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Reframing the sustainability transformation of mobility systems through cognitive sustainability: An integrated perspective on cost structures, decision-making, and emission dynamics

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Abstract

This work reinterprets the sustainability transformation of mobility systems from a cognitive sustainability perspective, integrating economic mechanisms, decision-making processes, and emission dynamics into a unified analytical framework. While traditional approaches emphasise cost structures and policy incentives, this work argues that the transformation cannot be fully understood without considering the cognitive dimension of decision-making. Total cost of ownership (TCO) is positioned as a central mediating construct that not only reflects economic rationality but also serves as a cognitively informed decision interface shaped by perception, trust, and information asymmetry. The analysis highlights that the relationship between costs and emissions is dynamic and non-linear over time, particularly in the case of electrification, where short-term emission increases can precede long-term sustainability benefits. By integrating economic, environmental, and cognitive layers, the study proposes a feedback-driven systems model in which policy instruments, cost structures, user choices, and emission trajectories evolve together. The results show that an effective sustainability transformation depends not only on optimising cost structures but also on shaping the cognitive frameworks through which these costs are perceived and internalised.

Keywords
cognitive sustainability, mobility transformation, total cost of ownership, electromobility, emissions dynamics, decision-making, policy instruments

1. Introduction

The sustainable transformation of mobility systems is usually viewed as a technological and economic optimisation problem, where the adoption of low-emission technologies is promoted through cost competition and regulatory incentives. However, empirical findings increasingly show that this perspective is incomplete. The transformation of mobility systems occurs not only through measurable economic mechanisms but also through the ways decision-makers perceive, interpret, and internalise them. In this sense, mobility systems should be understood as cognitive-economic systems in which cost structures, policy interventions, and technological alternatives are continuously shaped by human perception and decision-making.

This integrated understanding aligns with the emerging paradigm of cognitive sustainability, which expands traditional sustainability thinking by incorporating information processing, perception, and behavioural dynamics into systems analysis (Zöldy et al., 2022). In this context, sustainability transformations are not solely the result of optimised resource allocation but arise from the interplay of objective system parameters and subjective decision-making processes.

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This study, therefore, aims to develop a unified analytical framework that links the economic, environmental, and cognitive dimensions of mobility transformations. By positioning total cost of ownership (TCO) as a mediating cognitive-economic construct and incorporating the temporal dynamics of emission trajectories, the study contributes to a more comprehensive understanding of the reasons for and mechanisms behind the success or failure of sustainable transformations of mobility.

2. Economic mechanisms and external effects in transport systems

At the heart of sustainable transformations in mobility lie the structures of economic incentives, traditionally described in terms of external effects and cost internalisation mechanisms. Transport systems generate significant negative externalities – including greenhouse gas emissions, air pollution, and noise – which are only partially reflected in market prices (Campos et al., 2009; IPCC, 2023). The classical economic approach defines the optimal emission level as the intersection of the marginal damage and the marginal cost of emission reduction. Sustainability, therefore, is achieved not through complete elimination but through effective reductions in emissions (Máca et al., 2011).

From the perspective of cognitive sustainability, however, external effects are not only economically undervalued but also cognitively underrepresented. Users tend to base their decisions on immediate and visible costs, while long-term environmental impacts remain abstract and are often neglected. Therefore, even well-designed economic instruments cannot achieve the desired behavioural changes if they are not cognitively accessible or interpretable. As a result, policy instruments should not be viewed solely as means of influencing relative prices, but rather as components of a broader decision-making environment. Taxes, subsidies, and regulatory frameworks influence behaviour not only through their financial effects but also through their signalling in the cognitive space. A stable political environment strengthens trust, visible infrastructure improves perceived feasibility, and direct incentives reduce the perceived risks of new technologies. In this sense, the effectiveness of policy measures depends not only on the economic scale but also on the coherence between economic signals and cognitive processing (Hörcher and Tirachini, 2021; Raux, 2011).

3. Total cost of ownership (TCO) as a cognitive-economic interface

The total cost of ownership (TCO) plays a central role in linking the economic and cognitive dimensions of mobility decisions. In traditional economic analysis, TCO integrates capital, operating, and regulatory costs into a comprehensive life-cycle indicator (Wouters et al., 2005; Desreveaux et al., 2020). However, the true significance of TCO for transformations of mobility lies in its role as a link between macroeconomic policy and microeconomic decision-making. From a cognitive perspective, TCO can be understood more as a decision architecture than as a purely financial metric. It structures the evaluation of alternatives, simplifies complex system interactions, and transforms abstract cost curves into actionable decision criteria. Empirical evidence, however, shows that decision-makers rarely perform complete TCO calculations in practice. Instead, they rely on partial information, heuristics, and relevant cost factors such as purchase price or immediate operating costs. This leads to a persistent discrepancy between calculated and perceived TCO, which significantly influences technology adoption.

The example of electromobility illustrates this discrepancy particularly clearly. Although the total life cycle costs of electric vehicles can be competitive under certain conditions, higher purchase costs often dominate decision-making due to electricity procurement and risk aversion. At the same time, the perceived benefits of lower operating costs depend heavily on expectations regarding future energy prices, infrastructure availability, and political stability (Franzò et al., 2022). This sensitivity demonstrates that cost competitiveness is not a static outcome but a dynamic, context-dependent phenomenon influenced by both external factors and cognitive interpretation.

4. Temporal dynamics of emission trajectories

The dynamics of mobility transitions become even clearer when considering emission trajectories. Traditional sustainability assessments are often based on static comparisons or aggregated life cycle indicators that fail to capture the temporal dimension of environmental impacts. In fact, emissions evolve, reflecting both technological characteristics and systemic processes. Electrification is a well-documented example of this temporal complexity. The production phase of electric vehicles – particularly battery production – results in higher initial emissions than those of internal combustion engine vehicles, while operational emissions are significantly lower. Consequently, the environmental benefits of electrification only become apparent after a certain period of use, resulting in a time-delayed emissions profile (Lerchner and Zöldy, 2026).

This temporal dependency has important cognitive implications. Users tend to evaluate environmental performance based on simplified and static assumptions, which can lead to misperceptions. The presence of an initial phase with "emission disadvantages" can undermine the perceived sustainability of electrical technologies, even if the long-term benefits are substantial. This underscores the need for dynamic and systems-based representations of environmental impacts that can be cognitively processed and integrated into everyday decisions. Furthermore, emissions are not determined at the level of individual vehicles but result from the composition and evolution of the entire vehicle fleet. The sustainability transformation of mobility systems thus depends on aggregated decision-making patterns, which in turn are shaped by political incentives, cost structures, and cognitive factors. The resulting system exhibits a feedback dynamic: political changes alter cost structures, costs influence decisions, decisions change the composition of the vehicle fleet, and emissions evolve accordingly.

5. Model of feedback-driven systems

Cognitive sustainability expands the economic feedback loop by emphasising that all phases of the transformation process are mediated by perception. The interpretation of political signals, the perceived relevance of costs, and the understanding of environmental consequences influence the direction and speed of the transformation. In this sense, sustainability transformations of mobility systems can be described as adaptive learning processes in which both individuals and systems continuously adjust to new information and changing circumstances. Figure 1 shows a feedback-based system model that integrates three main levels of the mobility transition: the economic level (including cost structures, total cost of ownership (TCO), external effects, and policy instruments), the cognitive level (including decision architecture, perceived TCO, behavioral biases, trust, and risk perception), and the ecological level (including emissions trends, fleet dynamics, and life cycle profiles). The central construct – cognitive sustainability – represents the co-evolutionary process through which these levels interact, mutually influence each other, and jointly determine the speed and stability of the mobility transition.

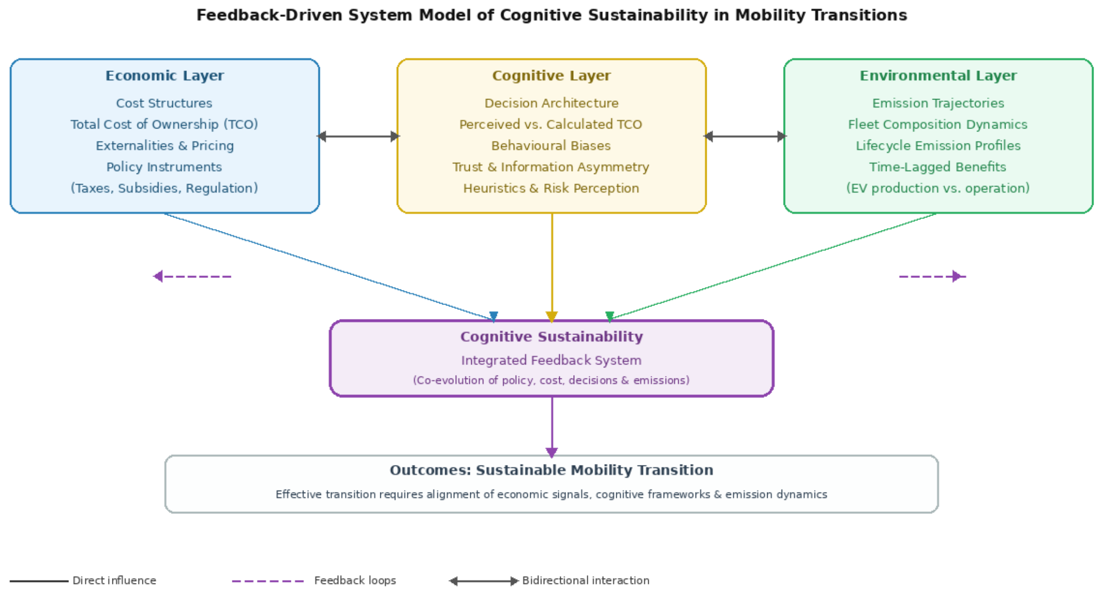

Figure 1. Feedback-driven system model of cognitive sustainability in mobility transitions

The model illustrates that direct impacts from each level flow into the integrated feedback system, while feedback loops from the system act back into the economic and ecological levels. Furthermore, the bidirectional interactions between the three main levels reflect the cross-domain dependencies that characterise real-world mobility transitions. Sustainable mobility outcomes are positioned as a product of this fully integrated, dynamically evolving system.

This perspective aligns with broader sustainability concepts, such as integrated socio-economic-ecological models (Hariram et al., 2023), which emphasise the interplay between economic and behavioural dimensions. Research in sustainable transport also shows that efficiency gains depend not only on resource allocation but also on behavioural responses to policy interventions. In this integrated system, the role of policy is fundamentally reinterpreted. Instead of merely acting as an external regulator, policy can be understood as shaping decision-making environments. Effective interventions should consider the objective cost structure, as well as the cognitive conditions for decision-making – including the transparency of cost information, the stability of regulatory frameworks, and the availability of technological options.

6. Policy implications for cognitive sustainability

The findings of this study suggest that future mobility policies must move beyond traditional economic optimisation and explicitly incorporate cognitive dimensions into their design. First, policy measures should consider cost structures not merely as financial parameters, but as communication tools that shape users' perceptions and evaluations of mobility alternatives. Second, the effectiveness of incentives depends on their stability and transparency: an unpredictable political environment undermines trust and delays behavioural change. Third, the benefits of sustainability must be translated into cognitively accessible formats, particularly by emphasising time-dependent emission trajectories instead of static comparisons. Fourth, integrating decision-support mechanisms, such as TCO-based labelling, real-time cost visualisation, and scenario-based communication, can significantly improve alignment between objective system performance and perceived outcomes. Fifth, infrastructure development should be understood not only as a physical investment, but also as a cognitive signal that reinforces technological feasibility and reduces perceived risk. Sixth, policy interventions should account for behavioural biases to ensure that short-term cost disadvantages do not overshadow long-term system benefits. Ultimately, cognitive sustainability requires a paradigm shift in political thinking: from influencing markets to shaping the decision-making environment. The success of the mobility transition depends not only on the effectiveness of system optimisation but also on how well users understand these systems, trust them, and act accordingly.

7. Conclusions

The sustainability transition of mobility systems cannot be reduced to a purely economic or technological optimisation problem, as its dynamics ultimately take place in the cognitive space of decision-making. This study has shown that cost structures, policy interventions, and emissions trajectories interact through perception-based processes in which the interpretation of information is just as crucial as the information itself. The reinterpretation of total cost of ownership as a cognitive-economic interface highlights that the effectiveness of economic signals depends on their perceived relevance and not solely on their calculated value. At the same time, the time-dependent nature of emissions dynamics reveals a persistent discrepancy between actual and perceived sustainability performance, which can slow down otherwise positive transitions.

In this context, policy must move beyond mere cost correction and create a decision-making environment in which economic, ecological, and cognitive dimensions are aligned. Consequently, sustainable mobility does not simply arise from optimal systems, but from how these systems are understood, valued, and used by users. Future research should focus on empirically validating the feedback-oriented model proposed here and on developing cognitive decision-making tools that bridge the gap between sustainability goals at the system level and decision-making processes at the individual level.

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