From Simulation to Insight: How Policy Timing and Fleet Composition Shape Electrification Outcomes

## Extended Abstract

### 1. Background and Motivation

The accelerating electrification of road transport supports international decarbonization goals and directly contributes to SDG7, yet it also exposes a growing structural challenge. As fuel consumption declines, the fuel-tax based model that traditionally financed road infrastructure becomes increasingly unstable. Projections indicate that under deep decarbonization pathways, fuel-tax revenues in the United States may approach zero by 2040, resulting in losses of approximately 138 billion dollars in annual public revenue (Raimi et al., 2023). This trajectory has led governments to consider alternative road-financing instruments that more accurately reflect actual road use and that remain functional as electric vehicle adoption expands.

Mileage based user fees (MUFs), which charge drivers proportionally to distance traveled, have emerged as a promising long-term replacement (Duncan et al., 2020). However, their performance is not technologically neutral. As electrification proceeds, the vehicle mix becomes more complex. Battery electric vehicles (BEVs), which eliminate tailpipe emissions, and plug in hybrid electric vehicles (PHEVs), which combine electric propulsion with combustion technologies, form heterogeneous fleets with distinct behavioral responses to pricing signals. Evidence shows that real world PHEV driving patterns vary widely across countries due to charging convenience, electricity prices and travel habits (Mandev and Sprei, 2024), highlighting the importance of technological composition in shaping transitions.

This heterogeneity creates ambiguity for policymakers. Introducing an MUF too early may discourage BEV adoption by raising per kilometer electric costs, potentially shifting consumers toward PHEVs that remain partly dependent on gasoline. Introducing an MUF too late may forgo substantial revenue recovery opportunities and undermine fiscal stability in the medium term. At the same time, subsidy strategies have implications of their own. Purchase subsidies accelerate adoption yet impose large fiscal burdens. Their effectiveness varies across markets depending on charging availability, consumer anxiety, and adoption targets (Huang et al., 2022).

Taken together, these dynamics reveal a critical policy question: How do subsidy structures and MUF timing jointly influence environmental performance and long term fiscal sustainability across markets that differ in technological maturity and PHEV presence? Existing research does not provide a full answer, since most studies isolate single policies or assume BEV only fleets (Fang et al., 2020). Prior work has examined optimal subsidy allocation and the fiscal implications of electrification in BEV oriented markets using agent based modeling (Dabush et al., 2025; Dabush et al., 2026). However, these studies do not account for hybrid technologies or jointly evaluate subsidies and MUFs. The present study addresses this gap directly.

## 2. Objectives and Contribution

This study develops an integrated policy sequencing framework that evaluates how BEV purchase subsidies and MUFs interact over time in markets with and without PHEVs. Three contributions stand out:

- **Technological composition as a structural policy determinant:** The model isolates the mediating role of PHEVs and shows how they reshape both environmental and fiscal outcomes compared with BEV only markets.
- **Regulatory timing as a decisive parameter:** The analysis distinguishes between early MUF introduction at 30% BEV penetration and late introduction after BEVs exceed 50%. Timing is shown to be a central design choice with asymmetric implications.
- **Development of a multi dimensional evaluation framework:** The study introduces three complementary indicators: an emission retention measure, a fiscal recovery rate, and a PHEV mediation index. Together, they offer a structured method for evaluating policy combinations in heterogeneous fleets.

Overall, the paper provides actionable insights for policymakers designing distance based pricing and subsidy programs during electrification transitions.

## 3. Methodology

This study expands the original modeling approach developed by Dabush et al. (2025) by adding PHEVs and inserting policy environments that combine purchase subsidies with MUFs. The study employs a large scale agent based model calibrated to U.S. market conditions. The environment includes three types of vehicles (BEVs, PHEVs, CVs) and two types of refueling infrastructure (charging stations and gasoline stations). The model simulates 20,000 heterogeneous consumers and 100 infrastructure investors located on a Watts Strogatz small world network (Watts and Strogatz, 1998). The network structure captures neighborhood clustering and occasional long distance links, both shown to influence EV diffusion (Fang et al., 2020).

### 3.1 Consumer decisions

Consumers choose among BEVs, PHEVs, and CVs using life cycle cost comparisons that incorporate purchase subsidies, electricity and fuel prices, MUF charges, residual values, daily driving distance, and charging availability. PHEV operation follows a weighted usage pattern of 17% electric travel and 83% gasoline travel, consistent with observed behavior (Huang et al., 2022). Charging accessibility shapes the feasibility of BEV adoption using spatial thresholds derived from empirical studies (Sousa et al., 2020).

### 3.2 Investor dynamics

Infrastructure investors compare expected profits from operating a charging station versus a gasoline station. Profit calculations incorporate capital expenditures, operating costs, equipment lifetimes and local demand, with behavioral adaptation modeled through imitative evolutionary dynamics following the Fermi rule (Szolnoki and Perc, 2010).

### 3.3 Policy environments

Two subsidy structures are modeled:

- A five year unlimited subsidy.
- A ten year gradually declining subsidy with a yearly 10% reduction.

The MUF is applied only to BEV kilometers, reflecting policies intended to restore revenue lost due to electrification. PHEVs do not pay the MUF, which creates a structural asymmetry relevant for the fiscal recovery analysis.

### 3.4 Timing regimes

The MUF is introduced under two alternative thresholds:

- Early timing at 30% BEV penetration.
- Late timing after BEVs exceed 50% of the fleet.

### 3.5 Evaluation metrics

To assess environmental and fiscal effects, three indicators are computed:

- Emission retention rate (ER): the proportion of emission reduction achieved by subsidies that remains once the MUF is introduced.
- Fiscal recovery rate (FR): the discounted ratio of cumulative MUF revenues to cumulative subsidy expenditures.
- PHEV mediation index (PMI): the ratio of policy performance in mixed markets to BEV only markets, computed separately for environmental and fiscal dimensions.

Each scenario is repeated across 3,000 independent simulation runs to ensure statistical robustness.

## 4. Results

### 4.1 Adoption dynamics

**Early MUF implementation (30% BEV)**

Early MUF introduction generates strong behavioral responses. Even at low MUF levels between 2.5% and 5%, BEV shares decline modestly. However, in markets with PHEVs the effect is substantially amplified. BEV shares fall by around 2.5% to 5.5% age points relative to the no MUF baseline even under low MUF levels, and as MUF levels increase to the 10% to 20% range, BEV penetration declines sharply while the time required to reach a 50% BEV share lengthens significantly. These results confirm that early MUF pricing increases the relative attractiveness of PHEVs due to their hybrid flexibility and lower sensitivity to per kilometer electric costs.

**Late MUF implementation (50 % BEV)**

When the MUF is introduced after BEVs exceed 50% of the fleet, effects are much weaker. In BEV only markets, even MUF levels as high as 60% barely disrupt the adoption trajectory. In PHEV inclusive markets, late MUF introduction slows diffusion only slightly, and BEV shares remain close to no MUF trajectories. This stability illustrates a transition toward technological lock in at maturity where infrastructure availability, learning, and established consumer expectations reduce sensitivity to new pricing signals.

## 4.2 Environmental performance

### Early timing

ER declines as MUF levels increase. At high MUF levels, ER becomes negative, meaning that the MUF erodes or reverses the environmental gains induced by subsidies. However, in mixed markets ER values consistently remain higher compared with BEV only markets due to the moderating effect of PHEV substitution, which prevents a complete collapse of electrification. For example, ER improves from negative 1.543 to negative 0.648 at a 40% MUF and from negative 2.781 to negative 0.998 at a 60% MUF under the unlimited subsidy structure.

### Late timing

ER is high across all MUF levels under both subsidy structures when the MUF is introduced after BEVs pass 50%. PHEV inclusive markets achieve ER values similar to or slightly higher than BEV only markets at moderate MUF levels. Environmental trajectories therefore remain robust under late MUF implementation.

## 4.3 Fiscal performance

### Early timing

FR increases quickly with MUF levels and reaches or surpasses full fiscal recovery at moderate MUF levels. Under the unlimited subsidy structure FR rises from 0.253 at a 2.5% MUF to 1.01 at a 10% MUF and 1.925 at a 20% MUF. PHEV inclusive markets track BEV only markets closely at all MUF levels, since PHEVs do not draw subsidies yet also do not contribute MUF revenue.

### Late timing

FR values increase more moderately at late introduction and remain lower in PHEV inclusive markets across all MUF levels. Because PHEVs avoid MUF payments and do not receive subsidies, they reduce the taxable mileage base and thereby damp fiscal recovery.

## 4.4 Mediation effects

**Environmental mediation**

Under early timing, PHEVs weaken environmental performance, with environmental PMI values below 1 in most cases. Under late timing, PMIs approach or exceed 1, indicating minimal environmental distortion.

**Fiscal mediation**

Under early timing, fiscal PMI values remain near 1 for low MUF levels. Under late timing, fiscal PMI values remain consistently below 1, demonstrating that PHEVs structurally reduce long term MUF revenues.

# 5. Discussion and Executive Insights

These findings extend previous evidence on BEV only environments (Dabush et al., 2026) by showing that the introduction of PHEVs fundamentally alters both fiscal and environmental dynamics. The mediation patterns observed here clarify and expand the mechanisms identified in earlier hybrid focused analyses such as Dabush and Cohen (2026), demonstrating that hybrid substitution effects are strongly dependent on regulatory timing. Three insights emerge:

**Technological composition fundamentally alters policy outcomes:** PHEVs behave as technological buffers, absorbing pricing shocks early in the transition yet undermining fiscal recovery later. Their dual role underscores the need for explicit integration of hybrid technologies into distance based pricing frameworks.

**Regulatory timing is a first order design parameter:** Early MUF introduction strengthens fiscal recovery but at the cost of reduced environmental performance and slower BEV diffusion. Late MUF introduction maintains environmental gains and preserves adoption stability but recovers a smaller share of subsidy expenditures.

**Coordinated policy design is essential:** Subsidies and MUFs must be treated as a combined policy pair rather than isolated instruments. A phased introduction approach is likely optimal: subsidies dominate at early stages, followed by MUF introduction once BEVs reach market stability, with adjustments for PHEV participation to sustain the fiscal base.

## 6. Policy Implications

- **Delay MUF implementation until markets reach technological maturity:** Introducing an MUF only after BEVs exceed 50% minimizes disruption to electrification pathways.
- **Redesign MUF systems to incorporate PHEVs:** Leaving PHEVs outside the MUF system weakens long term revenue recovery.
- **Maintain time limited purchase subsidies:** Short front loaded subsidy schemes combined with late MUF introduction balance environmental effectiveness with fiscal sustainability.

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