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Sustainable City Logistics: Rebound Effects from Self-Driving Vehicles

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Purpose: This paper investigates direct and indirect rebound effects caused by the implementation of different types of car driving technologies – electric cars, high-autonomous, and fully-autonomous vehicles in the sustainable city environment.

Methodology: Lifecycle Assessment analysis extended by the social and economic dimensions has been completed for the aforementioned vehicle types in order to identify, categorize, and systemize the possible negative impacts of the investigated car driving technologies within the local (city logistics) and global (world ecosphere) environment.

Findings: Differences between local and global induced negative impacts of the new driving technologies have been identified. The paper compares the most expected/unexpected rebound effects for the three types of vehicles in the local city logistics environment and under the consideration of global impacts.

Originality: The rebound effect is mostly based on energy consumption. In this research, we have identified and analyzed indirect rebound effects from the imminent adoption of self-driving vehicles that are relevant to either city logistics development or the global environmental system.

Keywords: Rebound Effect, Sustainability, Autonomous Vehicles, Life Cycle

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1 Introduction

It is estimated that 5 billion people will live in cities by 2030 (UN, 2018). This has not only a significant impact on the mobility concept's requirements, but also on the sustainable development in cities. It is not without reason that the United Nations is focusing on Sustainable Smart Cities in Sustainable Development Goal 11, i.e. cities in which all people can live together sustainably and have access to basic services, energy, housing and transportation, among other things (UN, 2018). Urbanization, sustainability, connectivity and mobility are among today's megatrends. They pose challenges to society and companies, but also offer solutions, such as the Sustainable City Logistics concept. At the same time, these solutions will only be made possible via the above mentioned developments. An overview of challenging issues of autonomous vehicles in the context of smart cities can be found in Daschkovska, Moeller, and Bogaschewsky (2019).

In science and practice it is discussed to what extent electric cars (e-cars), alternative propulsion systems or the use of autonomous vehicles in mobility concepts have the potential to contribute to climate protection as well as to meet future demands of society. Among other things, comparative Life Cycle Assessments (LCA) were conducted for electric cars, alternative powertrains and internal combustion engines, with the ecological dimension of sustainability at its core. These studies usually put only one phase of the life cycle at the center of their analysis. It thus lacks a holistic approach that takes equal account of all dimensions of sustainability as well as all product life cycle (LC) phases of a car. Furthermore, most of the LCA literature does not consider the environment of AVs and the analysis of induced and rebound effects is too short.

Against this background, we develop the Sustainability Rebound Effect Framework which is based on the theoretical model of Life Cycle Sustainable Assessment (LCSA) and a redefinition of direct and indirect rebound effects - known from energy efficiency analysis - taking into account the three dimensions of sustainability and the life cycle perspective. This framework allows for a holistic analysis as well as comparison of the three auto types: electric, high-autonomous ("hands-off") and fully-autonomous vehicles ("steering wheel optional"). In the four LC phases - raw material extraction, manufacturing, use and end-of-life management - we identify the respective critical sustainability factors that are evaluated with regard to expected rebound effects, negative impacts and drawbacks for the aforementioned car types and categorized according to their rebound type, namely global, local, direct and indirect influence.

The paper is structured as follows. After the introduction, related work in the areas of Rebound Effects and LCA in transport and LCA for Autonomous Vehicles (AVs) is presented. This is followed by definitions of autonomous vehicles, sustainability and LCSA as well as a description of rebound effects from self-driving technology. In chapter 4 we propose our Sustainability Rebound Effect Framework which is applied to the three auto types to identify potential rebounds and drawbacks. The paper ends with a conclusion.

2 Related Work

2.1 Rebound Effect in Transport

In recent years governments in many countries tried to implement sustainable concepts in order to stimulate an effective usage of the planet's resources (UN 2018). In this regard, technological progress allows to improve

and even increase the efficiency of resource and energy usage. However, there are several studies that demonstrate the backside of improving energy-efficiency by technological processes in form of so-called "rebound effects" (Brookes, 1979; Khazzoom 1980). For example, the Khazzoom-Brookes postulate states that for stable energy prices improvements in energy efficiency caused by technological progress can increase the energy consumption. But in fact, even rebound effects that could exceed 30% are very often ignored in energy efficiency and energy sufficiency policies (Sorrell et al., 2018). Based on Greening et al. (2000) rebound effects can be categorized as follows:

1. Direct effects: improvement in energy efficiency can lead to an increase in energy consumption. These effects are mainly divided into substitution effects and income effects.
2. Economy-wide effects: defined as the rebound effect on the overall economy.
3. Transformation effects: technological changes can lead to changes in consumer preferences that might influence the social system and trigger changes in the production systems.
4. Secondary effects: rebound effects observed in various production or service sectors. For example, improvement in energy efficiency reduces the costs of manufacturing and therefore decreases the price of the product, which stimulates consumption. As a result, the energy demand in the production sector will increase as well.

The last two rebound effects from the above mentioned classification are indirect rebound effects, which are usually difficult to evaluate (Wang et al., 2014). Greening's et al. definition of rebound effects in the energy industry

can also be applied in the transport sector. In this example, a higher efficiency of fuel leads to more driving. This is a simple example of the direct rebound effect. Dimitropoulos et al. (2016) have analyzed 76 primary studies which use a meta-regression analysis to measure the direct rebound effect in passenger road transport. It was identified that the rebound effect in these cases can average 20 % and that the long-term direct rebound effect of more fuel-efficient cars can be 32 % (Dimitropoulos et al., 2016). Another study by Sorrell and Stapleton (2018) has contributed to the limited research by estimating long-run direct rebound effects in road freight transport in UK and found that rebound effects are almost two times higher as estimated by Dimitropoulos et al. (2016). The most common problem for many of these studies in estimating rebound effects is the availability of more disaggregated data.

The main finding of Ottelin et al. (2017) is that the average rebound effect from reduced driving is less than from abandoning car ownership, and in some cases it can lead to backfiring. If rebound effects higher than 100 % occur, this is known as the "backfire effect" (Sorrell, 2009). Freire-González (2019) has computed the economy-wide water rebound effect using the example of Spain and found out that an improvement in total water consumption by 50 % leads to a backfire of 100.47 %. The same phenomena can be observed in the transport sector, where, as overall energy efficiency improves, overall energy consumption and pollution increase (Binswanger 2001).

2.2 LCA in Transport

Due to the technological process' increasing speed, increasing urbanization and overall growth in the world population, city logistics today faces

numerous challenges (e.g. congestion, insufficient service and deteriorating, and inadequate infrastructure) as well as an overestimated positive impact of technology improvement versus resource-energy consumption. A promising technology in the transport sector are self-driving vehicles with electric motors. With regard to LCA investigations in the automotive industry, several LCA studies with a focus on electric vehicles or components such as lithium batteries have been published (Egede et al., 2015). Hawkins, Gausen and Strømman (2012) provide a literature overview comparing the content of 51 environmental assessments of hybrid and electric vehicles. Similarly, Nordelöf et al. (2014) review 79 LCA studies that focus on environmental impacts of hybrid, plug-in hybrid and battery electric vehicles. Font Vivanco et al. (2014a) proposed an analytical framework to model the microeconomic environmental rebound effect which is based on hybrid LCA and applied to three types of electric cars where a remarkable impact at the product level is found.

Due to the lack of LCA studies that address the use phase Egede et al. (2015) develop a LCA framework that places Electric Vehicles (EVs) into a larger system of external and internal influencing factors (vehicle, user, infrastructure, and surrounding conditions) to analyze the influence on energy consumption in the use phase. The production phase of LCA is the core of Qiao et al.'s (2017) comparative study on life cycle CO₂ emissions from the production of electric and conventional vehicles (i.e. internal combustion engine vehicles) in China. Further comparative LCAs covering the whole product life cycle were performed by Del Pero, Delogu and Pierini (2018) as well as by Van Mierlo, Massagie and Rangaraju (2017). While the former carry out a case study on internal combustion engines and electric cars, the latter compare the environmental aspects of mainly compressed natural gas and

battery electric vehicles, along with liquid petrol gas, biogas, plug-in hybrid electric vehicles, hybrid electric vehicles and conventional diesel as well as petrol vehicles in the context of the Brussels capital region.

Bobba et al. (2018) assess the environmental impact of electric vehicles' batteries in second-use applications with an adapted LCA with the stages manufacturing, repurposing, reusing and recycling. With a focus on social aspects Traverso et al. (2018) developed a case study to assess the social impacts of a tire throughout its entire life cycle, but excluded the end of life of a tire due to inadequate data. With the growing number of battery-powered electric vehicles the challenges in managing End of Life Vehicles increase as well, such as recycling valuable materials or disposal of the hazardous waste. In order to cope with these challenges in the End of Life Management of electric vehicles Kuşakcı et al. (2019) are addressing reverse logistics networks in their work including recovery of used components, standards-conform regaining and/or disposal of chemicals, and efficient recycling of precious materials. In a conventional vehicle around 50 different metals are used, some of which are critical. Because specific recycling processes are lacking, there is a danger that these metals will be downcycled. Therefore, Ortego et al. (2018) propose the application of a thermodynamic methodology to assess metal sustainability. The aim is to identify the most critical components and, on this basis, make specific ecodesign recommendations from a raw material perspective.

2.3 LCA Methods for Autonomous Vehicles

The authors are currently unaware of any studies that investigate autonomous vehicles using the LCSA method or that systematically consider the three dimensions of sustainability equally in their analysis of AVs. However,

in a recent literature review on autonomous vehicles Faisal et al. (2019) identified 33 articles that study the impact of AVs mainly regarding the aspects perceived value of travel time changes, reduction of traffic accidents, congestion and delay, reduction of Green House Gas (GHG) emissions, public health, car ownership models or urban land use due to changes in parking demand, travel time and travel distance. In summary, Faisal et al. conclude that these are typically economic, environmental, societal, legal, political and governance impacts. With regards to LCSA this would cover the use phase.

Holstein, Dodig-Crnkovic and Pelliccione (2018) discussed ethical and social aspects as well as challenges in the context of autonomous vehicles and software engineering. In addition, Milakis et al. (2017) developed a framework to explore the potential effects of autonomous vehicles (Level 1-5) on policy and society. These aspects and considerations relate to the use phase of autonomous cars. Expected positive and negative environmental effects of shared autonomous vehicles that are discussed in the literature are presented by Pakusch, Stevens and Bossauer (2018). A nearly exclusively positive view on environmental and societal implications of autonomous driving focusing on potentials and advantages is given by Eugensson et al. (2013). Their reasoning takes into account among other things autonomous systems' direct and indirect positive environmental impacts, despite increasing traffic efficiency and in the context of reduced number of traffic accidents as well as personal and societal benefits and cost savings from avoiding crashes.

Unfortunately, many of the Life Cycle Assessment studies and LCA-based tools have ignored the importance of rebound effects. In this paper, we will discover possible rebound effects that occur in the different phases of the

autonomous vehicle life cycle. First, there is still lack of research on rebound effects of self-driving vehicles; second, studies on e-cars or autonomous cars only identify the rebound effect from the perspective of energy consumption and most often for the use-phase of their life cycle. Here we present a new perspective on the rebound effects in the three dimensions of sustainability (economic, ecological and social) taking into account specific factors which each belong to one of the four stages of the life cycle of self-driving cars.

The analysis in this article has an explorative character, based on our own considerations and supported by literature.

3 Autonomous Vehicle Life Cycle

3.1 Self-Driving Vehicles

Autonomous vehicles are currently being very intensively discussed in public, researched by universities and developed in the automotive industry. In the smart mobility concept self-driving vehicles have great potential to contribute to the development of sustainable cities. There are different levels of automation that could be applied. The most promising technology for city concepts are fully autonomous or self-driving vehicles which improve the efficiency of city logistics and ensure a high quality of the travel experience (Hörold et al., 2015; Chamoso et al., 2018). From the automation concept's perspective, there are five levels of automation introduced by the Society of Automotive Engineers International (SAE). This differentiation in automation levels has become the industry standard. At the first and second automation level, the driver has the possibility to influence the operational functionality of the vehicle. At the levels 3 – 5 the vehicle's driving

system can operate fully autonomous, but the level of autonomous control can vary (DoT 2016). The life cycles of new technologies as well as many components of the autonomous vehicles do not differ significantly from those of electric cars. The main phases are the traditional components of automotive LCA: phase 1 - raw material extraction, phase 2 - manufacturing, phase 3 - use and phase 4 - end-of-life.

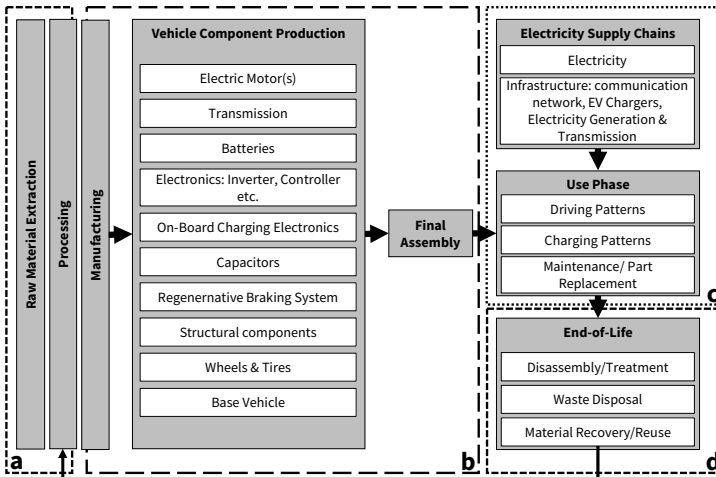


Figure 1: Simplified chart of the life cycle of an electric or autonomous vehicle (a: phase 1, b: phase 2, c: phase 3, d: phase 4) adapted from Hawkins, Gausen and Strømman, 2012, p.999.

Figure 1 shows a simplified flow chart of an LCA for electric and autonomous vehicles. The first and second phase represent raw material extraction and car production with processes in between. Additional processes include material transportation processes, production in processing facilities, distribution, electricity infrastructure, etc. (Hawkins et al., 2012). These

processes are not included in the diagram. In the use phase, the availability of a communication network for autonomous vehicles is as important as the availability of charging stations. Maintenance of autonomous or electric vehicles must also be included in the use phase. In the end-of-life phase of e-cars or autonomous vehicles, the processes of battery-specific recycling or down-cycling of many components of electric-cars are very important in terms of their environmental impacts.

3.2 Sustainability and LCSA

According to the well-known definition in the Brundtland Report, sustainability is the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Building on this relatively vague definition, the concept has evolved into a model with three dimensions of sustainability. This approach is also referred to as the three-pillar model of sustainability or the Triple Bottom Line (TBL), which requires equal consideration of economic, environmental and social aspects of sustainability (Elkington, 1994). Alternatively, the phrase "people, planet and profit" is used to express the operational implementation in companies.

The social dimension includes aspects relating to employees, local communities and customers, such as good and safe working conditions, the opportunity to develop skills and competences, respect for human rights (e.g. prohibition of child labor and forced labor), ensuring product safety, as well as a company's activity in community work and the creation of good community relations, but also compliance with the law and the fair treatment of suppliers. The ecological dimension encompasses land use, the protec-

tion of biodiversity, effects on climate, the efficient use of energy and resources, natural resource use, waste management and recycling as well as pollution prevention, i.e. the minimization of waste and emissions, minimizing use of hazardous substances, and the use of environmentally sound materials and energy. Finally, the economic dimension covers aspects like economic growth, profit generation, job creation, innovation and technology, contribution to the local economy, infrastructure investment, cost savings, paying tax responsible and no bribery or corruption (OECD 2011; van Weele 2014).

A major challenge remains the implementation of sustainability in companies and the measurement of sustainability for products and processes. An established method, at least for the environmental dimension of sustainability, is the approach of Life Cycle Assessment, which is internationally standardized via ISO. LCA is a holistic, system analytic tool that takes into account all environmental impacts (input and output related) as well as all relevant material and energy flows for all phases of the product life cycle (Kloepffer, 2008; Finkbeiner et al., 2010). Building on this, the Life Cycle Sustainability Assessment (LCSA) concept was developed, which refers to the evaluation of the ecological, economic and social impacts of a product throughout its complete life cycle (Finkbeiner et al., 2010; Zamagni, Pesonen and Swarr, 2013). Kloepffer (2008) described the LCSA framework with the formula $LCSA = LCA + LCC + SLCA$, according to which the three Life Cycle Assessments Environmental Life Cycle Assessments (LCA), LCA-type Life Cycle Costing (LCC) and Social or Societal Life Cycle Assessment (SLCA) are combined. An overview of methodologies and approaches to SLCA found in the literature is provided by Jørgensen et al. (2008).

3.3 Rebound Effects from Self-Driving Technology

In the European Roadmap Smart Systems for Automated Driving (2015) rebound effects in the context of automated driving are mentioned only very briefly in the chapter on challenges, but are not further discussed. Nevertheless, rebound effects must not be neglected even though they are difficult to estimate. The comfort of AV (less stressful and tiring) will encourage people to make longer and more frequent trips, as travel time can now be used efficiently. One aspect might be, that people may prefer to live even further in the suburbs (Iglinski and Babiak, 2017), which will lead to an increased energy demand. With an upcoming era of electric or even self-driving cars the consumption of energy will be divided between other production/service industries and the rebound effects will be modified. Many new functions in autonomous vehicles require a higher quality of assistance systems, resulting in higher energy consumption. Indirect rebound effects can be observed in the transport industry. For example when due to cost savings in transportation people save time and money and consequently prefer to use a car more often, traffic in the city will increase (Gossart, 2015). Wadud et al. (2016) also found that even if automation of vehicles can reduce road transport emissions and energy consumption, the negative impacts in this context might appear mostly by fully automated vehicles. Autonomous vehicles also promise to increase the mobility of the senior population as well as for non-drivers and people with a medical condition, leading to a 14% increase in annual vehicle miles traveled only in the USA (Harper et al., 2016). An increase in 2 to 47% in travel demand for an average household in the US due to reduced energy consumption in autonomous and connected vehicles has been discussed by Taiebat, Stolper and Xu (2019).

An overall increase in energy consumption for autonomous vehicles is the main statement of recent research in the field of self-driving cars. In this paper, we propose a reinterpretation of the traditional rebound effect, which is based on energy consumption. In this research we start from the perspective that the autonomous vehicle's main user lives in the city / urban area (use phase in LCA). Anything that happens with a car in the city environment can or cannot impact not only the user himself, but also affect other phases of the auto life cycle processes. In this paper, a city in Germany represents the location of the user. From the perspective of the three-dimensional sustainability in city transport, the rebound effects are classified in this work as follows:

1. Global Sustainability Rebound Effect (GSRE): the global effect will be measured based on the world-wide spreading of rebound effects.
2. Local Sustainability Rebound Effect (LSRE): LSRE can be observed in the local city area, where the potential user has his car in daily operation. The rebound effects in this case are present only for the local city environment.
3. Direct Sustainability Rebound Effect (DSRE): DSRE can be achieved when efficiency in one of the sustainability dimensions leads to increased use of the products or related services. For example in the economic dimension of sustainability the growth of economic stability transforms into the increased use of e-cars or autonomous vehicles. As a consequence the demand for new autos increases. This demand will also increase the production of new cars while increasing the use of these sustainable vehicles in the city area.

4. Indirect Sustainability Rebound Effect (ISRE): the indirect SRE is stimulated by technological changes, which influence user preferences and behavior, which impact the aspects of sustainability and therefore increase the effects / changes on the macro-environmental level. Consider again the example of DSRE. The increased demand for autonomous vehicles led to increased production of these cars. In the case of ISRE, the chain of events will continue: More car manufacturing will require additional volumes of raw materials (increased demand for raw material), which may belong to the group of rare materials. ISRE would be (from the perspective of the car user) the indirect increase in raw material prices.

4 Rebound Effects vs. Sustainability

4.1 Sustainability Rebound Effect Framework

A theoretical framework has been developed for the systematic analysis of possible rebound effects under the three dimensions of sustainability. Table 1 shows a scheme of this framework. The framework includes different life cycle phases of the product development phase: phase 1 to phase n . For each phase, several critical aspects that may be relevant to the identification of a rebound effect are defined by the parameter $f_{i,j}^p$, where

p is the phase of the life cycle, $p = \overline{(1, n)}$;

i is one of the sustainability dimensions, $i = \overline{(1, 3)}$;

j is the index for the numbering of the critical aspect in each phase, $j = \overline{(1, m)}$.

The last column of this framework demonstrates possible rebound effects that are specific for each parameter. There are four different types of rebound effects as well as their combinations that can be identified, e.g. "global, direct", etc.

Table 1: Theoretical Framework for Sustainability Rebound Effects

Item/Product	Critical Factor	Rebound Type
phase 1	$f_{1,1}^1$	local, global, direct, indirect
	$f_{1,2}^1$	
...	$f_{i,j}^1$	
phase p	$f_{1,1}^p$	
...	$f_{i,j}^p$	

In this study, we apply this framework to three types of electric vehicles: e-vehicle, semi-autonomous vehicle and autonomous vehicle. We examine four predefined phases of the vehicle life cycle and identify rebound effects based on the specific dimension of sustainability. For example, in the first phase "raw material extraction" for ecological sustainability, one of the critical parameters under number 2 in Table 1 is "air quality": $f_{1,2}^1$.

By applying the example of sustainability rebound effects in each dimension of the manufacturing life cycle phase, the following Table 2 demonstrates how the framework has been applied in this work.

Table 2: Sustainability Rebound Effects

Critical Factor	Auto	Rebound Type	Rebound Effect
Air Quality	all	Ecological Sustainability Rebound Effect:	Increased use of "green" and "sustainable" electric autos of all types improves air quality; people will recognize the changes in air quality and associate them with driving e-cars, therefore they will buy more of such e-cars in urban area.
		local, direct	
Procurement Costs	all	Economic Sustainability Rebound Effect:	From an economic point of view, the increased use of electric and autonomous cars in the urban area and the increased demand for such car types will lead to higher procurement prices and thus to higher production costs; at the same time the auto producers' budgets may reach
		global, local, indirect	

Critical Factor	Auto	Rebound Type	Rebound Effect
			their limits for other investments or innovation projects.
Working Conditions / Safety at Work	all	Social Sustainability Rebound Effect: global, local, indirect	The social rebound effect in the second phase of the e-car life cycle is indirectly reflected in a deterioration in the health and safety of workers in the factories of auto manufacturers; the effect may be due to increased demand for cars; this can also lead to greater exploitation of workers.

4.2 Ecological Sustainability: Rebound Effects

4.2.1 Raw Material Extraction Life Cycle Phase

The identified ecological rebound effects in the material extraction phase are valid for all three vehicle types and can be classified as global and indirect SREs (see Table 3). Due to by-products of extraction processes, an increase in toxins is expected, which will lead to contamination of land and water. Extraction machines with non-sustainable fuels cause a decrease of air quality and therefore negatively affect the ecosystem. Similarly, an increase in noise pollution by extraction machines might generate long-term damage for the ecosystem. Extraction machines might further increase Green House Gas emissions, which will negatively affect the climate. At the extraction site an increased demand in energy is to be expected, though the environmental impacts will depend on the energy source. Regarding the aspect of water consumption a limited availability of ground water might be caused and might result in poor quality which will destroy the ecosystem of animals and plants. The same applies to the rise in waste water. Because non-renewable resources that are limited in availability are being mined, more damaging extraction methods might be applied and as a rebound endanger the ecosystem. Due to the increasing demand for raw materials, land use could be negatively affected in the form of land sealing (e.g. factories, surface mining), and interventions in the ecosystem might lead to the destruction of habitats (flora, fauna).

Table 3: Ecological Rebound Effect in Phase 1

Critical Factor	Auto Type	Rebound Type
toxins		
air quality		
noise		
GHG		
energy consumption	all	global, indirect
water consumption		
waste water		
non-renewable resources		
land use		
interventions ecosystem		

It should be noted that the negative environmental impacts in phase 1 will be intensified by increased demand for raw material extraction caused by increased demand for cars in the use phase.

4.2.2 Manufacturing Life Cycle Phase

As Table 4 indicates, all identified environmental rebound effects in the manufacturing life cycle phase can be classified as local, global and indirect and apply to all auto types. Effects might be local or global depending on the location of the manufacturing site. Air quality might decrease because of production and manufacturing processes that use non-sustainable energy sources. The rebound effects here show negative effects for the ecosystem.

Table 4: Ecological Rebound Effect in Phase 2

Critical Factor	Auto Type	Rebound Type
air quality		
noise		
GHG		
water consumption	all	local, global, indirect
waste water		
toxins		
energy consumption		
waste		

In addition, the noise from factories at the extraction sites might damage the ecosystem in the long-term and GHG emissions of factories with non-sustainable fuels will negatively affect the climate. An increase in water consumption and waste water could limit the availability of ground water and deteriorate water quality, both resulting in the degradation of ecosystems. By-products of manufacturing processes can cause an increase in toxins, which might contaminate land and water as a rebound effect. Impacts of rebound effects due to an increased energy demand will depend on the used energy source. Additionally, an increase in scrap material during production processes could lead to further burdens for the ecosystem.

4.2.3 Use Life Cycle Phase

All auto types will cause local and direct environmental rebound effects in the life cycle's use phase (see Table 5).

Regarding the factor energy consumption an increase in demand is to be expected due to electricity needed for the charging of vehicles and the communication infrastructure. Potential negative impacts will depend on the source of power production. Since all three auto types will be emission free in the use phase an increase usage of cars might occur, as no negative impacts on the environment are to be expected (e.g. environment-conscious people travel more km). The use of one of the three car types will have no negative impacts on air quality and noise, and on the contrary might improve air quality and reduce noise pollution. This could also lead to an increase in car use and distances travelled. In the case of reduced noise pollution speed regulations and bans on night-time driving might be impacted and cause additional use of automobiles.

Table 5: Ecological Rebound Effect in Phase 3

Critical Factor	Auto Type	Rebound Type
energy consumption		
GHG	all	local, direct
noise		
air quality		

4.2.4 End-of-Life Life Cycle Phase

In the end-of-life life cycle phase all identified rebound effects can be classified as global and indirect, which is the case for all auto types. Main rebound effects are to be expected in the form of land and water contamination caused by toxins in increased waste. A second rebound effect is the de-

struction of the ecological system due to the increased waste at final disposals, which among other things can be attributed to more electronic waste and also due to increased land use for final disposal and recycling stations. For air quality, noise, GHG emissions, and water consumption the rebound effects depend on the chosen recycling process. An overview is given in Table 6.

Table 6: Ecological Rebound Effect in Phase 4

Critical Factor	Auto Type	Rebound Type
air quality		
noise		
GHG		
water consumption	all	global, indirect
toxins		
waste / final disposal		
land use		

4.3 Economic Sustainability: Rebound Effects

4.3.1 Raw Material Extraction Life Cycle Phase

The economic sustainability rebound effects in the first phase of the auto life cycle can be associated with critical factors such as commodity prices, less resources or new working places (see Table 7). The potential rise in commodity prices - caused by the fact that non-renewable resources are

finite and depletable - can be manifested in the form of the economic indirect SRE, when the scarcity of resources leads to competition and potential conflicts on the world market of rare materials. The shortage of some resources (e.g. lithium) will be reflected in the next indirect SRE, the political tensions due to access to resources and political pressure on countries with weak political authority over domestic resources. The potential increase in employment due to higher demand in the rare material market might lead to latently poor working conditions in countries with weak labor rights.

Table 7: Economic Rebound Effect in Phase 1

Critical Factor	Auto Type	Rebound Type
commodity prices		
scarce resources	all	global, indirect
employment		

4.3.2 Manufacturing Life Cycle Phase

The topic of job creation and working conditions is also important in the manufacturing phase: the SRE can be identified as indirect effect in local and global environments in the case of growth of autonomous vehicles' production volume. An increase in procurement costs might be indirectly caused by the increased number and demand for cars in urban areas. The same increase in demand for sustainable cars will be reflected in indirect SRE for various by-products in the manufacturing (toxins, waste water, etc.) in form of additional costs for pollution or penalty payment. More autos on

the markets require higher productivity from manufacturers that can resonate in another economic SRE: increase in demand on raw materials. The described factors are summarized in Table 8.

Table 8: Economic Rebound Effect in Phase 2

Critical Factor	Auto Type	Rebound Type
employment	all	local, global, direct
productivity		
procurement costs	all	local, global, direct
toxins / waste water / scrap / hazardous substances		

4.3.3 Use Life Cycle Phase

Most economic rebound effects from autonomous vehicles/e-cars appear in the use phase of their life cycle. A summary of these effects is presented in Table 9. Acquisition costs belong to the basics and at the same time, the highest ones (this aspect depends on the sharing or ownership model) that are reflected in indirect SRE, hindering the acceptance for self-driving technology. The same indirect SRE can be recognized for the initial maintenance costs of the car. The expansion of the number of charging stations directly leads to an increase in maintenance costs and to the expansion of the surface used by charging stations instead of green nature. Recharging the batteries of the new "sustainable" autos requires high voltage electricity, which currently allows for faster charging but at the same time shortens

battery life. As an economic direct SRE, we can identify an increase in the cost for battery maintenance, but as an indirect SRE, charging time can lead to less flexible travelling. In the case of semi- or fully autonomous autos, the user can benefit from inductive charging with an optimal position on the charging lot.

Table 9: Economic Rebound Effect in Phase 3

Critical Factor	Auto Type	Rebound Type
acquisition cost	all	local, indirect
maintenance cost		
charging stations	all	local, direct
charging time battery / energy source	all	local, direct, indirect
travel cost	all	local, direct
availability		
energy consumption	semi, full	local, direct
communication network / infrastructure		
energy demand communication network	semi, full	local, indirect
data	semi, full	local, indirect
driving style	full	local, direct
travel time		
reliability of the system		

The reduced travel costs will cause a direct SRE resulting in more travelling activity. The (non-)availability of a vehicle (depends on ownership or sharing) directly affects the flexibility of users and reflects a loss of time or delays. The energy consumption factor is a classic example for a direct rebound effect. If travelling increases due to autonomous vehicles, an appropriate communication and charging infrastructure has to be guaranteed. This would mean more investments in energy supply for the automobile industry and applications (travels). An increasing number of semi- and fully autonomous vehicles in city areas will require a higher amount of supporting communication infrastructure and as a consequence a more expensive maintenance system. The energy demand for this infrastructure will lead to new investments in energy supply. In the case of semi- and fully autonomous vehicles, the topic of increased data generation is very sensitive: It is unclear to whom this data belongs (e.g. car producer, user or service provider). This indirectly generates another economic SRE concerning potential conflicts between all interested parties involved and opens up a new level of problem characterized by trust issues. Another economic direct SRE concerns the increasing volume of distance travelled due to better or even optimal driving styles of fully autonomous vehicles from the perspective of transport system optimization and thus higher road capacity. Fully autonomous vehicles are changing the lives of drivers for the better by driving faster to the destination as they offer increased road capacity, less congestions and optimal route planning. Simultaneously, time is not wasted during these long travels, but can be used productively; this efficient driving directly generates new SRE in induced travelling with more distance travelled and probably more new autonomous vehicles on the roads. On the one hand, the reliability of control systems in autonomous vehicles plays a

very important role for the potential user, which, on the other hand, means a complete dependency of the user on these systems. This might involve time-consuming and cost intensive backups in the economic sense.

4.3.4 End-of-Life Life Cycle Phase

The final phase of a life cycle ends with recycling processes, which could mean a down-cycling process for all types of electric vehicles. With each cycle, the quality of the recycled material decreases, resulting in more material needed for car production. With proceeding dismantlement and treatment during the recycling process costs increase, which means that more waste produces more dismantlement work. The same challenge applies to waste management: higher costs are reflected in indirect SRE as more waste leads to more disposal.

In the situation of the global expansion of autonomous or electric vehicles, it is still necessary to build new recycling facilities that might require new land territories; indirect SRE is reflected in the fact, that areas intended for the construction of such recycling giants are not available for other land-use purposes at all or are only limited. Table 10 provides an overview of these rebound effects.

Table 10: Economic Rebound Effect in Phase 4

Critical Factor	Auto Type	Rebound Type
recycling		
disassembly / treatment	all	global, indirect
waste disposal		
land use		

4.4 Social Sustainability: Rebound Effects

4.4.1 Raw Material Extraction Life Cycle Phase

Social rebound effects, resulting from increased demand for cars and associated with the raw material extraction phase are all classified as global and indirect for all types of vehicles. Relevant factors are noise pollution, working conditions and safety at work, child labor, and water consumption as well as the use of conflict minerals (see Table 11).

Table 11: Social Rebound Effect in Phase 1

Critical Factor	Auto Type	Rebound Type
noise		
working conditions / safety at work		
child labor	all	global, indirect
water consumption		
conflict minerals		

While heavy noise at the extraction site negatively impacts the health of the employees as well as the health of the people in the surrounding communities, the limited availability of ground water and the associated decrease in water quality are detrimental to the living conditions of the population in terms of less drinking water and to local farmers who cannot irrigate their soils. Working conditions and safety at work could be particularly problematic in phase 1, and especially in the global context: i.e. the health and safety of workers will be endangered and exploitation of workers is possi-

ble. Next to the problem of forced labor, child labor and therefore the exploitation of children could increase and lead to them not having access to education. In addition, the procurement of minerals classified as conflict minerals may support wars and military conflicts in the respective countries and regions. Overall, this can result in the exploitation and endangerment of the local population.

4.4.2 Manufacturing Life Cycle Phase

In phase 2, expected rebound effects can occur both globally as well as locally and are to be classified as indirect (see Table 12); they emerge from all three car types alike. Noise pollution in the manufacturing and production processes is stressful for the employees and negatively affects their health, but also the living conditions for the local communities. Second, the issue of working conditions poses a risk to the health of employees and their occupational safety could be jeopardized. A further problem could therefore be the exploitation of the workforce.

Table 12: Social Rebound Effect in Phase 2

Critical Factor	Auto Type	Rebound Type
noise		
working conditions / safety at work	all	global, local, indirect

4.4.3 Use Life Cycle Phase

Table 13: Social Rebound Effect in Phase 3

Critical Factor	Auto Type	Rebound Type
noise	all	local, direct
safety		
trust / data protection	semi, full	local, direct
free time	full	local, indirect
energy consumption		
travel time		
acceptance		
accessibility (100 % mobility)	full	local, direct
comfort		
driving sytle		

The social SRE of noise and safety aspects is reflected in all types of electric cars in longer distances travelled as the vehicle noise is reduced directly and the safety conditions are increased. For semi- and fully autonomous vehicles, the factors of trust and data protection might lead to direct and local social SREs in the form of more kilometers driven and an increased demand for new cars. Self-driving vehicles allow users to get more free time due to the optimally planned driving process. This leads to another social SRE, as additional free time could be spent for more travels and/or not sustainable travel modes (plane, ship), or for other activities that consume

even more energy. In addition, fully autonomous vehicles are associated with an increasing need for real-time communication and energy infrastructure in the urban environment, which can indirectly lead to further social SREs, such as "electro smog" in the city, which may become a potential health risk.

The social acceptance of fully autonomous vehicles is a further critical factor: In the case of complete acceptance, it might lead to a social SRE in the form of increased usage of cars; conversely, doubts might hinder technological development. A major advantage of autonomous vehicles is 100 % mobility for all levels of the population including the elderly, physically challenged, children and those without a driver's license. That might increase the total number of travels and eventually more cars will have to be produced. Extra comfort when travelling with autonomous vehicles could increase the distance traveled; people who used to travel by foot, public transport or bike might switch to autonomous vehicles, which could reproductively influence their health. Another social aspect that should not be forgotten is the difference in driving style: In autonomous vehicles, driving may be very comfortable and less stressful for many people, but many users like to drive themselves, resulting in an unexpected social SRE such as loss of control during the driving process or less determined driving preferences. An overview of the presented rebound effects is given in Table 13.

4.4.4 End-of-Life Life Cycle Phase

Table 14: Social Rebound Effect in Phase 4

Critical Factor	Auto Type	Rebound Type
working conditions disassembly		
waste / final disposal	all	global, indirect
toxins / hazardous materials		

As the volume of new types of e-cars in urban areas might increase, the situation at recycling stations may worsen as recycling processes become more intense and can lead to social SRE in the form of negative health effects for workers. An increase in auto industry waste and more housing near recycling stations will be reflected in a social SRE, such as the degradation of the living conditions of local communities. More toxins or hazardous substances in the recycling process can endanger public health. See Table 14 for a summary of the rebound effects.

5 Conclusion

In this paper, we discussed the subject of rebound effects, which can even occur in a sustainable city environment. Rebound effects in three sustainability dimensions of urban areas were analyzed throughout the life cycle of three types of e-vehicles. For the analysis, a specific framework was proposed that combines LCA parameters and sustainability dimensions. The study presents several possible and sometimes unexpected REs that are identified from the perspective of city logistics. The results show mostly negative effects of an uncontrolled implementation of autonomous vehicle technology. At the moment these rebound effects only have theoretical relevance, because in practice they are very difficult to evaluate and validate. A large number of them indicate potential risks in various areas of a sustainable city after full implementation of autonomous vehicle technology, and require a closer investigation on this topic, either for vehicle producers or for urban developers.

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