# The rebound effect through industrial ecology's eyes : the case of transport eco-innovation

Font Vivanco, D.

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**Author**: Font Vivanco, David
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# Summary

Transport innovation has been and continues to be a vital engine of social progress and a key tool to mitigate pervading environmental issues such as climate change and air pollution. Expectations on environmental superiority have led to the coinage of the eco-innovation concept, which is commonly used in the design of environmental policy. Claims of eco-innovation in transport and other sectors are often supported by a variety of environmental assessment tools. Among these, approaches based on the principles of industrial ecology enjoy widespread popularity among scholars and policymakers, particularly those based on life cycle assessment (LCA). LCA offers a technology explicit and flexible analytical framework to study the environmental consequences from products, including trade-offs between supply chains and environmental pressures thanks to the life cycle perspective and the use of multiple indicators. However, the use of LCA to support policy has been at the spotlight in recent years for ignoring causal effects related to economic mechanisms and behavioural responses, which can have a notable impact in comparative assessments. Among these causal effects, the study of rebound effects enjoys widespread popularity due to the general agreement on their high capacity to detrimentally alter environmental outcomes.

The origin of the so-called rebound effect can be traced back to the seminal works of the English economist William Stanley Jevons, who argued that resource efficiency gains actually lead to increased overall resource use rather than a decrease as conventional wisdom would suggest. Jevon's theories, later on branded as the "Jevon's Paradox", regained attention by energy economists in response to various environmental crises: first during the 1970s with an energy crisis that ravaged major industrial economies with shortages and rising prices of oil and later during the 1990s in the context of the climate change debate. The bulk of the energy economics literature defined the rebound effect as the increase in the supply of energy services as a result of improvements in technological efficiency causing a decrease in the effective price of energy services. This definition, however, was considered too narrow by various other disciplines interested by the potential of the rebound effect concept to increase the realism of assessments of the environmental benefits of implementation of new products and technologies. Among the alternative disciplinary understandings, those from industrial ecology and other sustainability sciences have remained largely unnoticed, leading mainstream scholars to neglect their potential value.

Industrial ecologists found the original energy rebound effect framework insufficient to describe all the effects that were of interest. For instance, what happens when the technical change does not target decreases in energy use but in other environmental pressures such as air emissions and/ or waste? Have prices full explanatory power over consumption and production decisions? Can

broader definitions of efficiency, beyond changes in the ratio between inputs and outputs, be used in the context of rebound effects? The traditional energy rebound effect framework could not accommodate these concerns, and multiple novel insights unfolded, leading to a sparse collection of theories and definitions. Among these insights, some scholars coined the term "environmental rebound effects", mainly to refer to rebound effects dealing with multiple environmental pressures (resources, emissions and waste) instead of energy use alone. However, the design of an adequate theoretical framework consistent with conventional rebound theories and the full extent of research possibilities that this novel concept can unfold are currently far from being fully explored.

The aim of this dissertation is to investigate the role of rebound effects in shaping the environmental performance of transport eco-innovation, and to investigate the value of applying concepts and methods from the realm of industrial ecology and other sustainability sciences. To fulfil this aim, the following research questions are addressed:

**Q1**. Is life cycle assessment a good basis for the macro-level environmental assessment of transport eco-innovation?

**Q2**. Does transport eco-innovation effectively deliver environmental benefits when taking into account rebound effects?

**Q3**. Are concepts and methods from the industrial ecology domain valuable to study rebound effects?

**Q4**. What policies are available to mitigate the unwanted consequences of rebound effects? Which policies are the most effective?

**Chapter 2** explores the limitations of product-level LCA with a case study on diesel passenger cars in Europe. In this case study, the relevance of the rebound effect is tested by assessing the combined effect on both technology and demand once assumed that a rebound effect will take place from the increased fuel efficiency of diesel engines. The results describe a notable impact of the rebound effect on the original LCA results. Concretely, the rebound effect would have completely offset the environmental savings from historical technological improvements in diesel engines, leading to an overall increase in $CO_2$ emissions. The discrepancies between the original LCA results, which favoured diesel cars with respect to their gasoline counterparts, and those considering the rebound effect cast a critical light on the application of technology-oriented approaches for informing environmental policy. Such approaches are deemed valuable yet insufficient. Another outcome of this chapter is the realization that the rebound effect is treated differently within industrial ecology, with scattered and sometimes inconsistent definitions.

In **Chapter 3**, we gain further insights into how has the rebound effect been treated within industrial ecology by carrying out a comprehensive literature review. Specifically, this chapter examines the theoretical and methodological implications of the inclusion of rebound effects in environmental assessments, and the value of applying concepts and methods from the industrial ecology domain to study rebound effects. Further insights are gained regarding the 'environmental rebound effect' concept, which some scholars used to overcome various limitations of the classical energy rebound effect definition. Among these limitations stand out the study of multiple environmental pressures beyond energy use and related emissions. Three main strengths are identified: (1) the use of multidimensional, life cycle environmental indicators, (2) the improvement of the technology explicitness of rebound assessments and (3) the broadening of the consumption and production factors leading to rebound effects. Moreover, a number of definitional and conceptual inconsistencies are found, which calls for common guidelines. This in turn helps to understand why this emerging perspective has remained largely unnoticed by the specialized literature.

The operationalization and value of concepts and methods from industrial ecology are tested in various case studies presented in **Chapters 4**, **5** and **6**. These case studies investigate the role of price-based microeconomic environmental rebound effects in the context of transport eco-innovation. A total of ten past transport innovations that diffused though Europe have been used as a case study. **Chapter 4** provides results for plug-in hybrid electric (PHE), full-battery electric (FBE) and hydrogen fuel cell (HFC) cars, and **Chapter 6** expands on the latter two. **Chapter 5** yields estimates for diesel cars, bicycle sharing systems (BSS), car sharing schemes (CSS), catalytic converters in passenger cars, direct fuel injection (DFI) systems in passenger cars, high speed rail (HSR) systems and park-and-ride (P+R) schemes. While all the studied innovations present an overall improved environmental performance with respect to their alternatives according to LCA results, the inclusion of price rebound effects notably influences such relative performance overall. The results show a wide range of rebound estimates. Considering the overall trends from the various environmental indicators used, three out of the ten studied innovations describe a negative rebound effect or an overall improvement of environmental pressures (P+R, FBE and HFC cars), three (catalytic converters, PHE cars and DFI) describe the classical example of a partial offsetting of environmental savings and, most importantly, four (BSS, CSS, HSR and diesel cars) describe a backfire effect, that is, cases in which the rebound effect completely offsets environmental savings.

While studies using classical definitions for the rebound effect rarely find backfire effects, **Chapters 4**, **5** and **6** discuss why such effects could be more common than previously thought for environmental pressures. Three main differences arising from applying the environmental rebound effect perspective can be observed. First, applying a life cycle perspective can decrease the expected environmental savings by taking into account trade-offs occurring during the production and end-of-life stages. When the environmental savings are moderate, these can be more easily offset by additional environmental pressures from extra demand. Second, changes in the total cost of ownership (TCO) can be amplified by including capital costs, which is consistent with using a life cycle perspective. Third, when the environmental profile of the innovation under investigation is very different from that in other sectors, rebound effects from a reallocation of expenditures can be very high. This phenomenon takes place particularly when other environmental indicators other than energy are studied, as the energy use per economic input is more uniform across economic sectors than other environmental indicators. On top of that, such conditions are thought to be more likely as the technology detail is increased to the level of products and technologies rather than heterogeneous economic sectors, as is done in a large share of the literature. This is because products and technologies can present notably different environmental and economic profiles than the sectorial mix.

**Chapters 4** and **6** also touch upon the issue of bias in estimating rebound effects, which is key to control for highly sensible variables. The results of **Chapter 4** show that, in line with the literature, the household demand model used and the income groups considered can notably underestimate or overestimate the rebound effect size. The results also show that models often used in the field of industrial ecology, such as the use of proportional expenditure patterns and approaches using marginal shifts between income groups offer a less scientifically sound approach than those traditionally applied within economics, for instance econometric estimates such as expenditure and cross-price elasticities. This leads to suggest that further efforts should be dedicated to improve the knowledge transfer from the economics literature dealing with rebound effects to industrial ecology and related sustainability sciences. In addition, **Chapter 6** describes a high influence of methodological choices in environmental modelling, concretely the environmental assessment models and the environmental input-output databases used. Such choices would have a biasing effect comparable to that introduced by methodological choices to determine changes in demand. This represents a novel addition to the rebound effect literature, which has traditionally focused on the latter.

**Chapter 3** hinted at the existence of a distinct disciplinary understanding of the rebound effect within industrial ecology, which some scholars have labelled as the 'environmental rebound effect' (ERE) perspective. Expanding on this, **Chapter 7** investigates the foundations of this emerging perspective and its value in the context of environmental and broader sustainability assessments. The findings evidence that this perspective has evolved thanks to both assimilated and novel insights. In addition to the insights described in **Chapter 3**, it is found that an additional major difference refers to how the efficiency changes leading to rebound effects are understood. Specifically, that improvements in the technical efficiency relate to both changes in the ratio between fixed technical inputs and outputs – 'process efficiency' (as in classical definitions) as well as changes in the resources, emissions and waste generated to provide a given function– 'enviromental efficiency'. These differences together represent a valuable evolution from classical approaches from neoclassical energy economics to study rebound effects, and can potentially lead to more comprehensive and meaningful knowledge for tackling key environmental issues such as climate change and resource depletion. But perhaps most importantly, the ERE can help to find common ground between the existing rebound perspectives, as its application shows that it is both possible and valuable to articulate broader definitions for the rebound effect in a consistent way and in the context of environmental assessments. Thus, the broader scope of the ERE helps to understand the rebound effect as a set of core economic mechanisms that various disciplines have applied differently to address particular research questions. While the risk of excessive broadening is brought forward, **Chapter 7** also provides guidelines that strike a conceptually informed and practical balance between breadth and analytic specificity.

While this thesis focuses mostly on theoretical aspects and empirical application of the rebound effect, its recognized importance for policy is acknowledged and addressed in **Chapter 8**. This chapter explores and discusses options to deal with rebound effects, focusing on which could





be more effective for attaining effective environmental gains. A total of thirteen specific policy options are mapped, and the advantages and disadvantages of each are discussed. While there is scarce evidence to confirm their effectiveness for rebound mitigation, economic instruments such as carbon taxes and cap-and-trade schemes stand out in terms of rebound mitigation potential. This is because these instruments are able to tackle three general rebound mitigation strategies simultaneously: efficiency – consuming better–, structure – consuming differently– and demand – consuming less–, which have been argued to be needed in combination to tackle the exceptional environmental challenges we face. However, the effectiveness of rebound mitigation policies largely relies on adequate policy design and policy mix in order to avoid, inter alia, additional rebound effects, welfare losses and environmental trade-offs.

By way of summary, the knowledge base gained in **Chapters 2** to **8** help to answer the research questions presented above:

**Q1**. LCA offers a valuable approach to assess the environmental impacts of transport eco-innovation, especially due to the capacity to identify trade-offs within supply chains and environmental pressures. LCA is, however, insufficient to support claims of eco-innovation at the macro-level and policy in general, as economic and behavioural responses to technical change are overlooked.

**Q2**. Transport eco-innovation does not always live up to the expectations of environmental improvement when taking into account rebound effects. These cases, the so-called backfire effects, can be more common than previously thought when applying of concepts and methods from industrial ecology.

**Q3**. The application of concepts and methods from industrial ecology to study rebound effects offer more comprehensive results and broader applicability with respect to the original approaches from energy economics. Such contribution can be considered highly valuable in the context of environmental assessment, for instance by making possible to assess specific products and technologies and to identify trade-offs between supply chains and environmental pressures.

**Q4**. There are multiple policy options available to mitigate undesired rebound effects, among which economic instruments stand out due to their proven effectiveness and the capacity to tackle multiple environmental conservation strategies simultaneously. Their assessment from an industrial ecology perspective brings forward various relevant considerations, such as additional rebound effects and trade-offs between economic sectors, regions and environmental pressures.

Overall, this thesis provides novel insights to study and deal with the rebound effect in the context of increasingly complex sustainability challenges. A remarkable finding is the value of applying concepts and methods from the industrial ecology realm, which can be converged into the so-called environmental rebound effect perspective. This perspective has proven to be valuable through empirical application as well as in the design of rebound mitigation actions. Perhaps one of the most relevant findings is the fact that this perspective yields a greater diversity of rebound effect sizes than generally thought, including more occurrences of backfire effects, with the implications for environmental conservation strategies. Its full potential is however unexplored, and future research will reveal whether this perspective gains ground in rebound effect studies. A promising venue of research is its integration with macroeconomic rebound effect models, in order to increase their technology detail and environmental completeness. It is my intuition that further research in the field will show even greater diversity of sizes and influencing variables. In this context, both extremes of the rebound effect debate – either systematically downplaying or overplaying its importance– will progressively lose credibility, giving way to more informed and ad hoc solutions to the rebound effect issue.