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Article

Can Rebound Effects Explain Why Sustainable Mobility Has Not Been Achieved?

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Abstract: Since the report “Our Common Future” launched sustainable development as a primary goal for society in 1987, both scientific and political discussions about the term’s definition and how to achieve sustainable development have ensued. The manifold negative environmental impacts of transportation are an important contributor to the so-far non-sustainable development in financially rich areas of the world. Thus, achieving sustainable mobility is crucial to achieving the wider challenge of sustainable development. In this article, we limit our sustainability focus to that of energy use and greenhouse gas (GHG) emissions. We discuss whether rebound effects can reveal why sustainable mobility has not been reached. Rebound effects refer to behavioral or other systemic responses after the implementation of new technologies or other measures to reduce energy consumption. Three main strategies exist for achieving sustainable mobility: efficiency, substitution, and volume reduction. (1) The efficiency strategy is based on the idea that environmental problems caused by transport can be improved by developing new and more efficient technologies to replace old, inefficient, and polluting materials and methods; (2) The second strategy—substitution—argues for a change to less polluting means of transport; (3) The volume reduction strategy argue that efficiency and substitution are not sufficient, we must fundamentally change behavior and consumption patterns; people must travel less, and freight volumes must decrease. We found rebound effects associated with all three of the main strategies that will lead to offsetting expected savings in energy use and GHG emissions in the transport sector.

Keywords: rebound effect; sustainable mobility; interdisciplinarity; environmental discourse

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1. Introduction

Worldwide, the transport sector produced 7.0 $GtCO_2eq$ of direct greenhouse gas (GHG) emissions, which corresponds to approximately 23% of the total energy-related CO_2 emissions. Despite the introduction of more efficient vehicles and the adoption of new policies, continued growth in passenger and freight activity outweighed the results of all mitigation measures in the sense that emissions (and energy use) has continued to grow. From 1970 to 2010, the direct energy use associated with transport has grown by 250% worldwide—a growth rate that is higher than any other sector [1]. Regionally, such as in the EU, the transport sector was responsible for 25% of the energy-related GHG emissions. Although the recently adopted EU target is to reduce GHG emissions levels by 80%–95% from 1990 levels by 2050, the European Commission stated that the goal for the transport sector is 60% because of its complexity [2]. How to achieve a major reduction in energy use and in GHG emissions has been widely discussed within the political and scientific discourse about sustainable mobility [3–5]. Three main strategies for achieving sustainable mobility have been identified: (1) The efficiency strategy; introduce new technological solutions, such as more energy-efficient engines, lighter vehicle materials, catalytic devices for cleaning exhaust, and alternative fuels; (2) The substitution strategy; replace current transport means and systems; (3) The volume reduction strategy; reduce the transport volume. While the two first strategies seem to have gained wide policy acceptance, the reduction strategy is more controversial. For example, the European Commission has clearly stated that curbing mobility is not an option [2].

In the transport sector, we are far from meeting environmental targets [6,7]. One cause for this could be the so-called *rebound effect*—a behavioral change that partly or completely offsets expected savings from technological improvements or other measures that seek to lower energy use or GHG emissions. The rebound effect has gained increasing interest as a research topic in recent years, primarily as it relates to energy use and to a lesser degree to GHG emissions [8]. The rebound effect has also been included in the political and scientific climate discourse; however, the discourse has been mostly limited to mitigation aspects [1].

By far, energy economics and microeconomic theory have dominated the research pertaining to rebound effects. Although there is general agreement that rebound effects exist, opinions vary on their size and causes [9]. In this paper, we study the relationship between sustainable mobility and rebound effects, allowing for explanations of rebound effects other than those found in economic theories to explain why strategies that promote energy efficiency and reduction of GHG emissions may not be effective in the transport sector. For example, we draw upon insights on rebound effects derived from ecological economics, socio-psychological perspectives, socio-technological interaction, and urban planning as well as insights from theories about complex adaptive systems. The main point is to gain a better understanding of the explanations and mechanisms of rebound effects by looking at them from an interdisciplinary viewpoint.

Transport-associated rebound effects are mostly studied in connection to the transport of persons by car and to determine how improved fuel efficiency affects the distance travelled. Comprehensive literature reviews about rebound effects have also summarized studies about transport and rebound effects [9–11]. Recently, an international literature review was conducted that specifically looked at rebound effects of energy efficiency measures in the transport sector [12]. Our approach is novel in that previous articles or literature reviews have not addressed the coupling between rebound effects and sustainable mobility or looked at rebound effects from an interdisciplinary perspective.

2. Sustainable Mobility

2.1. Definition

Despite diverse interpretations of the concept of sustainable development in the research literature, the most frequently cited definition is from the Brundtland report, Our Common Future, published in 1987 by the World Commission on Environment and Development. This definition states that sustainable development is a development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." [13]. It contains within it two key concepts: the concept of 'needs', in particular, the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs [13].

Thus, an element of distributive justice over time and across geographical spaces is involved in the concept of sustainable development. Høyer [3] transferred the concept of sustainable development into the idea of sustainable mobility in the transport sector. According to him, sustainable mobility has the following conditions:

- Transport activities do not threaten long-term ecological sustainability.
- Basic mobility needs are satisfied.
- Inter- and intra-generational mobility equity are promoted.

With regards to the inter- and intra-generational mobility equity, everyone should have access to a specified minimum level of mobility in the present as well as in the future.

In a later publication, Holden *et al.* [7] found that sustainable mobility implied that the maximum threshold value for daily per capita energy consumption for passenger transport was 5.6 kWh and that the minimum threshold value for daily per capita travel distance by motorized transport was 9.2 km.

The scope of our study is to examine how rich countries, such as the U.S as well as in countries and regions in the EU and the Organisation for Economic Co-operation and Development (OECD), can achieve sustainable mobility, taking into account the problems related to rebound effects. Currently, energy use for person transportation in EU is a factor of 3–5 above the maximum threshold defined by Holden *et al.* [7] and dependent of the system boundaries used. In addition to direct energy use, indirect energy use and related GHG emissions could be included into the calculations for the propulsion of vehicles, *i.e.*, the energy required for the construction of infrastructure, for the manufacture of vehicles as well as for the provision of fuel. Rich countries basically use the three approaches or strategies mentioned previously to achieve sustainable mobility: efficiency, substitution, and reduction [4]. In everyday terms, these three strategies can be alternatively characterized as "travel more efficiently", "travel differently", and "travel less", respectively.

The *efficiency* strategy is about developing new and more efficient technologies to replace the old, inefficient, and polluting materials or technologies [14]. Two examples of this strategy are the following: (1) Reduce the carbon intensity of fuels by substituting oil-based products with natural gas, bio-methane or biofuels, electricity, or hydrogen produced from low GHG emission sources [1]; (2) Developing more efficient engines and designs for use in vehicles [4].

The *substitution* strategy is about changing to other, less polluting, or more energy-efficient means of transportation. For passenger transportation, this means switching from cars and planes to buses, trains, and streetcars; for freight transportation, switching from trucks to trains or ships [14]. A modal shift to lower carbon transport systems can occur by increasing investment in public transportation and in walking and cycling infrastructure [1].

The *volume reduction* strategy criticizes the idea that improvements in technology (efficiency) and changes in consumption patterns (substitution) are sufficient for the transport sector to reduce its GHG emissions in the range of 60%–80%. Society must also consume less transportation services. Fundamental changes in patterns of behavior and consumption must take place in order to achieve a goal of less mobility; for example, individuals must avoid taking journeys whenever possible. In addition to individuals traveling less, freight volumes must also decrease [4,14]. Measures aimed specifically at reducing transport volumes are densifying urban landscapes, restructuring freight logistics systems, and using advanced information and communication technologies [1].

2.2. The Challenge with Mitigation of GHG Emissions and Energy Use

The scientific and policy discourse on sustainable mobility frequently states that the three strategies outlined above are independent of each other. However, theories on rebound effects point to possible inherent influences between the three strategies. The discourse also states that each strategy is necessary to achieve sustainable mobility [5,7].

Much of the increase in environmental pressure from the transport sector can be explained by a pronounced increase in the volume of freight and person transport. This increase in volume has, in many cases, outweighed any benefits derived both from an increase in energy efficiency and from a shift toward more environmental modes of transportation [3,4,15]. An aviation study conducted by the Swedish Environmental Protection Agency provides a striking example of this observance. After estimating consumption-related emissions and proposing reduction strategies [16], they concluded that "at present, there appears to be no technical solution that can limit the climate impact of aviation enough to allow for extensive flying." In other words, reducing the volume of long-haul flights is the only truly sustainable option if aviation is to take its equal share of the goal of reducing global GHG emissions in the range of 60%–80% [17].

Many studies have been conducted on the rebound effect related to energy efficiency improvements of passenger cars [9]; however, the findings cannot easily be translated into results for the heavy-duty vehicles (HDV) used in the freight sector. Moving freight is highly complex and quite different from moving people. For example, the cost structure of the two is different. The energy cost of driving is only part of the cost for freight transport; labor and capital cost must also be included [18–20]. In addition, the costs incurred by shippers, carriers, logistic providers, and goods handlers must be considered. From the consumer's perspective, this creates a basic difference between passenger transport and freight transport, as passenger transport is consumed directly whereas freight transport is only a small portion of the cost of the goods consumed. As a consequence, improvements (e.g., in fuel economy) should have a substantially higher impact in the price of the final goods in passenger transport compared to goods in which transport is a small portion of the total cost [19].

The path of technological development for freight transport has also been different. The freight sector has focused on logistical efficiency, whereas the focus in passenger transport has been on the mitigation of GHG emissions through the use of alternative fuels and technological solutions. Both sectors have stressed the need for a modal shift (from private car to public transportation for passenger transport, and from road to railroad and sea for freight transportation) in debates, but this idea has had limited success. On the contrary, both sectors have seen a shift in the opposite direction.

When it comes to the third strategy—reducing mobility—a clear difference between the two can be observed. Reducing passenger transportation has been on the policy agenda and involves implementing specific policy measures that aim to achieve this goal. For the case of freight transportation, however, this strategy has been more or less absent.

Our research questions are the following:

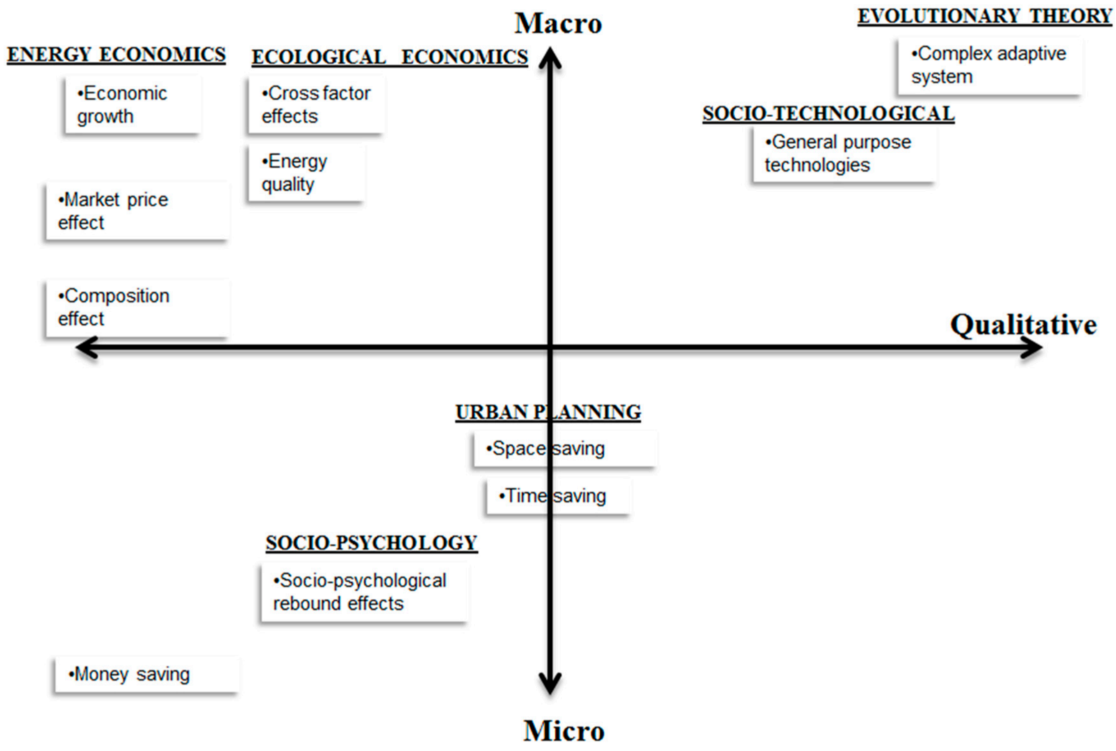
- What is the relationship between sustainable mobility and rebound effects?
- How do different disciplinary positions deal with transport-associated rebound effects and could this hamper strategies for achieving sustainable mobility?

3. Literature Review

In this section, we present an overview of theoretical perspectives that have used different epistemologies, methodologies, and methods for describing and understanding rebound effects. We also study different aspects of the rebound effect so that no perspective, method, or aspect takes priority over any of the others. Our intent is to learn how different theoretical perspectives have contributed to the scientific discourse about rebound effects by looking more closely at their evidence, methods, assumptions, and reasoning [21]. While it could be argued that such an approach could be challenging, we believe that such a discussion will contribute to a more thorough understanding of rebound effects.

Most of the research about rebound effects is within an energy economics paradigm, which is reflected by the large number of papers that have been written in this paradigm over the last 35 years. In recent years, however, research has shifted from energy economics to an interdisciplinary approach that includes several disciplines and methodologies. This interdisciplinary approach is still in its infancy with rather few contributions to the literature. By looking at rebound effects from various disciplines and perspectives, our aim is to provide a new framework of understanding through an integration of knowledge [22]. Figure 1 shows the positions found in the rebound discourse along two axes: research that focuses mainly on the micro or macro dimension falls along the vertical axis, and research that can be described as quantitative or qualitative falls along the horizontal axis. The figure is not intended to fully describe or distinguish between the various disciplinary methodologies since they should be described much more comprehensively and the perspectives vary across dimensions and research strategies. The main point of the figure is to illustrate how the respective perspectives have contributed to the scientific discourse on rebound effects.

Figure 1. The contribution of different perspectives to the scientific discourse on rebound effects.



It should be noted that the schema shows our interpretation of the contributions of various perspectives in the rebound effect discourse and is meant to be a starting point for our in-depth discussion of the perspectives. We argue that there are six different perspectives on rebound effects that understand underlying assumptions, causes and the size of rebound effects differently. These six perspectives are the following:

- Energy economic
- Ecological economic
- Socio-technological
- Urban planning
- Socio-psychological
- Evolutionary

In the following sections, we provide a more comprehensive outline of the positions found in the scientific rebound discourse and present their explanations of rebound effects. To narrow down the energy economics literature, we have selected some key contributions that focus on explaining (and not measuring) rebound effects within the energy economics paradigm. For other perspectives, we cover the relevant literature published in peer-reviewed journals and books. We do not cover all sectors; instead, we highlight how different positions deal with transport-associated rebound effects.

3.1. The Energy Economics Perspective

The rebound effect is defined in energy economics as the difference between the original engineering estimate and the real energy savings after implementing new technologies [9,10]. This definition is based on the economic model of supply and demand. If supply is increased, prices drop and demand rises. In terms of energy economics, rebound effects refer to the energy savings that were initially expected but were lost because of the energy-economy-environment interaction. As a result, this approach can over-estimate the net benefit from energy efficiency improvements. The rebound effect is commonly expressed as a percentage of the expected savings from a specific measure to improve energy efficiency. An overall rebound effect of 100% means that the expected energy savings are entirely offset, leading to a zero net savings [23].

The energy economics literature regarding rebound effects commonly distinguishes between direct, indirect, and economic-wide rebound effects. A direct rebound effect occurs when improvements in energy efficiency increases the use of products and services. For example, consumers who purchase a new and more fuel efficient car might drive more because it becomes cheaper to drive [24]. The money saved can now be used on fuel for trips that were earlier made by foot, bike, or public transportation. Critics argue, however, that this explanation of the direct rebound effect does not account for income growth over the past decade or for saturation effects. In other words, there is a limit to how much of a service can be consumed [25]. In his examination of direct rebound effects, Sorrell [26] distinguished between substitution and income effects. Substitution accounts for how the increase in the demand for an energy service is rooted in an allocation of income to this service. An increase in the energy efficiency of the service causes it to become cheaper.

An indirect rebound effect occurs when the money saved on reduced fuel consumption is spent on other energy-intensive goods and services, such as air conditioners or a second car in a household. Another indirect rebound effect results when energy efficiency technologies (e.g., electrical cars) need considerable energy in the production phase of their life cycle.

The sum of the direct and indirect rebound effects from energy efficiency improvements is termed the economy-wide rebound effect [9].

Jevons paradox, which is often used synonymously with the rebound effect in the literature, implies that energy efficiency improvements may result in higher energy use over the long run even though energy may be saved in the short run. This idea is based on Jevons's argument whereby "*It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption; the very contrary is the truth*" [27]. Herring [28] stated that "the Jevons paradox is an observation based on economic theory and long-term historical studies and that the size of the rebound effect is a matter of considerable dispute: if it is small (*i.e.*, the increase in fuel-consuming activities is less than 100% of the energy efficiency improvement) then energy-efficiency improvements will lead to lower energy consumption; if it is large (*i.e.*, the increase in fuel-consuming activities is greater than 100% of the energy efficiency improvements) then energy consumption will be higher." In Table 1 we have given an overview of rebound effects associated with the energy economics perspective.

Table 1. Overview of rebound effects based on Jenkins, Nordhaus and Shellenberger [11].

Type	Consumers	Producers
Direct	**Income**: A decrease in the price of the energy service will increase its demand.	**Output effect**: Firms may respond by increasing their energy services to expand output.
	Substitution: A prioritization for cheaper energy services over other goods and services.	**Substitution**: A prioritization of the energy services for other inputs of production (e.g., labor).
Indirect	**Embedded energy**: Energy-efficient technologies require energy to manufacture and install.	**Embedded energy**: Energy-efficient technologies require energy to manufacture and install.
	Re-spending effect: Net cost savings increase the demand for goods, services, and factors of production.	**Re-investment effect**: Net cost savings lead to investment in production, which drives the demand for goods, services, and factors of production.
Macroeconomic	**Market price effect**: A widespread decrease in energy demand because of energy efficiency improvements results in lower energy prices that, in turn, spur the use of energy-related services. **Composition effect**: Favor energy-intensive sectors of the economy, where energy makes up a large part of production costs **Economic growth effect**: In energy, productivity (holding all else equal) enhances greater economic output, growth and increases demand. Lower costs for energy services translate into an increase in real income, encouraging greater investment and consumption.	
Economic-wide	Sum of direct, indirect, and macroeconomic effects	

The main method of estimating rebound effects has been "econometric," which uses price elasticity to estimate rebound effects. It is based on the elasticity of demand for useful work with respect to its energy cost or to the price of energy or the elasticity of demand for energy with respect to its price [19]. An alternative method is general equilibrium modeling [29]. Both methods define rebound effects as behavioral changes associated with a lower cost of transport because of improvements in energy and fuel efficiency.

The rebound effect for road transport within an energy economics perspective manifests itself in an increase in the number of vehicles, an increase in fuel consumption through an increased use of other technical innovations (more advanced car equipment such as air conditions and heated mirrors), or an increase in vehicle-kilometers traveled. The vehicle-kilometers traveled is the easiest way to measure this kind of rebound effect. For example, the cost of driving one kilometer is less when vehicles are more energy efficient, so drivers may respond by driving further. The indirect rebound effect is more difficult to measure. In this case, drivers of fuel-efficient cars may respond by using their cost savings for a vacation or for purchasing other goods.

A large variation in the size of the direct rebound effect is found among studies connected to automobile travels. A recent literature review by Jägerbrand *et al.* found a variation from 3%–105% [12]. They concluded that the variation depends on how the rebound effect is defined in particular studies, the country under study, methods, models, on the economic model used, and whether it is measured in the short or long run. In their review of 17 studies, Sorrell [9] and Sorrell *et al.* suggested that the long-run direct rebound effect for personal automobile transport is 10%–30% [9]. They concluded that the relative consensus on estimates, despite wide differences in data and methodologies, indicated that their finding was relatively robust [30]. Moreover, most of these studies assumed that the response to a change in fuel price was equal in size to the response to a change in fuel efficiency. Some suggested that the direct rebound effect for personal automobile travel declined with income [31,32]. It is evident that measurement problems exist for aggregate studies. A geographic bias toward the U.S. is also present. Another literature review presented in the latest Intergovernmental Panel on Climate Change (IPCC) report [1] stated that fuel cost elasticity in North America is in the range of −0.05 to −0.30 and pointed to several studies that showed a decline [31,33]. IPCC also reported that the rebound effect was larger when the marginal cost of driving was a high share of household income and suggested that the effect may be higher in countries with more modal choice options or higher price sensitivities. Other types of rebound effects were apparent, such as a shift to purchasing larger cars concurrent with cheaper fuel or a shift from gasoline to diesel vehicles that lowered driving costs [34].

Research is poor, however, for most countries and regions outside the OECD. Similarly, an effect was found for freight transport systems; shifts to larger HDVs (or other less expensive systems) diverted freight from lower carbon modes, mainly rail, and also induced additional freight movements [35,36].

Freight business operators have a strong incentive to reduce energy intensity; fuel in a German setting was found to account for approximately 33% of the operating costs in the road freight sector, 40% in shipping, and 55% in aviation [37]. However, a large variation among countries and regions could be expected depending on the relative share that transport has compared to other costs. A reduction in transportation costs could create some additional freight movement [18]. A shift in the type of freight transport mode could imply a tradeoff between costs and lower carbon emissions [38]. Many large logistics providers seek to reduce emissions by 20%–45% in the period 2005/2007 to 2020 [39].

Matos and Silva [18] analyzed road freight transportation in Portugal from 1987–2006. They considered the elasticity of freight transportation with respect to its energy cost and estimated the direct rebound effect to be 24.1%. According to the authors, the demand for HDV freight transport was governed by the energy cost of transportation, the economic output (GDP) at constant prices, and the price of oil.

De Borger and Mulalic [20] used time regression to estimate the short-and long-term rebound effect for the trucking industry in Denmark from 1980–2007. The long-term rebound effect (16.8%) was higher than the short-term effect (9.8%) because the firm rearranged their operation to capitalize on their efficiency gain, for example, by investing in more energy-efficient trucks. The use of control variables as well as a method with more interaction could cause the differences between this study and the Portuguese one.

Anson and Turner [29] studied the size of the economic-wide oil rebound effect from energy efficiency improvements within the Scottish commercial transport industry. They used a computable general equilibrium model and found an economic-wide rebound effect of 36.5% in the short run and 38.3% in the long run. The minor difference between the short- and long-term effect is because the latter effect also included the disinvestment effect. The disinvestment effect may occur in domestic energy supply sectors if direct and derived demands for energy are not sufficiently elastic to prevent falling energy prices from leading to a decline in revenue, profitability, and the return on capital in these sectors.

Winebrake, Green, Comer, Corbett and Froman [19] discussed terminology as well as the theory behind the rebound effect, variability in terminologies, general challenges with interpreting and comparing rebound estimates, and research in the passenger vehicle sector. They also discussed the following factors that influence elasticity estimates:

- Commodity type
- Transport region
- Availability of alternative modes
- Interdependent factors

Winebrake, Green, Comer, Corbett and Froman [19] also provided differences between the short- and long-run adjustments to the direct rebound effect for HDVs which we have summarized in Table 2.

Table 2. Long- and short-run adjustments for freight transport, based on Winebrake *et al.* [19].

Short-run adjustments	Long-run adjustments
• Lower per ton-kilometer and per ton-kilometer trucking costs are passed along via lower freight rates; • Less efficient vehicle use; • Less efficient road speeds; • Less efficient routing	• Internalize lower transportation costs and adjust their practices; • Overall market responds to lower shipping costs. Shippers are able to charge less for products, which in turn increases their demand; • Less efficient location of distribution centers

Jägerbrand *et al.* found that rebound effects were not studied for waterborne or rail transport [12]. In the case of air travel, one study estimated the direct rebound effect to be 19% for an air traffic network of 22 airports in the U.S. [40]. The authors set up a model, using ordinary least-squares and two-stage least squares regression, that captured interactions between airline and passenger responses and ensured that the simulation model accounted for demand effects, changes in airline operations, and the impact of airport capacity constraints. They stated that their result could be a first step toward a better understanding of the magnitude of the rebound effect in aviation.

The underlying assumptions for economic reasoning suggests that efficiency improvements can have a price content (*i.e.*, save money) that will incentivize consumers to increase demand. By explaining rebound effects through either income or substitution effects, the research relies on multiple assumptions about human behavior and consumer choice. For the most part, existing publications neglect these assumptions. For instance, economic analysis usually rests on a simple model of rational choice behavior, which assumes that consumers will act rationally, act according to cost-benefit considerations, and generally maximize their personal benefits. These simple models have been criticized from the perspectives of more comprehensive models of human behavior and the utilitarian notion of insatiability of needs [16].

Neoclassical economics draws its epistemology from classical mechanics and addresses consumer preferences, the role of technology, and the conditions for market equilibrium. In a circular flow model, factors of production and goods appear to flow endlessly between firms and households, with no accounting for natural resources, ecosystem services, or waste production. A key assumption of neoclassical production theory is that factors of production are substitutable, scarce, essential, and independent inputs of economic production; the availability of one input is independent of other inputs [30].

3.2. The Ecological Economic Perspective

Research on rebound effects from an ecological economic perspective has been concerned with the role that energy use and energy quality play in economic growth. Energy quality means that different energy sources are measured beyond their heat content and their ability to do useful work. Useful work is defined and measured in different ways, such as in vehicles, passengers, or ton-kilometers. This position has not dealt with specific sectoral rebound effects but rather with the probable size of the economic-wide rebound effect. Cross-factor rebound effects occur when an increase in the productivity of labor or capital increases the demand for energy (for example, if mechanization and automation uses energy or if energy efficiency technology saves time) [41,42].

Generally speaking, neoclassical authors have concluded that improved energy productivity, which could come from energy efficiency improvements, plays a relatively minor role in economic growth, whereas ecological economists have concluded that it plays a dominant role [11,30]. Sorrell [26] claimed that in an "orthodox" economical analysis, rebound effects are small; thus improvements in energy productivity make relatively small contributions to economic growth. Decoupling energy consumption from economic growth is thus considered to be both feasible and cheap. In contrast, an "ecological" perspective suggests that rebound effects are large, and improvements in energy productivity make an important contribution to economic growth. Decoupling is thus both difficult and expensive.

The ecological economics perspective implies that capital, labor, and energy are interdependent inputs and have synergistic effects on economic output. This perspective is based on the understanding that increased availability of high-quality energy sources has provided the necessary conditions for most historical improvements in economic productivity. Ecological economics is inspired by ecological and system theory and views economic production as being wholly sustained by an irreversible, unidirectional flow of energy and materials that travels from the environment, through the economic system, and returns to the environment in the form of waste and low - temperature heat. Ecological economists have repeatedly argued that improvements in energy quality are a crucial but neglected causal variable in explaining economic growth [11,30]. They claim a causal relationship between energy consumption and economic growth: The increase in the availability of energy has driven economic growth in the past, and the reduced availability of high-quality energy may act as a limiting factor in the future. Primary inputs into the economy are energy and materials with a high availability or exergy content (*i.e.*, the ability to perform useful work); the ultimate outputs are waste materials with a low temperature heat or exergy content [30].

3.3. The Socio-Technological Perspective

A key point in the rebound effect debate is not the innovation in itself, but the effect of efficiency improvements associated with general-purpose technologies (GPTs). This effect is also called the frontier effect [11] and the transformation effect [43]. Innovations such as cars, refrigerators, and mobile phones have led to intrinsic changes in societal behavior [9,44]. The opportunities offered by these technologies have such long-term and significant effects on innovation, productivity, and economic growth that economy-wide energy consumption is increased [9]. The rebound effect may be particularly large for GPTs such as steam engines, railroads, automobiles, and computers [9]. A GPT has the potential to change consumer preference, alter social institutions, and rearrange the organization of production [43,45]. For example, increased automotive use can change society in unexpected ways. Buying a car increases both the use of existing roads and the demand for more roads, which can encourage the growth of large supermarkets instead of small local stores. The large, tempting array of goods in the supermarket can spur more consumption. [45]. Also, airplanes have changed the world dramatically when they evolved into large jet-powered commercial aircrafts. This change has spurred an increase in leisure and business travel over long distances [46].

3.4. The Socio-Psychological Perspective

Energy efficiency improvements may change the symbolic value of products and services and can, in turn, alter consumer preferences. For instance, "green" or "climate-friendly" technologies can positively affect consumers' attitudes toward using them, and lead to increased usage. Likewise, efficiency improvements may diminish any social stigmatization of energy-intensive goods, making them appear more socially acceptable to consumers, and thus encourage demand. "Psychological rebound effects" suggest separate effects according to the symbolic and social content of efficiency improvements. Accordingly, psychological rebound effects are defined as an increase in energy service demand because of a change in consumer preferences that can be attributed to an increase in technological energy efficiency [47].

Peters, Sonnberger, Dütschke and Deuschle [47] suggested that combining a psychological perspective with a lifestyle perspective, which included differences in both resource levels and value orientations, allows for a more comprehensive understanding—the so-called socio-psychological understanding—of the rebound effect. The lifestyle perspective originated because a critique of common socio-demographic variables indicated that these variables had lost their explanatory power in modern society; education, income, and profession are not sufficient behavioral indicators. The focus of this approach shifted away from an unequal distribution of resources and toward how the resources were used, which depended on individual values, attitudes, and preferences. They suggested that rebound effects and consumption patterns are determined not only by income level but also by the values and attitudes of individuals and their peer groups. Behavioral changes after an energy efficiency improvement could differ amongst various lifestyle groups. The authors also pointed to the interdependency between structural and socio-psychological dimensions; for example, the educational level of a lifestyle group could influence its problem awareness.

Soland [48] found that faith could justify a person's denial of responsibility for environmental problems caused by technological solutions and mentioned a series of psychological barriers in this context. He also pointed to the dissonance between the unwillingness to change current lifestyles and the awareness that climate change is a threat that needs to be addressed. People create socio-psychological denial mechanisms to overcome this dissonance and believe that responsibility should lie in the hands of policy makers and technology.

Soland [48] integrated de Haan's concept of moral cost and mental accounting of environmental load [49] with the moral balance model of Nisan and Kurtines [50] to explain the socio-psychological mechanism of mental rebound. In de Haan's model, energy efficiency technology leads to a reduction in the mental environmental budget, which allows households to consume equivalent environmental loads. The moral balance model postulates that individuals keep track of their actions—their good deeds and bad deeds—to maintain their moral self-regard and keep their moral self in balance [50]. Compensating good deeds with morally problematic behavior is called moral licensing and can be defined as "people's perception that they are permitted to take an action or express a thought without fear of discrediting themselves" [51]. Furthermore, Kouchaki [52] introduced "vicarious moral licensing," in which morally problematic behavior was excused if in-group members had behaved morally in the past.

Santarius [53] employed a slightly different definition in his description of a moral hazard. A moral hazard occurs when an efficiency improvement causes an environmentally harmful product to be considered environmentally benign; consumers use more because the product is no longer considered harmful. This type of rebound effect is connected to the symbolic meaning of energy-efficient technologies, where the idea that the energy efficiency improvement of a product equals environmental benign that boosts demand of a product. Santarius also described the moral leaking effect in which the purchase of more energy-efficient products eased people's conscience and moral licensing (an indirect rebound effect) in which the purchase of an environmentally benign product results in demand for other damaging products.

A study by Borgstedt *et al.* [54] found differences in environmental awareness across milieus. For example, buying green energy was widely attributed to a "socio-ecological" milieu but this environmentally friendly practice was counterweighted by a preference for long-distance flights. "Traditional" milieu did not buy green energy but had a more positive "eco-balance" than the socio-ecological because of their financial restrictions and anti-consumerist values.

Use of electricity as a solution for the reduction of GHG-emissions and local pollutions in transportation are widely discussed. However a number of rebound effects regarding e-mobility are possible: (1) e-mobility complements rather than replaces internal combustion engine mobility; (2) relative cost savings in the purchase and use of electrical vehicles results in increased mobility, (3) absolute cost savings in the purchase and use of electrical vehicles results in increased consumption of energy-consuming goods or services, (4) energy efficiency improvements can make it less troublesome to use something previously considered environmentally harmful (the moral hazard effect), and (5) use of an energy-efficient product justifies consumption of other energy-wasting products or strengthens other actions and attitudes (the moral licensing effect). Additionally, positive rebound effects can occur when environmentally friendly practices (like e-mobility) raise concern for environmental protection and encourage other such practices [41].

Ohta and Fujii [55] conducted an empirical survey in Japan of people who purchased "environmentally friendly" vehicles (e.g., a Toyota Prius with a hybrid engine). They found that drivers of these vehicles drove 1.6 times farther per year than with their previous vehicle [55]. In another study, de Haan *et al.* [56] investigated whether people would upgrade small or already fuel-efficient cars to hybrid vehicles and if households would tend to increase the number of vehicles owned when purchasing a hybrid vehicle. They concluded that, on average, owners of small or already fuel-efficient cars did not switch to new hybrid vehicles but that hybrid-vehicle buyers were twice as likely as buyers of normal cars to increase the number of cars in their household. On the other hand, normal car buyers were twice as likely as hybrid buyers to be first-time car buyers—possibly because the long waiting times for hybrid vehicles could have caused a pre-selection of buyers from multi-car households.

Underlying assumptions within this research field typically builds on models from social and behavioral psychology, such as the theory of planned behavior (TPB) [57] and the Norm Activation Model (NAM). These models assume that behavior is first and foremost driven by conscious thought. However, practice theories [58] and theories of affect [59,60] from sociology, human geography, and other fields have shown that conscious thought is but one of many factors involved in behavior; semi-conscious factors, embodied capacities, and tacit know-how are often at least as important. The sidelining of these processes in the transport literature may be one factor explaining value-action gaps, which is also not addressed in most psychology-informed studies about changes in travel behavior. These gaps refer to the difference between stated values and intentions and actual behavior [61,62] and constitute significant challenges to models such as TPB and NAM.

3.5. The Urban Planning Perspective

The spatial structure of cities can influence the GHG emissions of its inhabitants in several ways. Dense and concentrated cities require less motorized transport and depend to a lesser extent on private cars than do low-density, sprawling cities [63]. Building types associated with high density cities (apartment buildings) require, other things being equal, less energy for space heating and cooling than low-density building types (single-family homes) [4,64]. Improving public transport, cycling infrastructure, and conditions for pedestrians contribute to reducing the number of car travelers, whereas increasing road capacity to make car traffic flow more easily contributes in the opposite direction [65]. Moreover, although considerable attention (and funding in many cities) has been directed toward improving public transportation, most cities have at the same time increased their road capacity to make provision for expected growth in car traffic. The predicted congestion reduction benefits of increased road capacity are reduced, however, by generated traffic [66,67]. This induced travel can increase congestion, parking costs, crashes, pollution, and other environmental impacts. Similarly, increased road capacity often leads to more car-oriented land-use patterns and more car-dependent transport systems, resulting in additional increases in vehicle travel and reduced transportation choices over the long term [68].

In a case study of a proposed roadway expansion project in Copenhagen, Denmark, Næss *et al.* [69] found that cost-benefit results were significantly affected if a portion of the induced traffic effects was ignored. If the induced traffic was partly accounted for, then lower travel-time savings, more adverse environmental impacts, and a considerably lower benefit-cost ratio was obtained. They concluded that "by exaggerating the economic benefits of road capacity increase and underestimating its negative effects, omission of induced traffic can result in over allocation of public money on road construction and correspondingly less focus on other ways of dealing with congestion and environmental problems in urban areas" [69].

The same consequence can ensue when traffic management systems, based on information and communication technology (ICT), are used to reduce traffic jams. Hilty, *et al.* [70] found strong rebound effects "whenever ICT applications lead to time or cost savings for transport." In this case, fluidifying traffic could provide incentives for non-drivers to start using a car because it would be less time consuming and tiring to do so.

Although data is scarce, a reversion to cycling and walking appears to be happening in some cities, mostly in OECD countries [71,72]. Policies, based on urban design principles, that increase modal shares of walking and cycling in Copenhagen, Melbourne, and Bogata have been deliberately implemented [73]. However, dense, compact cities that reduce the amount of travel, car dependency, and energy use for transport could lead to compensatory travel on weekends and in the summer. Compensatory travel can be understood as a surplus phenomenon [74]. The time and money that is saved by traveling shorter distances to daily and weekly "bounded" destinations results in an accumulated "surplus" of time and money and provides opportunities for longer leisure trips, including an increased amount of air travel to farther destinations.

Compensatory travel could also be explained as an escape [4]. People who are dissatisfied with their dwelling and its surroundings will want to spend a large proportion of their leisure time elsewhere. In addition, residents of dense urban areas who prefer a more natural environment must compensate for the lack of nature in their residential environments and are "forced," so to speak, to make leisure trips. Næss [63] conducted a survey in Copenhagen and found that when socioeconomic and attitudinal variables were taken into account, the frequency of flights was higher among respondents living close to the Copenhagen city center. However, there was hardly any correlation between the high frequency of flights and short travel distance or travel time within the metropolitan area. A possible explanation of the higher frequency of flights among inner-city respondents was that the "urban" and cosmopolitan lifestyle that was prevalent, in particular, among young students and academics contributed both to an increased propensity of flights and to a preference for inner-city living [75].

3.6. The Evolutionary Perspective

Giampietro and Mayumi [76] addressed the following three conceptual problems associated with the Jevons paradox: (1) How to define and measure energy efficiency when dealing with complex adaptive systems operating on multiple tasks across different hierarchical levels and scales? (2) How to distinguish between changes in the technological coefficient and energy efficiency when the profile of tasks to be performed is changed (e.g., when the same set of tasks as opposed to a different set are performed)? (3) How to separate changes in extensive variables from changes in intensive variables (e.g., population increase *versus* energy efficiency improvements)?

The authors applied an evolutionary perspective to link increases in efficiency and sustainability. According to evolutionary theory, living systems have the ability to change both their structure and function over time, while preserving their individuality. An increase in efficiency (doing things better) makes it possible to allocate a larger fraction of the available resources to adaptability (learning how to do different things).

The authors claimed that when we deal with complex adaptive systems operating across multiple scales, an alternative approach is required to analyze their performance in relation to sustainability. They suggested that evolving metabolic systems organized in nested hierarchies need innovative theoretical frameworks that go beyond the reductionism paradigm to address circular causations (*i.e.*, the chicken-and-egg paradox) and multiple scales and used the concepts of holons and holarchies and intensive and extensive variables to further illustrate their point. The Jevons paradox reflects the natural tension between two contrasting principles (the minimum entropy production and the maximum energy flux) that drive the evolution of these systems.

According to Giampietro and Mayumi [76], natural patterns of evolution entail contrasting goals with different objectives, which can only be understood by using different hierarchical levels and scales. They reported that contrasting goals can appear paradoxical because conventional scientific analytical tools are limited in their ability to perceive and represent evolution. Furthermore, they gave a profound critique of using measurements like the EEI (economic energy intensity), which is a ratio between the energy consumed by the economy and the GDP produced by the economy. These measurements could provide a false impression that technological processes decrease the dependence of modern economics on energy. They further stated their point by citing Daly [77]: "Optimal allocation of a given scale of resources within the economy is one thing (a microeconomic problem). Optimal scale of the whole economy relative to the ecosystem is an entirely different thing (a macroeconomic problem)." They argued that extensive variables should be used to deal with sustainability issues such as total energy consumption and population.

They questioned that dematerialization has taken place in developed economics and found a similarity between the two variables "intensity of metabolism" and "size" when comparing socioeconomic and biological systems. They found that the Jevons paradox was true not only for energy but also with regard to resources in general. Technological improvements in efficiency of a process represent improvements in intensive variables, defined as "improvement" per unit of something and under the ceteris paribus hypothesis that everything else remains the same. They claimed that efficiency improvements would not modify the existing portfolio of behaviors. The introduction of technological improvements into a social system generates room for the current level of activity within the original option space and the option space itself to expand.

Ruzzenenti and Basosi [78] studied rebound effects in the road freight transport system from the perspective of evolution and thermodynamics. In the aftermath of the first oil crisis in 1973, technological enhancements of engines, improved aerodynamics, institution of size and speed limits, and market deregulation came to the freight transport system. Initially, these changes were intended to reduce fuel consumption, but they also led to improved vehicle performance. Between 1970–1995, freight ton-kilometer by long haul trucking increased by 130%, while the freight transport sector, in general, grew by 65%—above both GDP and industrial production. Despite the drop in specific fuel consumption of trucks, energy consumption in the freight transport sector increased at a rate unmatched by any other sector. Globalization—through market integration and through a shift from a fordian to a post-fordian mode of production (*i.e.*, from a unique place or plant to a production chain scattered throughout an area, often in different countries)—could explain this phenomenon. Outsourcing, which reduced production costs, specialized activities, and optimized management costs, can be considered a distinctive feature of the post-fordian production model.

In their article, Ruzzenenti and Basosi analyzed European trucks, where technological improvements were initially made to reduce consumption. By the mid-1980s, however, improvements were made to increase power. An efficiency improvement may actually be used for a power enhancement in a time-frame analysis. However, in most cases, devices are made both more powerful and more efficient. Machinery that becomes more efficient by increasing its complexity and cost will also result in a positive feedback to the power output. If energy costs are low and time is scarce, energy efficiency enhancements will be converted into more power. They argued that energy conservation policies should manipulate energy costs or impose time-rate limits (e.g., increase the weight of trucks and decrease their speed).

Increasing weight affects the efficiency process; whereas, decreasing the speed reduces the power output of the process. Thermodynamically speaking, complex systems are more efficient than simple systems but use more energy (e.g., outsourcing and globalization in commercial freight transport). Therefore, reducing the complexity would be a potential solution. There is also a trade-off between efficiency and power; for example, cars could become more efficient, but improvement over time could make them more powerful.

4. Discussion

Rebound effects occur only after a technology has been implemented and are not related to the implementation stage of the technology or to barriers to implementation. The concept is mainly discussed in connection with energy efficiency improvements; but its connection to induced traffic, to resource-use in general, and to green technology and environmentally friendly products is also discussed. The price of energy is not the only factor that explains changes in energy consumption behavior; environmental awareness, habits, and lifestyles are also factors that modify it and lead to the mitigation or, more frequently, amplification of the rebound effect.

It may be worth noting that the literature regarding the rebound effect does not distinguish between policy-driven rebound and "autonomous" rebound [79]. Simple emission standards, with a minimum number of grams of CO_2 per kilometer, lead to more efficient cars, but innovations in production, regardless of the policy, could also lead to more energy-efficient vehicles. What is being debated, regardless of the reason behind the technology improvements, is that the expected effect is not equivalent to an "engineering estimate" because of systemic and behavioral adjustments.

Our literature review suggests that rebound effects are plural because a number of mechanisms are involved. Presently, only direct rebound effects can be precisely quantified; measurements of macro (indirect, economy-wide or society-wide) rebound effects cannot be determined accurately because of their complexity. However, their effects could in many cases be the most important. If we accept the shortcomings of the positivistic research paradigm, then there is room to understand the indirect and society-wide rebound effects from a qualitative and theoretical perspective.

Current forecasts in the transport sector have pointed to energy efficiency gains as being an important part of reducing global energy consumption. Attempts to meet GHG emissions targets by relying exclusively on energy efficiency gains are likely to fall short [11,26]. Rebound effects have been previously associated with energy efficiency measures or the efficiency strategy. This paper has emphasized that they can also be associated with substitution and reduction strategies.

4.1. What Are the Implications of Rebound Effects on Sustainable Mobility?

Table 3 provides a summary of identified rebound effects associated with the transport sector. We find transport-associated rebound effects within five of the six perspectives that were discussed above. The ecological economic perspective has not dealt with specific sectoral rebound effects but rather with the probable size of the economic-wide rebound effect. In addition, the table lists (1) whether the rebound effect is valid for personal or freight transport or both; (2) a description of its cause; (3) whether the rebound effect is direct or indirect; and (4) a categorization of which sustainable mobility strategy the rebound effect could be associated with.

Table 3. Transport-associated rebound effects.

Transport type	Cause	Type	Effect and sustainable mobility strategy
Energy Economics Perspective			
Person	Cheaper cost of driving	Direct	A more fuel-efficient car could provide incentive for more driving and car driving could substitute for cycling and walking. Associated with the efficiency and substitution strategy.
Freight	Lower transportation costs	Indirect	A more fuel-efficient vehicle could lead to less efficient vehicle utilization and routing, higher road speeds, and, in the long run, also influence the location of distribution centers. Associated with the efficiency strategy.
Freight	Lower freight rates	Indirect	A more fuel-efficient vehicle or better logistical utilization could reduce costs for shippers, which will then charge less for transport. Could be associated with the efficiency strategy.
Person/Freight	Re-spending of saved money	Indirect	Could lead to the substitution of other energy-consuming products or services such as long-distance flights.
Person/Freight	Introduction of fuel efficiency standards	Indirect	Could lead to substitution in the wrong direction—from a relatively more environmentally benign transport form (draws freight away from rail).
Person/Freight	Omission in accounting for indirect energy use for transport means	Indirect	Indirect energy use could outstrip some of the gains in the use phase of the vehicle. Energy required for the construction of infrastructure, the manufacture of vehicles, as well as the provision of fuels should be considered. Associated with both the efficiency and substitution strategy.
Urban Planning Perspective			
Person/Freight	Time savings	Indirect	Efficiency measures that aim to save time, such as transport planning and the use of ICT systems for traffic management, could lead to increase transport volume and offset the initial time savings.
Person	Densifying urban landscapes	Indirect	Could lead to compensatory travel. Associated with the reduction strategy since a goal of densification could be to reduce travel distances.
The Evolutionary Perspective			
Freight	Establishment of new structures	Indirect	Globalization of the freight transport system could trigger a more complex system that could lead to an increase in the overall energy use. More efficient logistical systems could be both a cause and an effect.
Person/Freight	Power enhancement of engines	Direct	Producers could respond to energy savings by manufacturing a larger model of the same car.

Table 3. *Cont.*

Transport type	Cause	Type	Effect and sustainable mobility strategy
Socio-Psychological Perspective			
Person/Freight	Not considering the total energy use of the product when buying efficient products	Direct	Could lead to increased use of the product. Mainly associated with the efficiency strategy; could also be associated with the substitution strategy.
Person	Environmentally benign behavior in everyday life	Indirect	Could lead to the indulgence effect (*i.e.*, compensatory behavior while on vacation, such as choosing to travel long distances by air). Everyday behavior could be associated with all three strategies.
Person	Lifestyle changes related to sustainable behavior	Negative direct and indirect	Purchase of an energy-efficient car, increased use of public transportation, and reduction in everyday travels could lead to an alteration in lifestyle.
Socio Technological Perspective			
Person/Freight	Changes in societal behavior by introduction of GPTs	Direct and indirect	Introduction of different transport means such as cars and airplanes has changed society so that economic-wide energy consumption has increased.

A number of empirical studies about fuel efficiency and rebound effects have been undertaken in what we classify as the energy economics position. Some studies looked at the economic-wide rebound effects of the transport sector. However, the main emphasis has been on passenger transport by vehicles, with some contributions on freight transport by road. For rich countries looking at the direct effect from an energy economic perspective, it can be concluded from previous studies that most of the savings are realized because the direct effect for both passenger and freight transport is between 10%–30%.

However, there has not been any discussion about the role that the transport sector itself plays in economic growth or calculations of rebound effects for ships, trains, and airplanes with the one exception described previously. Contributions within the energy-economics perspective belong to a positivistic research tradition, involving quantification and modeling within strict system boundaries. This perspective is embedded in methodological individualism. The sum of all actors' actions constitute the whole—energy savings and the related money and productivity gains at the micro level for households and firms contribute to changes at the macroeconomic level. This perspective also give some important additions connected to understanding indirect and economic-wide rebound effects.

Ecological economics states that energy quality and cross-factor effects between labor, capital, and energy (the role of energy as mediator for economic growth) is much more important than what is assumed by neoclassical models. This also implies that rebound effects are larger than those assumed within a neoclassical understanding of rebound effects [11].

The main emphasis of socio-psychological research is on the micro level and on quantitative measures. However, the introduction of lifestyle and focus-group interviews may cause it to lean more toward the meso level and to qualitative research than the energy economics position. The socio-psychological position is concerned with environmental displacement and people's attitudes, perceptions, and actions. Some displacement problems could be evident in cases of electrical and hybrid cars, as well as in overall environmental budgeting. Long-distance flights are also mentioned, but as a counteraction to environmentally benign behavior in everyday life for "green people." This position gives additional important information as to why rebound effects occur. Theoretically, it is possible that environmental consensus gives lower total emissions; however, this is not exhibited in a study of people having "green" attitudes as a group [47].

GPTs and complex adaptive systems have both been considered with macro or society-wide transformations over a long time period, 50–100 years in some cases. This research used theoretical reasoning that criticized the positivistic research paradigm for being unable to cope with rebound effects [9,76]. All transport modes are mentioned in the GPT literature because they have all been central to the development of modern society; however, most of the discussion has been on passenger cars and how they have transformed society. The main method used has been theoretical argumentation, with some empirical studies over a long time span. Although GPTs are technologies that have transformed society over time, they are expected to have a larger effect in the beginning of technological diffusion and become smaller later on. Complex adaptive systems are concerned with how improvement in efficiency has tended to increase the complexity and energy usage in the system over long time periods. For complex adaptive systems, the evolution of the car and the freight transport system have been used as examples for broader societal changes and to illustrate dualities between the micro and macro level.

Transport-related urban planning emphasized a middle ground between quantitative and qualitative research. A focused case looked at the increase in traffic caused by improvements in road standards, which were intended to lead to less congestion and saved time; however, the increased traffic completely or partially offset the expected savings [66,67]. Urban planning has addressed how infrastructure provision and planning can influence transport growth: The transport system and road capacity as well as people's choices have been the scope of research, where the polycentric city has the potential to lead to reduced everyday travels and the amount of time spent travelling.

We argue that rebound effects are context specific and vary according to the definition of the concept, the methods applied, transport means, the country or region under study, as well as the time period under study. However, it is crucial to have a systemic understanding of the transport sector and its relation to other section in society—in other words, to include indirect effects as well as society-wide effects of mitigation measures in the transport sector. It will be better to promote mitigation measures that aim at transitions, such as reducing transport volume or reducing the use of cars and favoring more walking and cycling through urban planning, to reach the goal of 60%–80% emissions reduction in the transport sector by 2050. Efficiency measures do not change the structure of vehicle mobility; vehicle mobility still needs fuel and infrastructure provision. Improvements in road standards or in vehicles support existing infrastructure and lock in current technologies and transport patterns.

Substitution to other transport forms could be beneficial if you move toward less polluting transport forms; however, changes in life-cycle emissions as well as impact categories must also be accounted for. Reduction strategies, such as densification, aim for a transition in travel behavior (e.g., through urban planning) have been challenged by the compensatory travel hypothesis. It is evident that creating car-dependent cities in order to reduce vacation travel is nonsensical—taxes and regulations that directly directly target the "rebound activities" are much more efficient [80].

Absolute emission reductions are unlikely if growth in transport volumes and infrastructure continues to outweigh efficiency gains [81]. In current "sustainable" green-growth strategies, the significance of rebound effects—that energy consumption will grow as a result of lower prices—has not been considered [53,82]. One key issue is the contribution that energy efficiency improvements (or more generally, increasing inputs of "useful work") make to aggregate productivity and economic growth. This is extremely complex, but the mainstream view that energy plays a relatively unimportant role in economic growth could be incorrect. Furthermore, rebound effects can limit the environmental improvements possible through policies on sustainable products and technologies and, in particular, question the goal of decoupling resource consumption from economic growth [26]. Implementing efficiency into a conventional neoclassical economy with eternal growth as its overriding goal could contribute to growth, thereby offsetting the initial savings.

Efficiency, substitution, and reduction strategies are discussed in terms of their ability to decouple energy use from related emissions and economic growth. It is usual to distinguish between absolute decoupling, in which the transport volumes decrease and GDP increases, and relative decoupling, in which they grow at different rates [83,84]. Several connections are found between economic growth and transport volume. Transport is both a driver for and a result of economic growth where there is a difference between passenger and freight transport. A distinction can be seen between passenger transport and freight transport in relation to economic growth. Passenger transport is more an effect of economic growth while freight transport is a stronger cause for economic growth. It is well-known that higher incomes are associated with higher levels of car ownership and usage [85]. A World Bank study [86] found that that savings from fuel switching, mode shifting, and changes in emission coefficients were eclipsed by an overwhelming growth in the economy and population. Freight transport volumes grow with GDP (no decoupling is seen) and passenger and freight transport volumes increase with economic growth. Rebound effects connected to transport could challenge the decoupling hypothesis.

4.2. Methodological Challenges

The gap that arises between expected and actual energy savings from increased energy efficiency is not merely caused by rebound effects. For example, at the micro level, it could also be influenced by whether the technology works as anticipated (*i.e.*, in terms of the desired efficiency improvement actually being realized). Rebound effects are also difficult to isolate by positivistic research methods because the measurements require extensive recording and specific well-defined boundaries. Fully controlled macro-economic experiments are impossible to carry out, so there are limits to the accuracy of any measurement of the size of rebound effects.

The rebound effect has different impacts at different levels of the economy, from the micro-economic (the consumer) to the macroeconomic (the national economy), and its magnitude at each level of the economy has not yet been determined. Nonetheless, increasing evidence suggests that it is not uncommon for total energy use and GHG emissions to grow in the transport sector even while efficiency improves, suggesting, at the very least, that efficiency improvements are not necessarily sufficient for curtailing energy use and GHG emissions in the transport sector. However, this does not necessarily demonstrate that energy use and related GHG emissions grow because of efficiency improvements [28].

The formal problem confronting all rebound measurements is that it is "impossible to derive an absolute number from a ratio or a change in a ratio; without further factual information, an 'extensive' number cannot be deduced from an 'intensive' one" [76]. When it comes to modelling changes in efficiency, a formal model can handle the quantification of changes only by keeping the same set of attributes, the same set of proxy variables (intensive and extensive), and the functional relationships associated with the formal identity of the modelled system. Therefore, within the given model, the handling of quantitative changes requires only an update of the value taken by the given set of selected variables. Unfortunately, qualitative changes cannot be handled by using the same old formal identity of the system under investigation. If the model of a car evolves into something different, the modeler must add new attributes to obtain a new quantitative characterization of the modelled system [76].

Even if rebound effects could be managed at the micro level, the effect throughout society would be hard to capture. It is questionable that the rebound measured in individual consumer goods during a relatively short time period would be a worthwhile measurement for capturing the size of the rebound effect throughout society. However, a shift from measuring micro-level rebound effects, such as improvements in kilometers per liter, to looking at the productivity of driving should occur. Thus, constraints in the total energy consumption should be promoted along with energy efficiency improvements [24].

4.3. Solving the Rebound Problem?

As long as purchasing power remains the same or increases, energy and resource efficiency improvements that result in saving money is like squeezing the balloon. Avoiding such effects seem impossible unless purchasing power decreases. "In a situation with economic growth, the metaphoric balloon is on top of that pumped up with more and more gas" [87].

Rebound effects can only be avoided if productivity increases (labor or resource productivity) are not turned into more production and consumption and are instead turned into other benefits (such as reduced work time—*i.e.*, more freedom) or by lowering the labor productivity to balance the growing resource productivity [88]. Clearly, a tax increase is one option, but what would be done with the increased revenue to prevent rebound at the government level?

Growth resulting from the more intelligent use of inputs to achieve greater efficiency and sustainability could eventually be cancelled out by increases in production and consumption. In growing economies, savings achieved by eco-efficient technologies can be used for other consumption. In other words, to obtain a sustainable society, growth requires more and more efficiency. We argue, in line with Degrowth supporters, that the real problem is embedded in the current economic system and that improved efficiency will not lead to a major reduction in the use of natural resources, energy use, or GHG emissions. Furthermore, they claim that rebound effects are made possible by the combination of economic growth policies that reject limits on production and consumption. Companies want to mass produce and sell products that are cheap (*i.e.*, light and small, quickly and economically made with lower resource costs), easy to use, fashionable, and appealing. They have no reason to reduce profits by reducing the scale of their business or volume of products; they want to sell more and gain market share [45,88].

5. Conclusions

The final transport volume has been subject to less policy attention; that is, whether applying a strategy of eco-efficiency has actually reduced the environmental pressure in transportation or just moved the pressure to other regions or to related economic activities. In certain circumstances, the efficiency, substitution, and reduction strategies could lead to both an overall increase in transport volume and an increase in both the related energy use and GHG emissions, which may partially or completely offset savings from those strategies.

It is our firm belief that rebound effects will be evident as long as the economy keeps growing and that one reason policy makers hesitate to curb mobility is because of its strong coupling to economic growth.

In this article, we have found it valuable to study rebound effects from the lenses of several disciplines, since rebound mechanisms are better understood and reveled than by than by a monodiciplinary approach. An interdisciplinary approach should also be used in forthcoming empirical research on rebound effects. In addition, more knowledge is needed about the reasons for people's transport patterns and the connections between different transport modes for everyday and leisure travel. The connections between economic growth, transport, and rebound effects also needs to be better researched.

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Author Contributions

Hans Jakob Walnum and Carlo Aall designed the research with valuable inputs from Søren Løkke. Hans Jakob Walnum wrote most of the paper. Carlo Aall wrote additions in the abstract, in the introduction, in the sustainable mobility part, and in the discussion and conclusion part of the paper. Søren Løkke wrote additions in the sustainable mobility part and in the discussion part of the paper. All authors have been involved in participation and arrangements of two Ph.D. seminars held by Aalborg University, which have investigated rebound effects from an interdisciplinary perspective. The seminars have been an essential basis for selection of author's literature and subsequent analysis. These seminars were: (1) Rebound seminar arranged at 31 October 2012 in Aalborg, as part of the Ph.D. course "Advanced LCA—consequential modeling, EIO LCA, iLUC, and rebound effects"; and (2) "Interdisciplinary understanding of macro rebound effects. How can we understand and mitigate them?" held 15 August 2013 in Copenhagen.

Conflicts of Interest

The authors declare no conflict of interest.

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