Decarbonizing German Heavy-Duty Transport: A Scenario-Based Study of Hydrogen Truck Fleet Evolution

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Abstract

Decarbonizing heavy-duty transport is essential for European climate neutrality by 2050, yet the transition pathway for hydrogen-powered trucks in Germany remains uncertain due to nonlinear feedbacks among policy, infrastructure, and total cost of ownership. This study quantified how these interdependencies shape the German heavy-duty vehicle fleet from 2020 to 2050 and identified key levers for hydrogen diffusion. A System Dynamics simulation in Stella Architect integrated a Bass diffusion formulation distinguishing innovation and imitation-driven adoption. The model represented competition among fossil-fuel trucks, battery-electric vehicles (BEVs), and hydrogen fuel cell electric vehicles (FCEVs) through attractiveness-based adoption, hydrogen refueling station (HRS) expansion with delays and minimum threshold, and dynamic CAPEX learning and hydrogen price decay. The model was verified through multiple tests and calibrated to German data (2020-2025), showing ~535,000 diesel trucks, 10,597 BEVs (Q3 2025) and 188 FCEVs, using p=0.0083 and q=0.5 for hydrogen. Baseline projections showed fossil-fuel decline, BEVs emerging as primary successor by 2049, and hydrogen remaining niche without external acceleration. Scenario analysis showed increasing policy-driven innovation disproportionately accelerates early uptake, but long-term diffusion depends most on hydrogen fuel costs: with initial 11 EUR/kg and decay d=0.03 toward ~5 EUR/kg by 2050, baseline yields ~10,000 hydrogen trucks, while doubling price reduction produces >25,000. Infrastructure streamlining (reduced bureaucracy and construction time) moderately increases the 2050 hydrogen fleet (~9,000 to ~12,000). Meeting targets requires shifting from upfront subsidies to operational-cost reductions while maintaining adequate HRS coverage for self-reinforcing diffusion.

Keywords: green hydrogen, trucking sector, heavy-duty transport, hydrogen truck

1. Introduction

The decarbonization of the HDV sector is a critical prerequisite for achieving climate neutrality in Europe by 2050 [1]. While light-duty segments have seen rapid electrification, long-haul freight remains a "hard-to-abate" sector because of the high energy density, long-range, and payload requirements that battery-electric vehicles (BEVs) struggle to satisfy [2]. Consequently, hydrogen has emerged as a strategic alternative, offering shorter refueling times and better range performance, similar to conventional diesels. Despite the promise of hydrogen, its transition pathway remains unclear. The current literature largely focuses on isolated technical parameters, such as fuel cell durability, hydrogen production costs, and spatial infrastructure optimization [3], [4]. However, the real-world adoption of hydrogen trucks is not driven by these factors in isolation; rather, it is a complex, nonlinear process defined by feedback loops between government policy, infrastructure deployment, and the total cost of ownership (TCO) for logistics operators.

Existing studies often rely on linear forecasting or narrow optimization models that fail to capture these systemic interdependencies. There is a notable absence of research that models the overall transition of the German HDV fleet by simultaneously considering the dynamic interactions between these variables. Without a model that accounts for these complexities, policymakers risk designing support schemes that fail to trigger self-sustaining market growth.

This study addresses this gap by developing an integrated SD model to simulate the evolution of the German HDV fleet from 2020 to 2050. Using a Bass diffusion framework, we simulate how different policy interventions, hydrogen price reduction rates, and infrastructure development levels influence market penetration. By providing a clearer roadmap for the strategic transition of the German HDV sector, this research contributes a systems-level perspective that connects the current divide between technical feasibility and market-ready policy design.

2. Literature Review

The transition of Germany's HDV sector is characterized by competition between diverse propulsion systems. Conventional diesel powertrains, optimized for thermal efficiency (40–45%), remain the primary source of lifecycle carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions in freight [5]. Battery-electric trucks offer superior local energy efficiency (80–90%), but face constraints related to charging infrastructure and battery weight [6], [7]. Hydrogen-based technologies, specifically fuel cell electric vehicles (FCEVs) and hydrogen-fueled internal combustion engines (H_2-ICEs), complement these systems by providing the energy density and rapid refueling required for long-range logistics [8]. Despite challenges in hydrogen purity requirements and high capital expenditures (CAPEX), hydrogen remains critical for segments where electrification is technically impractical [9].

As of early 2026, the German HDV sector is experiencing slow but persistent erosion of diesel dominance. Although the fossil-fuel fleet remains at approximately 535,000 vehicles, battery-electric truck adoption has accelerated and reached 10,597 units by Q3 2025 [10]. FCEVs are in the early-adopter phase, with 188 registered units [11]. While H_2-ICEs are currently limited to prototype demonstrations, recent developments, such as the announcement of small-series production for next-generation hydrogen trucks by late 2026, signal a shift toward commercial readiness.

Decarbonization is governed by a multilevel policy framework. Regulation (EU) 2019/1242, strengthened by the 'Fit for 55' package, mandates a 90% reduction in fleet-wide CO_2 emissions for HDVs by 2040, with interim targets and a 100% zero-emission requirement for city buses by 2035 [12]. The Alternative Fuels Infrastructure Regulation (AFIR) mandates a dense, interoperable hydrogen refueling station (HRS) network along the Trans-European Transport Network (TEN-T) by 2030, with a maximum distance of 200 km between stations [1].

Domestically, Germany supports this via the National Hydrogen Strategy and the Klimaschonende Nutzfahrzeuge und Infrastruktur (KsNI) guideline, which subsidizes up to 80% of the cost premium for hydrogen trucks compared to diesel [13]. As of January 2026, a new federal funding program with a budget of 220 million EUR further incentivizes the combined deployment of refueling stations and commercial hydrogen vehicles to bypass the historical "chicken-and-egg" dilemma [11]. Furthermore, the CO_2-based truck toll system serves as a fiscal lever to improve the total cost of ownership (TCO) for early adopters [14].

The market, however, remains constrained by an interdependency in which limited infrastructure inhibits vehicle adoption, and vice versa [15]. Germany is currently restructuring its HRS network, moving away from legacy 700-bar passenger-car stations toward 350-bar facilities optimized for commercial throughput [16].

Future market development is characterized by high uncertainty, requiring "prediction bands" to account for variations in policy and technological learning. Projections for 2030 suggest a shift in new registrations toward a mix of 48% BEVs and 20% hydrogen-powered trucks [17]. Cost reduction is a primary driver; renewable hydrogen at-the-pump prices are projected to decline from 11 EUR/kg in 2020 to approximately 5 EUR/kg by 2050 [18]. Supported by regional initiatives such as HyLand, BayFELI, and the Hydrogen Acceleration Act, these efforts aim to establish hydrogen value chains within European industrial and logistical corridors [19], [20], [21].

3. Theoretical Framework

This study employs SD as the primary methodological framework because the transition of the German HDV fleet is characterized by the complex interplay of social dynamics, government policy, infrastructure availability, and economic factors and constitutes a high-order, nonlinear system in which aggregate behavior patterns emerge from multiple interacting feedback loops [22]. Industrial dynamics, as defined by Forrester, provides the necessary theoretical and quantitative rigor to move beyond static snapshots, enabling the integration of qualitative influences into a cohesive structure in which variables interact over time [22], [23]. By utilizing *Stella Architect* for this simulation, the research benefits from a platform that visualizes causal mechanisms, ensures mathematical unit consistency, and supports the tracing of key leverage points within the system's stock-and-flow architecture [24]. This approach is particularly well-suited for long-term strategic analysis (2020–2050) as it allows for the simulation of reinforcing feedback loops, which drive technology adoption, alongside balancing loops, which represent infrastructure constraints and resource limits [23]. Ultimately, while no model can perfectly replicate reality, the SD methodology provides a robust, transparent, and reproducible framework for evaluating how specific policy interventions affect the trajectory of the German HDV fleet [22].

The Bass diffusion model, first introduced by Frank M. Bass (1969), serves as a foundational mathematical framework for forecasting the market penetration of new technologies, distinguishing itself from earlier growth models by explicitly separating the population of potential adopters into innovators and imitators [25]. Innovators are characterized by their tendency to adopt new technology independently, effectively initiating the diffusion process, whereas imitators are influenced by social pressure and word-of-mouth communication generated by previous adopters [26]. Mathematically, the model is formulated as a differential equation defined by two key parameters: p, the coefficient of innovation, which represents the influence of external factors (such as advertising or media), and q, the coefficient of imitation, which captures the internal market dynamics driven by social interaction [26], [27]. By providing a structured approach to analyze these distinct behavioral drivers, the Bass model has become the standard for forecasting technology adoption in industrial and scientific literature over the past five decades [25]. This framework is particularly vital for this study, as it allows for the simulation of how hydrogen-based heavy-duty transport transitions from a small base of early innovators toward widespread adoption as infrastructure and social influence begin to dominate the market landscape.

The model integrates three competing drivetrain technologies–fossil-fuel (FF), battery-electric (BEV), and hydrogen fuel cell (FCEV)–within a unified Bass diffusion structure, allowing for distinct adoption dynamics across varying levels of technological maturity.

The model architecture comprises three interdependent modules.

i. *Adoption Module*: Governed by the Bass diffusion framework, this module calculates the transition rate for each technology based on *the p* and q coefficients. The transition between "untapped" and "tapped" market stocks is endogenously determined by an Attractiveness Factor, where the relative competitiveness of a technology is weighted against the sum of all competing drivetrain attractiveness scores (Equation 1).

$$Actual\ Attractiveness = \frac{Base\ Attractiveness}{Sum\ Total\ Base\ Attractiveness} \tag{1}$$

ii. *Infrastructure Module*: This module addresses the "chicken-and-egg" barrier by implementing a feedback loop in which hydrogen fleet growth drives HRS expansion, which in turn improves user confidence and adoption rates. Station deployment is modeled using a stock-and-flow structure that accounts for planning, construction, and decommissioning phases and is operationalized with a minimum vehicle threshold "pulse" delay (Equations 2-3).

$$Constructing\ Flow = DELAYN(Planning; Time\ Needed; 8) \quad (2)$$

$$HRS\ Coverage = DELAY1\left(MIN\left(1; \frac{Operational\ HRS}{MAX(1; Required\ HRS)}\right); HRS\ Response\ Delay \right. \quad (3)$$

iii. *Cost Module*: This module calculates the TCO by dynamically computing CAPEX and OPEX. CAPEX reduction is driven by an endogenous learning curve linked to the stock of accumulated experience, whereas fuel costs (modeled as a dynamic price-at-pump decay function) directly influence the operational attractiveness of FCEVs over the simulation horizon.

The annual transition rate of hydrogen trucks is modeled as a function of both external and internal market influences, reflecting the dual drivers of innovation and social imitation within the Bass diffusion framework, as well as the service level provided by HRS. The total transition rate is calculated as the sum of adoption driven by independent innovation and adoption resulting from social interaction, multiplied by the HRS coverage factor, as expressed in Equation (4):

$$Transition\ Rate = (Adoption\ by\ innovation + Adoption\ by\ imitation) * HRS\ Coverage \quad (4)$$

The structural adequacy of the model was verified through a suite of tests, including boundary adequacy, dimensional consistency, parameter verification, behavior, and extreme condition tests. The endogenous feedback loops (specifically the reinforcing loops R1 and R2 representing cost learning and infrastructure scaling, and the balancing loops B1 and B2 representing market substitution and saturation) ensure that the model’s behavior is generated internally by the system structure rather than by exogenous curve-fitting. These loops are shown in Figure 1. This robust approach allows the model to capture the nonlinear transition from a diesel-dominant market toward a zero-emission diversified fleet, providing a transparent causal mechanism for evaluating policy levers, such as subsidies and toll surcharges.

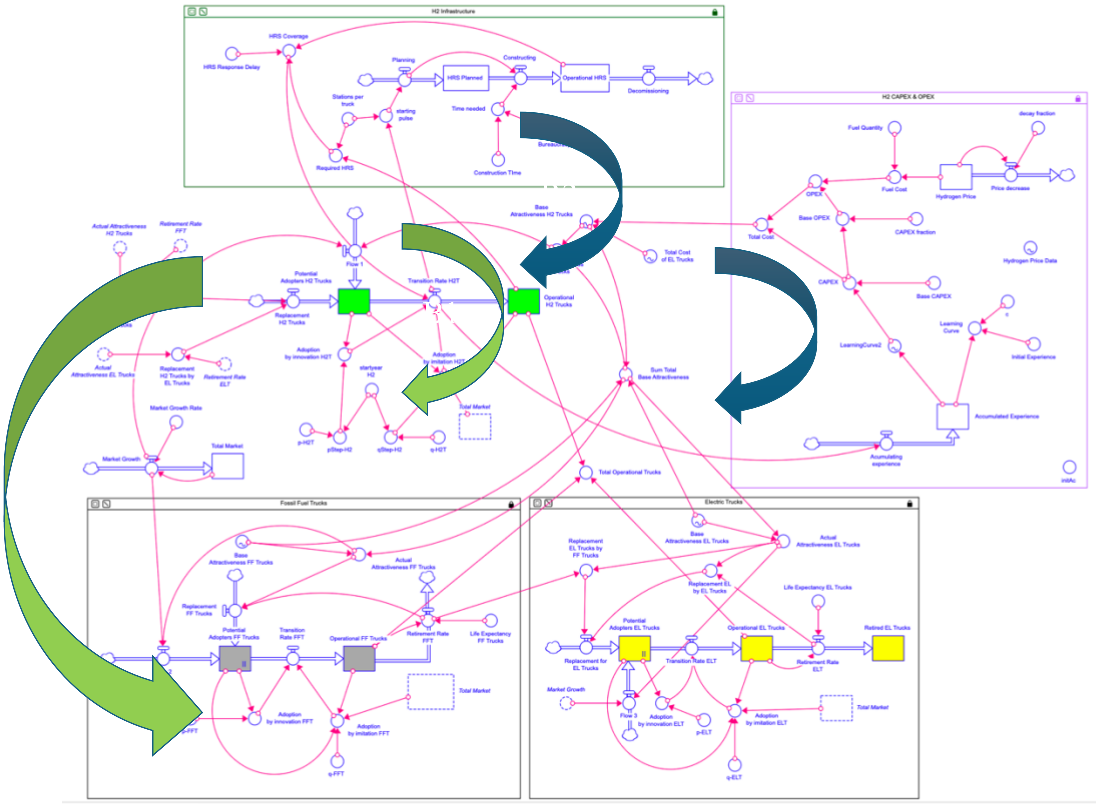

Figure 1: Structure adequacy test; Reinforcing loops R1 and R2, Balancing Loops B1 and B2.

4. Results

To ensure the model's structural integrity, the simulation was calibrated against historical German HDV registration data for the 2020–2025 period. The adoption parameters were iteratively adjusted to reproduce the observed market trajectories. For hydrogen trucks, values of $p=0.0083$ and $q=0.5$ were employed, consistent with the theoretical ranges established by Bass [26]. The model successfully captured the early-market stagnation and subsequent growth phase, demonstrating convergence with empirical data by 2025. Minor deviations in the intermediate years are attributed to exogenous factors, such as supply-chain bottlenecks and project-specific delays, which remain outside the model's structural scope.

The baseline simulation projects the long-term fleet composition under the current structural conditions, assuming no major exogenous shocks or policy accelerants. The simulation results, illustrated in Figure 2, depict the endogenous distribution of market share across the three competing drivetrain technologies. The baseline trajectory revealed a long-term transition characterized by two distinct phases:

i. Fossil-Fuel Erosion: As the dominant baseline technology, fossil-fuel trucks experience a steady, predictable decline as they are replaced by zero-emission alternatives at the end of their operational lifetimes.

ii. Divergent Growth Paths: BEVs emerge as the primary market successor, driven by cumulative cost reductions and infrastructure maturity, eventually challenging the market dominance of conventional powertrains by 2049. In contrast, FCEVs exhibit a slower, more deliberate growth path. Without aggressive exogenous acceleration, hydrogen remains a niche-to-mid-tier solution within the simulated timeframe.

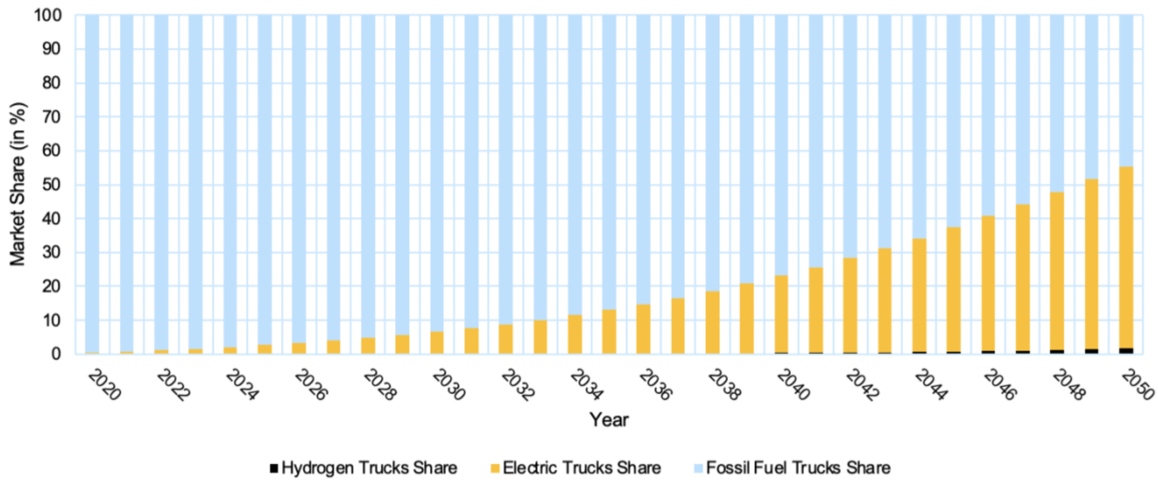

Figure 2: Evolution of the market share of heavy-duty truck technologies in Germany (2020–2050)

This baseline confirms that the model's internal feedback loops are sufficient to support a steady adoption of hydrogen, although they do not, by themselves, trigger the rapid exponential scaling required for market-wide dominance.

4.1 Scenario Analysis: Drivers of Market Diffusion

To assess the sensitivity of the transition dynamics, a scenario analysis focused on three key leverage points was conducted: government push (policy-driven innovation), hydrogen fuel price (economic feasibility), and infrastructure deployment speed. These variables were chosen for their direct impact on the technology's competitiveness within the model's attractiveness functions.

4.1.1 Scenario 1: Government Push (Innovation Acceleration)

The "Government Push" variable encompasses regulatory interventions, financial incentives, and strategic funding frameworks intended to lower entry barriers. Methodologically, this intervention is operationalized through the innovation parameter p within the Bass diffusion framework. While the baseline scenario assumes a background innovation rate ($p=0.0083$), this scenario explores the systemic response to enhanced policy support: current policy level (p=0.0083), enhanced support (p=0.0125; 1.5× baseline), and strong intervention (p=0.0166; 2.0× baseline).

The simulation demonstrates that increasing the innovation parameter (p) induces disproportionate acceleration in the adoption curve. By stimulating early adopter behavior, stronger policy interventions initiate the diffusion process earlier, which subsequently activates the imitation-driven (q) feedback loops sooner. As illustrated in Figure 3, this leads to a compounded effect: the larger the fleet size in the early years, the more rapidly the imitation mechanism drives total market penetration.

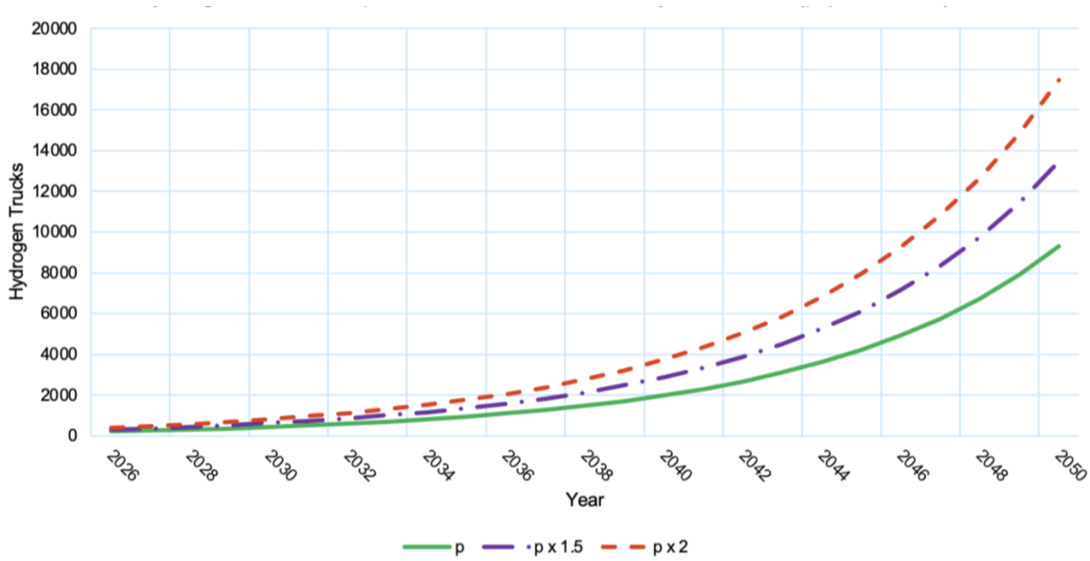

Figure 2: Hydrogen truck adoption under different policy scenarios (p-parameter).

4.1.2 Scenario 2: Hydrogen Price Reduction Rate

In the model, the hydrogen price is represented as a stock variable that evolves over time, with an initial at-the-pump cost of 11 EUR/kg, consistent with historical baseline data [18]. The price trajectory is governed by a decay fraction (d=0.03), which simulates the expected annual proportional decline in hydrogen costs as production scales and technological learning matures, aiming for a target of approximately 5 EUR/kg by 2050. To assess the sensitivity of the HDV fleet transition to these economic dynamics, three trajectories were analyzed by varying the decay fraction d: baseline (d), accelerated decline (1.5×d), and strongly accelerated decline (2.0×d).

As shown in Figure 4, a faster decline in hydrogen prices leads to a significantly higher adoption rate and a larger hydrogen truck fleet over time. The simulation reveals a high degree of sensitivity in hydrogen truck diffusion regarding fuel cost developments. While the baseline scenario (d) results in a fleet size of approximately 10,000 hydrogen trucks by 2050, doubling the price reduction rate (2×d) more than doubles the fleet size to over 25,000 units within the same period. This nonlinear growth trajectory confirms that fuel costs act as a critical gatekeeper for FCEV adoption; as the hydrogen price reaches parity with or falls below competing energy sources, the model triggers a rapid shift in technology preference. Consequently, in the market dynamics module, a more competitively priced hydrogen fuel directly correlates with a declining market share for both battery-electric and fossil-fuel trucks, as FCEVs capture a larger proportion of the total heavy-duty fleet.

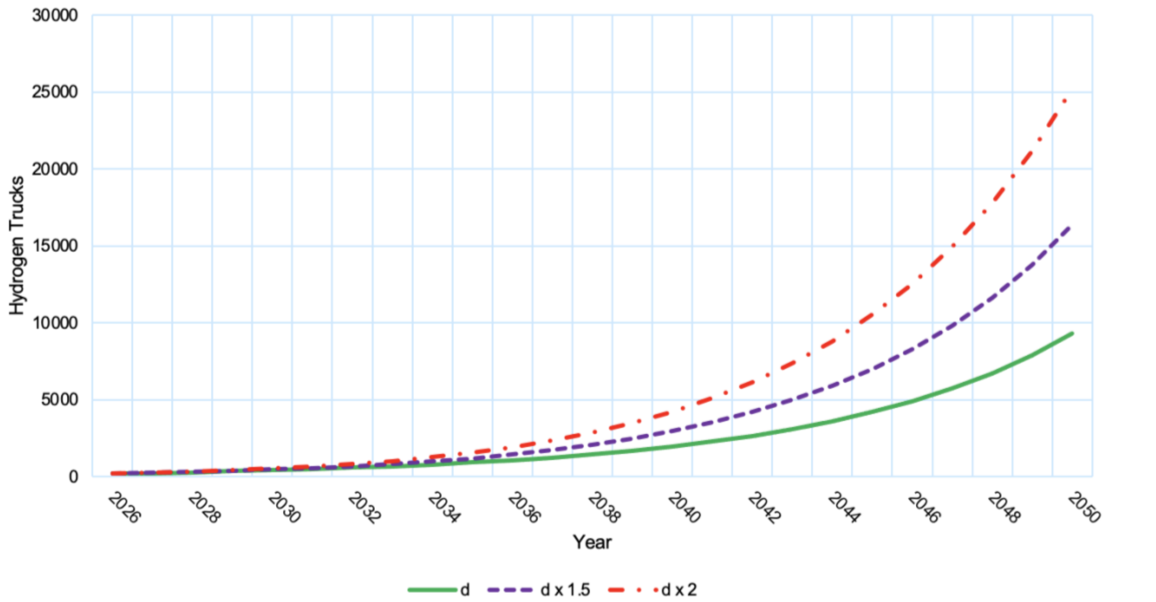

Figure 3: Hydrogen truck adoption under different hydrogen price reduction rates.

4.1.3 Scenario 3: Infrastructure Delay

Infrastructure development represents a primary systemic bottleneck in the transition to hydrogen-powered freight. The model incorporates an endogenous infrastructure delay that acts as a balancing loop against vehicle adoption: as hydrogen truck demand increases, a signal for additional HRS is generated; however, a significant time lag (comprising construction by 1 year and administrative bureaucracy by 2.5 years) prevents immediate capacity expansion. This delay directly constrains the hydrogen truck adoption rate, as the system limits fleet growth until sufficient refueling capacity is commissioned. To evaluate the systemic impact of this bottleneck, we analyzed three scenarios by varying the bureaucracy time *bt* required for HRS deployment: the baseline scenario (bt=2.5 years), a reduced-bureaucracy scenario (bt=2.0 years), and an aggressive streamlining scenario (bt=1.0 year).

As shown in Figure 5, a shorter infrastructure delay facilitates a faster overall transition by expanding network capacity more responsively to demand. However, the simulation results indicate that the fleet size sensitivity to bureaucratic time is lower than that of the previously analyzed policy or fuel-price drivers. While reducing bureaucratic time from 2.5 to 1 year increases the 2050 hydrogen truck fleet from approximately 9,000 to 12,000 vehicles, the impact remains moderate. This suggests that while infrastructure streamlining is necessary, it is not a standalone "silver bullet"; rather, it must be coupled with demand-side incentives to achieve meaningful fleet scaling. The results confirm that infrastructure availability serves as a critical systemic gatekeeper, but its effectiveness as a lever is contingent upon the concurrent economic competitiveness of hydrogen fuel itself.

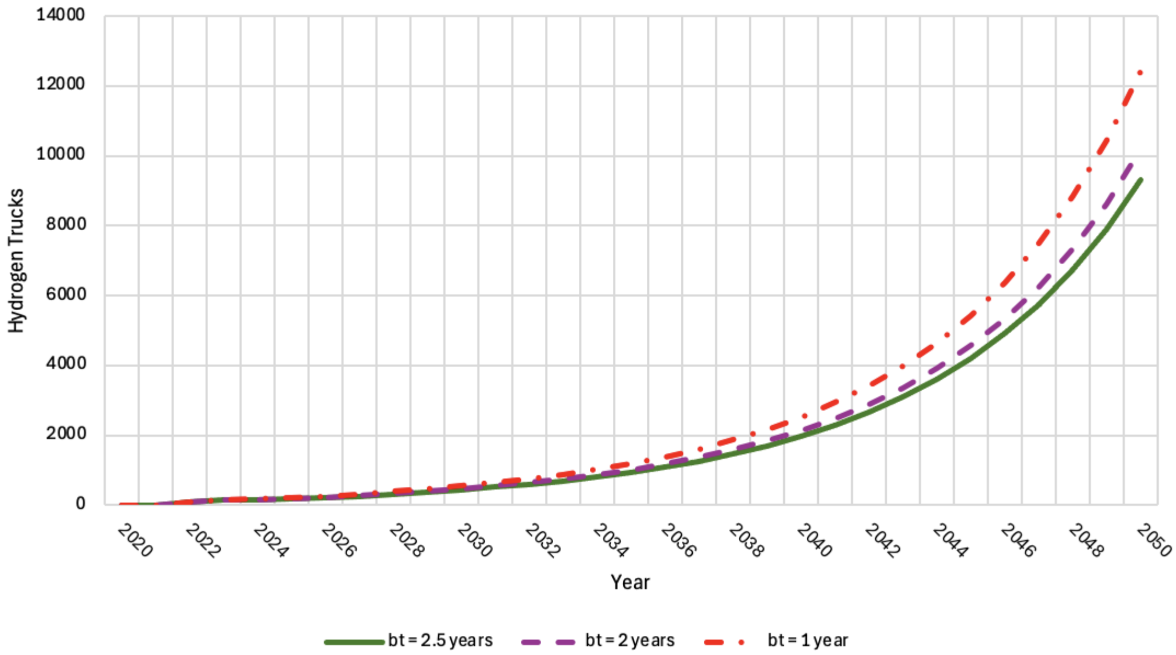

Figure 4: Hydrogen truck adoption under different delaying times

4.2 Scenario Comparison: Normalized Sensitivity Analysis

After analyzing each variable individually to examine its influence on the system, the next logical step is to compare their relative impacts to determine which variable dictates the hydrogen truck adoption rate most strongly in both the short and long terms. To enable a meaningful comparison across variables of different units and magnitudes, a normalized sensitivity analysis was conducted. Each key parameter (*p, d,* and *bt*) was adjusted by ±1% in the direction that positively influences hydrogen adoption, and the resulting percentage change in the total hydrogen truck fleet size was measured. By normalizing these parameter changes, the influence of *p, d,* and *bt* becomes directly comparable.

Figure 6 illustrates the marginal sensitivity of the hydrogen truck fleet to small parameter changes. In the short term (2026–2035), the system exhibits considerable inertia, and the effects of all three variables remain relatively modest. Increasing *p* by 1% results in only a small increase in the fleet, with a 1% increase in *d* producing a similar effect, while a 1% reduction in *bt* has the smallest initial impact around 2028–2030. By 2035, the divergence becomes visible: both *p* and *d* generate noticeably more additional trucks than reductions in infrastructure delay, indicating that economic and government-driven mechanisms begin to outweigh administrative acceleration even in the medium term.

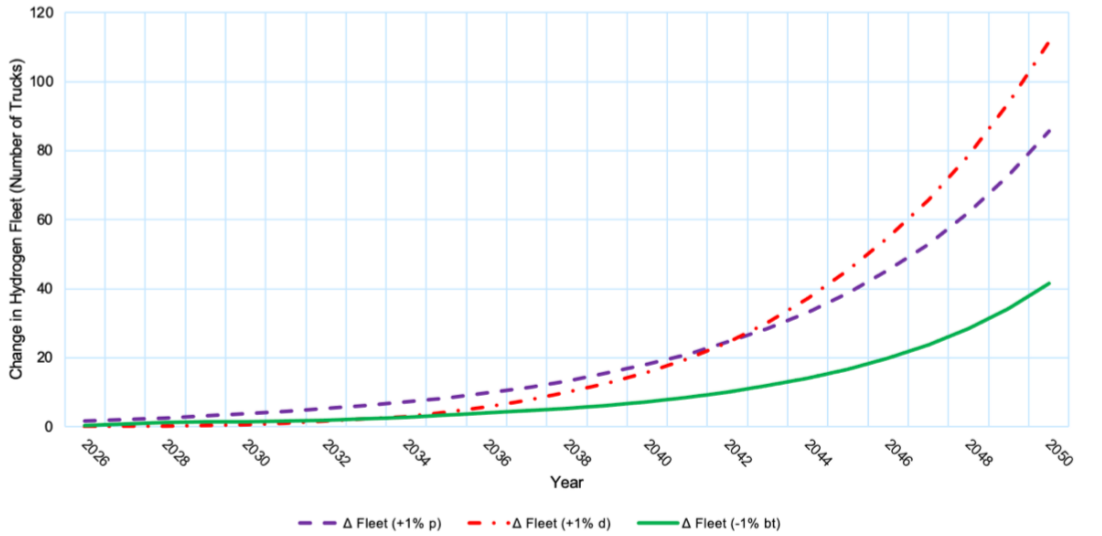

Figure 5: Marginal Sensitivity of hydrogen fleet to key drivers (±1%).

Between approximately 2035 and 2045, the divergence between the variables increases. Around 2040, both *p* and *d* generate approximately twice as many additional trucks as a reduction in *bt*. From 2041 onward, d begins to show a slightly stronger effect than *p*, suggesting that cost competitiveness increasingly drives adoption as the market matures. In the long term (2045–2050), the differences are substantial: by 2050, a 1% increase in the hydrogen price decline rate (d) results in the largest number of additional trucks, followed by a 1% increase in the innovation parameter (p). The reduction in bureaucracy time (bt) still has a positive effect but remains significantly smaller in magnitude. Overall, the results suggest that while short-term effects are limited due to system inertia, long-term fleet expansion is structurally more sensitive to economic factors, particularly hydrogen price development and innovation dynamics, whereas administrative acceleration has a comparatively smaller marginal impact.

5. Conclusions

This study utilized an SD framework to analyze the transition of the German HDV fleet and provide a long-term projection of the interplay between fossil-fuel, battery-electric, and hydrogen-powered technologies. Our results demonstrate that the transition toward hydrogen is not a uniform process but a dynamic evolution shaped by shifting drivers over time. In the short term, policy interventions (such as regulatory mandates and targeted financial incentives) are the most effective levers for stimulating initial market uptake. However, as the system matures, the transition's momentum becomes increasingly sensitive to economic factors, specifically the parity between fuel costs and TCO.

This analysis highlights three fundamental insights for policy design. First, while infrastructure readiness (specifically the deployment of HRS) is a necessary systemic condition, it acts more as a supporting framework than a primary driver of acceleration. Infrastructure delays create bottlenecks; however, streamlining bureaucratic processes alone will not catalyze mass-market diffusion without concurrent demand-side incentives. Second, the competition between battery-electric and hydrogen-powered trucks is primarily governed by cost competitiveness and technological maturity. Given the current economic advantages of battery-electric platforms, hydrogen trucks occupy a niche, albeit essential, role in the broader decarbonization strategy. Third, the simulation reveals that market forces, absent strong exogenous policy impulses, are insufficient to meet rapid decarbonization targets.

A successful transition requires a two-step policy approach. Early support should focus on subsidies and cost reduction to help hydrogen technology survive its initial, high-risk stages. As the market grows, policy should shift toward keeping fuel prices stable and ensuring that infrastructure expands at the same pace as the number of trucks on the road. Future research should test how this system holds up against unexpected global energy shifts or major technological breakthroughs. Ultimately, this study shows that moving to zero-emission heavy-duty transport is a complex challenge, and success depends on perfectly balancing government policy, infrastructure development, and economic incentives to create a sustainable and diverse transport future.

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