LEVERAGING BIG DATA FOR MANAGING TRANSPORT OPERATIONS

Deliverable 2.4

Report on trade-off from the use of big data in transport

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Executive summary

Different types of rebound effects are addressed. This encompasses direct and indirect rebound effects, as well as society-wide, or overall rebound effects. Different application areas of rebound effects are presented. They cover rebound effects in connection with energy efficiency measures and climate gas reduction measures, as well as in connection with measures aimed to reduce other environmental pollutants. Critique of the rebound effects is also presented. We then turn to strategies to mitigate the rebound effect and suggest approaches for assessment of rebound effects from the use of big data in transport. Two very different approaches are presented, that either focus on 1) the ICT-infrastructure or 2) the transport system. The two approaches are addressed in the two following chapters, first in the analysis of rebound effects from ICT and cloud computing (Chapter 5), then in connection with the LeMO case studies (Chapter 6). Passenger transport and freight transport are dealt with separately, also in connection with the various transport modes: road, rail, water and urban transport. The purpose of the chapter 7 is to map the aspects that may be relevant for further research in LeMO case studies and may be further elaborated in the next project phase in a report with consolidated case study findings.

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Glossary

Abbreviation	Expression
CEC	Commission of the European Communities
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IET	The Institution of Engineering and Technology
ITS	Intelligent Transport Systems
LCA	Life Cycle Assessment
LeMO	Leveraging Big Data for Managing Transport Operations
NMVOC	Non-Methane Volatile Organic Compounds
NOx	Nitrogen oxides
RoRo	Roll-on/Roll-off

1. Introduction

1.1 Abstract

The report gives an introduction to the concept of rebound effects. In LeMO, the rebound effect is defined as *the difference between the expected and observed environmental impacts from new technologies aiming at efficiency improvements.*

Different types of rebound effects are addressed. This encompasses direct and indirect rebound effects, as well as society-wide, or overall rebound effects. Different application areas of rebound effects are presented. They cover rebound effects in connection with energy efficiency measures and climate gas reduction measures, as well as in connection with measures aimed to reduce other environmental pollutants. Critique of the rebound effects is also presented. We then turn to strategies to mitigate the rebound effect and suggest approaches for assessment of rebound effects from the use of big data in transport. Two very different approaches are presented, that either focus on 1) the ICT-infrastructure or 2) the transport system. The two approaches are addressed in the two following chapters, first in the analysis of rebound effects from ICT and cloud computing (Chapter 5), then in connection with the LeMO case studies (Chapter 6). Passenger transport and freight transport are dealt with separately, also in connection with the various transport modes: road, rail, water and urban transport. The purpose of the final chapter is to map the aspects that may be relevant for further research in LeMO case studies and may be further elaborated in the next project phase in a report with consolidated case study findings.

1.2 Purpose of the document

The main purpose of this document is to provide knowledge of the limitations of big data exploitation in transport, in terms of environmental impacts. The aim is to improve the understanding of how rebound effects contribute to this, and how these unintended effects can be avoided.

1.3 Target audience

The target audience of this report are transport policy makers, transport industry, research community, and technology providers.
More specifically, the target audience for this deliverable includes:

- Partners and Advisory & Reference Group in the LeMO project
- European Commission
- EU Parliament
- Horizon 2020 projects and related transport projects (cf. clustering activities)
- Organisations and experts involved in the LeMO case studies
- Public and private transport organisations
- Authorities (regional and national level) that develop and enforce policies and legislation

2 The Concept of Rebound Effects

2.1 Introduction to understanding the concept

In LeMo deliverable D2.3 – “Report on Ethical and Social Issues”, rebound effects are pointed to as an environmental trade-off, which limits the big data exploitation or creates unintended consequences.

The concept of rebound effects is commonly used to explain or describe the behavioural or systemic responses to the implementation of a new technology. It can also be applied to other measures to reduce energy use and emissions in relation to climate change. In principle, it can be used in reference to any natural resource or environmental problem. It should be emphasized that rebound effects are a consequence of human behaviour, as shown by Jägerbrand *et al*. (2014, p. 24-26).

In energy economics, rebound effects is illustrated through *Jevons paradox*:

> *The introduction of a new efficient steam engine initially decreased coal consumption, which led to a drop in the price of coal. This meant that more people could afford coal, making coal economically viable for new uses, which led to an increase in coal consumption (Jevons 1865)*

The concept of rebound effects can also be traced back to the late 1960s—early 1970s discourse on environmental and ecological system dynamics (Commoner 1972; Ehrich and Holdren 1971; Meadows *et al*. 1972; Odum 1969; 1971). In that discourse, rebound effects were considered an aspect of the feedback mechanisms of nature, which can be both positive and negative. The rebound effects are then understood to be a result of human manipulations with, or in isolation of parts of the larger systems, and can lead to chains of effects emerging in other parts of the environmental or ecological system. Thus, rebound effects can be understood as unpredictable backfires against anthropogenic encroachments in nature. The implementation of technologies intended to reduce energy use, which in real life turns out to result in the opposite result – an increase in energy use (as in Jevons paradox), can be understood as an example of such backfires. However, the rebound effects are not undesirable *per se*, as it can imply an enhanced social welfare if the benefits surpass the externalities generated (Llorca and Jamadb 2017, p. 106-107).

The use of the concept rebound effects is common within mainstream economics theory and analysis. Other, significant contributions to the concept can be found within the discipline of de-growth economists (Schneider 2008).

Rebound effects are diverse, often requiring an interdisciplinary approach to fully understand them. Knowledge of social as well as technological structures and relations is necessary. An engineering approach can over-estimate the net-benefits from improvements in energy efficiency (IET 2010). As a result, it has been suggested that improving the understanding of the rebound effect concept could be obtained through including disciplines and perspectives such as industrial ecology, in addition to the dominant economist and engineering views (Hertwich 2005; Madlener and Alcott 2009).

It is useful for the analysis in LeMO to have a good definition of rebound effects. One definition that is common among energy economists is the one devised by Matos and Silva (2011: 2834):

> *A rebound effect is the difference between the projected energy savings and the actual energy savings resulting from the increased energy efficiency.*

However, in LeMO, we prefer to follow the recommendation of Font Vivanco *et al*. (2014) to re-interpret the concept to better allow for broader environmental assessments, in addition to the energy alone. Thus, we speak of an environmental rebound effect, and apply this definition:

> *A rebound effect is the difference between the expected and observed environmental impacts from new technologies aiming at efficiency improvements*

2.2 Three categories of rebound effects

2.2.1 Direct rebound effects

Direct or “comfort”’ rebound effect occurs when e.g. improvements in energy-efficiency encourages greater use of the products and services. E.g. when consumers purchase a new car, which is more fuel-efficient than the old, they might drive more because it becomes cheaper for them to drive (Owen 2010). Direct rebound effects are sufficiently large to cause a “backfire” – that is they lead to overall increase in energy consumption.

Direct rebound effects were first noted in the 19th century in relation to the steam engine (as mentioned in Chapter 2.1) when the new technology raised productivity and energy efficiency, but increased society’s total energy demand (Sorrell 2010).

The direct rebound effects were first brought to the attention of energy economists through the Khazzoom-Brookes postulate:

> *With fixed real energy price, energy efficiency gains will increase energy consumption above where it would be without the gains (Khazzoom 1980)*

Rebound effects and induced demand have been empirically shown in the U.S. over three decades (1980-2010), as fuel efficiency improvements in combination with expanded road capacity caused additional vehicle distance travelled, partially offsetting the benefits of the measures taken (Byun *et al*. 2017).

2.2.2 Indirect rebound effects

There are also indirect rebound effects. They occur e.g. when money saved on reduced fuel consumption are being spent on other energy-intensive goods and services, such as:

- Air conditioners
- A second (or third) car in a household

Also, when energy-efficiency technologies (e.g., thermal insulation) needs considerable energy in the production phase of their life cycle, there are indirect rebound effects. For example, in some processes for production of thermal insulation, there is substantial emission of the compound 1,1,1,3,3-pentafluorobutane (HFC-365mcf), with the chemical formula $CF_3CH_2CF_2CH_3$ (Mersiowsky and Krähling 2002). This compound is a very strong greenhouse gas, actually 890 times stronger than CO_2.

2.2.3 Society-wide rebound effects

The sum of the direct and indirect rebound effects from energy efficiency improvements is often called the society-wide, economy-wide, or overall rebound effect. It is commonly expressed as a percentage of the expected energy savings from a specific measure to improve energy efficiency.

Economic models estimate that the overall rebound effect is highly variable, and ranges from 5 % to 60 % (Gillingham *et al*. 2013; Nässén and Holmberg 2009). The society-wide rebound effects for the years 2010-2030 have been estimated to be about 50 % (Barker *et al*. 2009).

2.3 Rebound effects from three main measures

2.3.1 Rebound effects in connection with energy efficiency measures

The use of big data in transport has potential to contribute towards achieving energy savings. One example is that the use of big data use can provide choices for optimisation of transport routes, which has the potential of fuel savings. Thus, a look at how rebound effects are understood in connection with energy efficiency improvements can be useful.

It is recognised that the magnitude of rebound effects is highly disputed (Herring 2006). If the rebound effect is small, such as when the increase of fuel consuming activities is less than 100 % of the improvement in efficiency, then the energy efficiency improvements will lead to a lower energy consumption. This is illustrated in Figure 1 where a 100 % drop in energy use is offset by a 70 % rebound effect, giving the result only 30 % energy reduction.

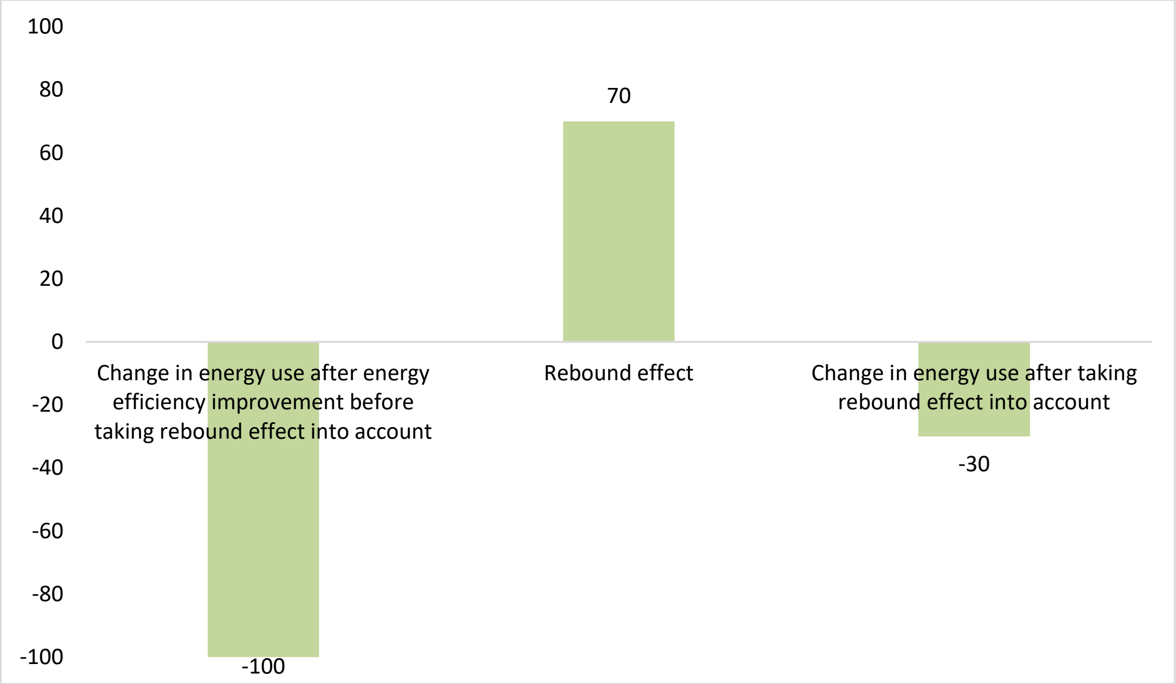


Figure 1 Rebound effect of 70 %, resulting in 30% energy reduction

If the rebound effect is large, such as when the increase of fuel consuming activities is larger than 100 % of the improvement in efficiency, then the resulting net energy consumption will be higher. Figure 2 illustrates this, where the 100 % drop in energy use is more than eaten up by a 130 % rebound effect, giving as result 30 % increase in energy use. This is termed “backfiring”.

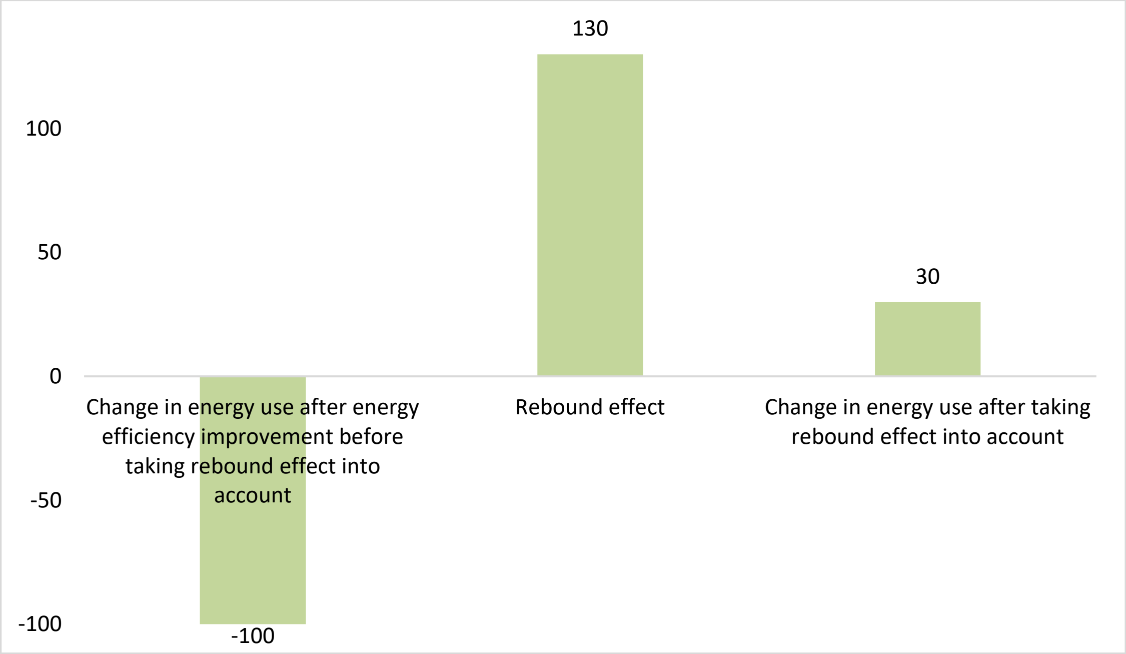


Figure 2 Rebound effect of 130 %, resulting in 30 % energy increase

A key problem in resolving the two positions is that it is not possible to run “controlled experiments” to be able to measure whether the energy use is higher or lower than if there had been no efficiency improvement implemented. It has to be estimated from various more or less reliable data sources. Even so, there is mounting evidence that, at the national or sector level, it is not uncommon for total resource consumption to grow even while efficiency improves, suggesting that improvements in efficiency are not sufficient for curtailing energy consumption. This is shown for the European freight transport by Llorca and Jamasb (2016) who obtained a rebound effect of 18 % for the energy efficiency improvements during the 1992-2012 period for this transport segment.

2.3.2 Rebound effects in connection with measures to reduce the emission of climate gases

Reductions in the emission of greenhouse gases (GHG) in transport, also termed climate gases, can also be a motivation for increased use of big data. The transition to renewable energies in transport is an important measure for obtaining these reductions. Rebound effects are occurring in connection with this measure, to lower the effect of the measure. An example is when energy consumers believe their energy is derived from renewable sources, they may be less concerned about conserving it. In hybrid cars, where electricity replaces part of the fossil fuel consumption, the cars can contribute to the reduction in climate gas emissions, depending on how the electricity is produced. If these cars are used more often, or on longer trips, due to this, there is a potential rebound effect. In an empirical survey in Japan it was shown that a year after purchasing what they considered to be an “environmentally friendly” car (e.g., a hybrid or 100 % electric vehicle), drivers who bought such cars were driving 1.6 times as far as they had done with their previous vehicle (Ohta andFujii 2011). Others claim that the argument that those who have fuel-efficient cars drive them more and hence use more energy is overplayed and inaccurate, and that the backfiring effect of Jevons (1865) is not supported empirically in the modern economy (Gillingham *et al*. 2013).

The rebound effects have in particular reduced the intended effect of one group of policies on renewable transport energy: that is the case for the policies on implementation of bioenergy (Andersen 2013a). For bioenergy, the transition from fossil sources of energy to renewable sources implies moving down the ladder in terms of specific energy content. This is due to the fact that the energy rich carbon atoms are densely packed in fossil fuels, but a renewable energy source such as biodiesel is more loosely packed and is present with significant amounts of oxygen atoms (approx. 10 % in biodiesel). Fossil hydrocarbons thus contain more carbon than biofuels do, per volume unit. When the whole energy chain is taken into consideration, this does not necessarily change the situation, as there is much input of fossil energy to the bioenergy chains, in particular during energy crop and distribution.

It is possible to point to rebound effects by integrating their analysis into life cycle assessments (Andersen 2013a, cited in Gossart 2015). When the whole life cycle is taken into account, rebound effects can be clear in life cycle stages that previously have not been assessed. The debate of biofuels as climate mitigation policy clearly demonstrates this, as multiple life cycle assessments have revealed that the production phase of biofuels emits large amounts of climate gases (Reinhard and Zah 2009; Schmidt 2010).

In the examples above, the rebound effect constitutes that the policies for reductions in the emission of greenhouse gases from transport actually counter the intended effect of the policy. Regarding fuels used in transport vehicles, the biofuels policy of blending biodiesel with fossil diesel has been shown to have a potential rebound effect in the form of the formation and spreading in the air of new type of toxic exhaust emissions (Andersen 2013b). This is an example of an unintended impact of the policy for reductions in the emission of greenhouse gases (Andersen 2013c). It is also considered a rebound effect, when taking into account the statement from Chapter 2.1 that in principle, the concept of rebound effects can be used in reference to any natural resource or environmental problem and understood as unpredictable backfires against anthropogenic encroachments in nature.

2.3.3 Rebound effects in connection with measures to reduce other environmental pollutants

Transport activities cause many other environmental problems than emissions of climate gases and air pollutants (Andersen 2003). Among the other environmental problems are those that emerge from the production phase of the life cycle of transport vehicles. Of particular concern are problems from the manufacture of catalytic converters that reduce vehicle emissions of NOx, NMVOC, and others. The functioning part of the catalytic converters are made from scarce metals, such as platinum and palladium. These metals are only found in very small concentrations in the Earth’s crust. Ores of platinum in as low a concentration as 7 parts per million (ppm) are currently being mined. About 1 million tons of mineral ore are refined to produce 7 tons purified platinum metal (Frosch and Gallopoulos 1989). Massive mining operations are necessary to excavate the metals resulting in the movement of massive volumes of earth, and leaves behind polluted tailings and ground water.

2.4 Critique of the concept rebound effect

The concept of rebound effects and its use has been subjected to critique, e.g. published as part of the book “The Conundrum - How Scientific Innovation, Increased Efficiency, and Good Intentions Can Make Our Energy and Climate Problems Worse” (Owen 2012). Three main points of criticism were:

- It is only at the micro end of the economics spectrum that the number of mathematical variables can be kept manageable. But looking for rebound only in individual consumer goods, or in closely cropped economic snapshots, is as futile and misleading as trying to analyse the global climate with a single thermometer
- Miles per gallon is the wrong way to assess environmental impact of cars. Far more relevant is to consider the productivity of driving
- Promoting energy efficiency without doing anything to constrain overall energy consumption will not cause overall energy consumption to fall.

These three bullet points should be taken into consideration when assessing rebound effects from the usage of big data in transport, as they represent constraints to the application and use of the concept.

3 Managing (or reversing) the rebound effects

Studying the rebound effects enables us to better understand the contradictions they imply and to imagine the means to overcome them (Gosshart 2015). Some argue that if they are controlled, technologies could support the decoupling between increased wellbeing and worsening ecological impacts (van den Bergh 2011). The obvious way to manage rebound effects, thus reducing their impact, is to take them into account when making policies for energy savings or environmental improvements. However, this is not straightforward. This is addressed in a study of European policies, where the conclusion is that the concern about rebound effects has generally not been translated into tangible policy action (Font Vivanco *et al*. 2016). The reasons for this inaction are not fully understood and much remains unknown about the status of the rebound effects. These knowledge gaps hamper the development of effective policies and could lead to undesired policy outcomes, such as the creation of additional rebound effects and environmental trade-offs. Policy strategies that can mitigate rebound effects are those that cause the following changes (Girod *et al*. 2014):

1) Economy-wide increases in environmental efficiency
2) Shifts to greener consumption patterns
3) Downsizing consumption

Policies so far for mitigating the rebound effect have been scarce and not ambitious (Font Vivanco *et al*. 2016). The uncertainties of rebound estimates have sometimes been used to justify inaction. The inability to launch policies for constrained demand within the existing GDP-based economic growth paradigm is another reason. A systems perspective would enable policy makers to better predict and verify the success of a rebound mitigation policy (Ibid.). More transformative changes in the current socio-economic structures may also be required (Sorrell 2010).

Most policies are designed to effect single environmental impact categories, such as energy use or GHG emissions. More comprehensive environmental impact, expressed through multiple impact categories, are however outside the scope of most rebound effect policies. Applying narrow definitions of the rebound effect that can lead to a “whack-a-mole” type of game when addressing single environmental impacts through policy (Font Vivanco *et al*. 2016). Thus, the definition we use in LeMO, as presented in Chapter 2.1, appears appropriate for analysing rebound effects connected to the use of big data in transport.

4 Assessment of rebound effects from use of big data in transport

To assess rebound effects from the use of big data in transport, we suggest two approaches, which each takes into consideration quite different types of effects:

1) Increased use of big data leads to increased volumes of **ICT-infrastructure** to acquire, store and process data. More smart devices (e.g. IoT devices), sensors, data centres and higher capacity of networks are needed. Rebound effect of big data can be assessed by taking into consideration this necessary increase in infrastructure, and the environmental impacts (including energy use) of its manufacture, operation, maintenance, and end-of-life handling. This corresponds to what is called "1st order effects", by the authors of the OECD report "Impacts of information and communication technologies on environmental sustainability: Speculations and evidence" (Berkhout and Hertin 2001). Thus, an increase use of big data in transport is causing environmental impacts, which can be considered as rebound effects.
2) A certain use of big data in transport is motivated by an expectation of a result. The expected result of the measure can e.g. be to avoid traffic jams, and thus reduce the waste of energy, as the energy (fuel/el.) in cars will be used for propulsion instead of idling. If the avoidance of traffic jams is successful, but there are unintended effects of this measure, which leads to increased energy use, we can speak about a rebound effect. Such unintended effects could e.g. be that longer total distances are travelled to avoid the traffic jams. Thus, the rebound effect of a specific measure of big data in transport is assessed by looking at the results of the measure, in terms of effects on the **transport systems**.

In this report, we have devoted a separate chapter for each of these two approaches. In Chapter 5 we look at aspects of the first approach, the ICT-infrastructure. Chapter 6 is using the second approach, focusing on the transport system. Both approaches should be used in a comprehensive assessment of rebound effects from use of big data in transport.

5 Rebound Effects from ICT and Cloud Computing

5.1 *Introduction*

We include in this report also other types of rebound effects than those who are primary connected to transport activities. Due to the fact that LeMo is about big data, we find it in place to include knowledge of rebound effects from the technologies that big data is integrated with and could not exist without. There are rebound effects that are important to understand, connected to information and communication technologies (ICT) themselves, independent of their use in transport activities. These are presented in this chapter, together with one tightly connected concept – cloud computing.

5.2 *Energy consumption trends in ICT*

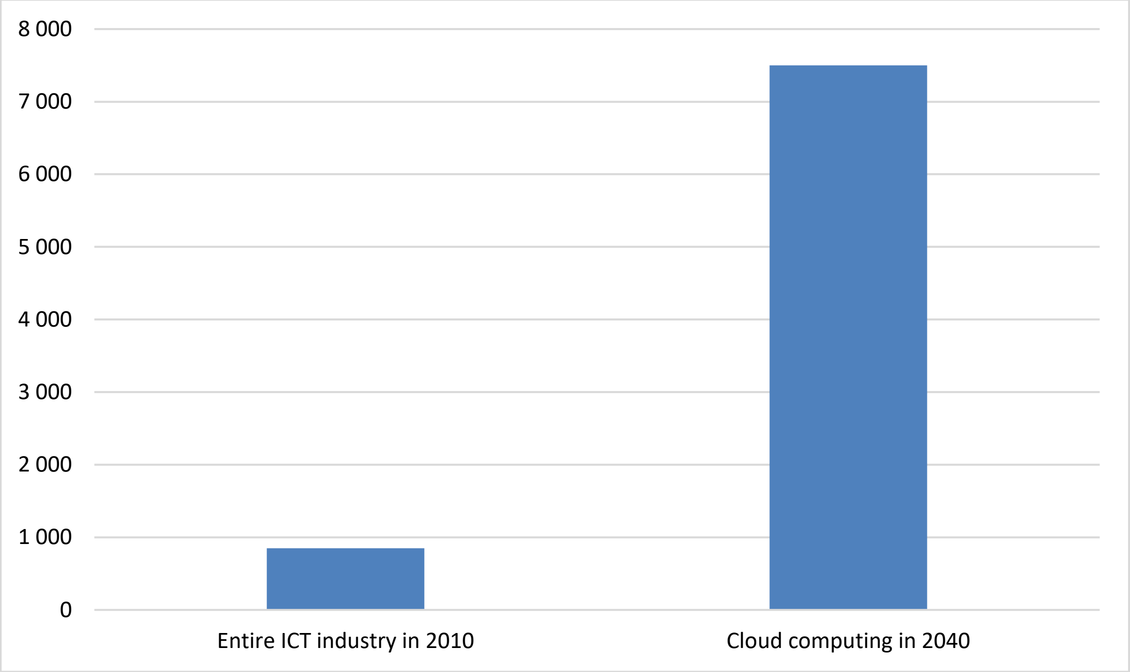
Society´s new digital lifestyle of collection, storage and use of big data require infrastructure that consumes large amounts of electricity. That the rebound effects connected to ICT are of great concern is evident in the fact that the first European legal act mentioning rebound effect was on this very topic (Font Vivanco *et al*. 2016). As early as 1996, the former Commission of the European Communities (CEC) expressed concern about the risks of rebound effects reducing the positive impact that ICT can have on resource utilisation, traffic management, and sustainable development in a communication entitled “The information society: From Corfu to Dublin. The new emerging priorities” (CEC 1996).

More recently, a specific question that has been asked is whether this new ICT infrastructure can actually contribute to reducing the overall energy use of society, or is it simply catalysing a substantial rebound effect that could rapidly increase (skyrocket) ICT-related energy consumption over the next decade? (Corcoran and Andrae 2013). The most significant result was that that the proportion of direct electricity consumption by ICT devices will drop from about 50 % to 35 % or less. There is a strong trend to move electricity consumption onto the network and data centres infrastructure where energy costs are less transparent to consumers. The changes that has occurred in the display products, combined with the replacement of desktop computers with laptops and thin clients, has however led to an overall drop in the direct energy usage of ICT devices. Analysis showed a decline in electricity consumption from 7.4 % in 2012 to 6.9 % of total global electricity consumption in 2017, however a worst-case scenario showed a rise to 12.0 % driven primarily by expansion of the network and data-centre infrastructure (Ibid).

5.3 *Cloud computing rebound effects*

Cloud computing is a technology concept (or “model”) for enabling ubiquitous, on-demand access to a shared pool of configurable computing resources (Mell and Grance 2011). In Adelmayer et al. (2017) a rebound effect is considered a cause why the result of savings from efficiency improvements are not or only partially realised. In cloud computing, the potential savings do not only result from energy efficiency improvements, but also from organisational resources (e.g. workforce).

Walnum and Andrae (2016) addressed specifically the paradigm shift of cloud computing in questioning if it facilitates energy savings or if rebound effects hamper the savings. The electricity consumption from ICT infrastructure has been considered small but with growing significance. According to Oscarsson (2014), cloud computing can consume between 5 000 and 10 000 TWh in 2040, depending on how energy efficient it will be. This can be compared to the global ICT industry, which consumed between 700 and 1 000 TWh in 2010. The average of the range of each of these two estimates shows this dramatic growth in Figure 3.



Source: Data from Oscarsson (2014)

Figure 3 Electricity consumption (in TWh) of the entire ICT industry in 2010 and of cloud computing in 2040

It has been determined that communication technologies in a worst-case scenario can use as much as 51 % of the global electricity consumption in 2030 (Andrae and Edler 2015). This share of the electricity consumption would be responsible for 23 % of the global GHG emissions in 2030 when taking into account how the electricity is expected to be produced (Ibid).

When assessing the energy-efficiency aspect of the transition to cloud computing it is important to take into account that possible direct rebound effects can occur if consumers or producers save money by using cloud computing, resulting in greater use of the technology. This experience of saving money could be from the reduced cost of storing the data by switching to cloud storage. Cloud computing provided new services and opportunities for people to access a larger amount of data through new services providing fast connections saving download time (Ibid). These factors are drivers for the increased demand for cloud computing services and will therefore lead to increased energy use from the infrastructure, such as the electricity to run and cool the data centres.

In order to assess the economy-wide effects of cloud computing, its effect on energy consumption in other areas (housing, mobility etc.) needs to be understood. There are expectations that energy use in buildings will decrease, due to smart solutions for managing the energy usage (GeSI 2015; Malmodin and Bergmark 2015). However, rebound effects of smart energy management to consider are increases in production and consumption, which counteract the energy savings from the new technology for energy use management (Walnum and Andrae 2016).

6 Rebound effects and the LeMO case studies

Deliverable 5.3 “Creating Shared Value for the European Transport Sector” describes a methodology to map the taxonomy of stakeholders in the LeMO community. It outlines the dimensions that are relevant to the implementation of big data in the transportation field.

LeMO stakeholders are identified along different transport modes and sectors.

Transport modes relevant for LeMO stakeholders are:

1. Air
2. Rail
3. Road
4. Urban
5. Water
6. Multimodal

Transport sectors relevant for LeMO stakeholders are:

1. Passenger
2. Freight

In line with the outlined taxonomy, this chapter will further examine rebound effects that are specific to those dimensions that are relevant for the LeMO case studies. In the following sections we will describe rebound effects in passenger and freight transport sectors, along the LeMO case transport modes; road, rail, water and urban. In order to cover different aspects, we will be looking at both direct and indirect rebound effects as well as economy-wide rebound effects.

The purpose of this chapter is not to provide a comprehensive study on rebound effects across different transport modes and sectors, but rather to map the aspects that may be relevant for further research in LeMO case studies and may be further elaborated in the next project phase in a report with consolidated case study findings (Deliverable 3.2). Hence, we have used examples that illustrate the potential rebound effects, even when it is not strictly caused by the use of big data applications. Existing research in this area is still scarce.

6.1 Passenger transport

We already showed that the rebound effects expressed as increase in vehicle travel are related to increased fuel efficiency, cheaper fuels or increased road capacity resulting in increased traffic speed.

A classic example of a direct rebound effect in private passenger transport occurs when fuel efficiency for private cars increases, accompanied by a reduction in fuel costs, which may lead the car drivers to drive longer distances which ultimately results in greater overall fuel consumption.

One report (Maxwell *et al*. 2011) estimates that mobility is responsible for 15-25 % of the environmental impacts in the EU. While fuel efficiency per car has improved, the savings have been offset by growing consumption of private car travel. The report cites studies in OECD countries which have estimated the rebound effect associated with fuel efficiency in private cars to be between 10-30 %. A 10 % increase in fuel efficiency actually provides a 7-8 % net reduction in fuel consumption and a 1-3 % increase in vehicle mileage (Victoria Transport Institute 2010, cited in Maxwell *et al*. 2011).

It is also interesting to observe the secondary effects when energy efficiency improvements may themselves change the demand for other goods and services. Sorrell (2007) provides an example from personal automotive transport when the use of a more fuel-efficient car may reduce demand for public transport, but at the same time increase the demand for leisure activities that can only be accessed with a private car.

Another interesting aspect is related to the consideration of time when making transport choices: on the one hand, technologies allow us tasks to complete tasks faster at the expense of using more energy, while on the other, time efficiency may lead to a parallel rebound effect with respect to time. An example of such rebound effect in transport is when faster modes of transport (e.g. air travel) encourage longer commuting distances, while the total time spent commuting remains similar (Sorrell 2007).

Looking at examples of rebound effects in air passenger transport, there is a consequence linked to a modal shift which shows that introduction of the mandatory purchase of seats for infants on airplanes led to a switch to other modes of transport in order to save money, which in turn led to a higher number of deaths on highways compared to the number of saved lives on airplanes due to the safety seats use. Another study found that longer waiting times and higher costs of air travel linked to safety procedures after the September 11th terrorist acts, led to increase in fatalities due to the traffic shift from air to road (Rossiter and Dresner 1991; 2004, cited in IET 2010).

6.2 Freight transport

The introduction of fuel efficiency standards to decrease fuel use of heavy-duty trucks is one of the major policy regulations to reduce environmental effects in the commercial transport sector. Engine technology enhancements and regulations such as lower speed limits have lowered fuel consumption and contributed to increased fuel efficiency per tonne-kilometre (Jägerbrand *et al*. 2014).

Despite the drop in specific fuel consumption of trucks, energy consumption in freight transport has increased significantly. Through lower fuel use per tonne-kilometre driven, the costs for transport of goods per unit has decreased and longer distances plus more frequent journeys has become cost-efficient.

Consequently, movement of goods for different steps in the manufacturing process has increased. There is a causal link between fuel efficiency gains, the lower costs of transport and the growth of outsourcing. Lower costs enable outsourcing, i.e. the transport of goods to varying locations for different steps in the manufacturing process, which is the main reason for traffic density growth. This is a new development in the overall commercial freight economic system of production and is relevant to economy-wide rebound effects (Ruzzenenti and Basosi, 2008 cited in Jägerbrand *et al*. 2014).

Studies of direct rebound effects in freight transport are few: estimated rebound effects are approx. 13–22 % in the short run and 12–45 % in the long run, with significant differences among different studies (Jägerbrand *et al*. 2014).

One study found that a 5 % increase in energy efficiency in the freight transport sector leads to rebound effects in the use of oil-based energy commodities in all time periods, in the target sector and at the economy-wide level. Despite the 5 % increase in energy efficiency, “transport” related oil consumption only falls by 3.2 % in the short run and by slightly less, 3.1 % over the long run. The “transport” oil rebound effect is thus 36.5 % in the short run and 38.3 % in the long run (Anson and Turner 2009, cited in Maxwell *et al*. 2011).

Another paper analysing the energy efficiency and rebound effects for road freight transport in 15 European countries during the 1992-2012 period found a fuel efficiency of 91 % and a rebound effect of 18 % on average, concluding that the achieved energy efficiencies are largely retained. One of the findings of the study is that the rebound effect is higher in countries with higher fuel efficiency and better quality of logistics (Llorca and Jamasb 2017).

E-commerce is an area with a potential to reduce the environmental footprint of freight transport by optimising transport logistics. But while some studies show that e-commerce does help to decrease logistics expenditure, others found that the savings depend on load rate of vehicles, delivery distance and other factors (for example, in dense urban areas traditional retail has smaller environmental footprint than e-commerce). E-commerce also increases the number of smaller units for delivering freight; which in turn increases packaging (IET 2010).

6.3 Road transport

An OECD report (conducted by Dimitropoulos *et al.* 2016) on rebound effects in road transport, provides national-level estimates of the rebound effects for 18 countries. The report concluded that empirical estimates vary, ranging from negative numbers (i.e. increased fuel efficiency results in reductions of car travel) to greater than 100 % (implying that improvements in fuel efficiency induce so much additional car travel that they eventually increase fuel use).

For passenger vehicles, the direct rebound effect is reported to be between 10–70 % in Europe and 10–30 % in the USA. In developing countries rebound effect would be high due to a big demand for energy (Maxwell *et al*. 2011).

When it comes to hybrid cars, they are often seen as a technology to decrease fuel consumption of passenger cars. One study from 2005 (de Haan *et al*. 2006) conducted among buyers of the Toyota Prius 2 analysed direct rebound effects that could occur when buying hybrid cars, specifically whether people tend to switch from small and/or fuel-efficient cars to the new hybrid car, and whether the average vehicle ownership may increase if the hybrid car is often purchased in addition to an already owned vehicle. The conclusion was that neither the vehicle size nor the average household vehicle ownership increased.

While electric cars can reduce the CO2 emission from transport, that depends on the electricity mix. In case of a rapid increase of electric cars use in the short-term, the electricity needed for charging would be largely generated by coal fire power stations (IET 2010). In addition, production of electric cars is resource- and energy-intensive due to the need for much copper in the electrical wires and precious metals for batteries. This is also true for hydrogen cars with fuel cells.

Another aspect where we may observe rebound effect in road transport is related to Intelligent Transport Systems (ITS). This is due to the fact that they may generate more traffic as a result of the increasing accessibility and reducing travel times. Traffic signals make journey times shorter for cars and other road users. ITS in the form of traffic information via mobile systems, navigation and traffic control also reduce journey times for road traffic. Tunnel monitoring and control provide short blocking times following accidents and incidents and also contribute to reduced travel times (Jägerbrand *et al*. 2014).

6.4 Rail transport

Due to the expected environmental benefits, many countries have been adopting policies to induce the modal shift to international rail transport. On average, the CO_2 emissions per person-kilometre for trains are about a factor of two lower than road transport. But there is dispute about the overall reduction in GHG emissions by this modal shift for freight transport. Rebound effects, such as increasing emissions of road transport due to lower load factors should also be taken into account, according to Climate Technology Centre and Network[1].

High speed rail is often considered a low-carbon technology, due to its low space demand and high energy efficiency per passenger kilometre. However, high speed rail systems are often not compatible with existing rail infrastructure. One study (Spielmann *et al*. 2007, cited in IET 2010) found that implementation of a high-speed rail system (including energy and infrastructure supply) in Switzerland, had a high environmental rebound effect. The study was based on the assumption that the time saved due to increased travel speed would be used to travel more.

IET (2010) provides an interesting example of unexpected effects linked to technological innovation in railroad passenger transport, while noting at the same time that no scientific study has been conducted to support it: namely that some journey times for railways for the

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[1] https://www.ctc-n.org/technologies/modal-shift-freight-transport. Accessed 10 Oct 2018.

same route are longer than before. One explanation is that trains are now faster and that in order to maintain even intervals on the fast tracks, some stops have been abolished, meaning that journey times for passengers from there have actually increased. Another explanation is that stops at stations are longer in order to allow boarding for an increased number of passengers. Finally, as there are more trains on the network, speeds have actually dropped in some cases.

6.5 Water transport

While there is a considerable amount of literature and studies on rebound effects in road, urban and rail transport, rebound effects in water transport have not been thoroughly studied. There appears to be a lack of data and existing literature on the topic.

Jägerbrand *et al*. (2014) conclude that rebound effects likely exist e.g. in water passenger transport and short sea shipping. Water transport is often more energy-efficient than other transport modes, however, direct CO_2 emissions per distance vary widely depending on type and size of the ships - smaller ships produce higher CO_2 emissions per ton-kilometre.

One case study (Hjelle and Fridell 2012, cited in Jägerbrand *et al*. 2014) shows that short sea shipping by RoRo (roll-on/roll-off) and container services may be CO_2 efficient but that this depends largely on speed, load factors and distance of operation. Therefore, advantage of RoRo compared to truck transport in terms of CO_2 emissions may be small.

Rebound effects can also be observed in a modal shift to sea transport. Such shift usually demands an increased speed and more efficient cargo handling to attract new commodities, which increase fuel consumption. Besides, when taking into consideration that trucks also become more efficient and less polluting, the environmental impact is not necessarily smaller than the one from ships or trains (Ibid.).

6.6 Urban transport

In urban transport, rebound effects can be observed when improved urban road capacity to reduce traffic jams actually generates additional peak-period trips. There is evidence that improved highway capacity attracts new traffic while measures to counteract traffic jams ends in unexpectedly crowded new facilities (Goodwin 1996 cited in Maxwell *et al*. 2011).

Reduced congestion lowers travel times and the cost of driving, but also tends to increase driving: urban traffic congestion maintains a self-limiting equilibrium. Vehicle traffic volumes increase to fill available capacity until congestion limits further growth. Travel that would not occur if roads are congested, but will occur if roads become less congested, is called latent travel demand.

This effect is partly a result of induced vehicle travel, i.e. an increase in total vehicle mileage due to increased vehicle trip frequency, longer trip distances or shifts from other modes. As a consequence, this increases mobility, but at the same time it also increases crash risk, pollution emissions, sometimes leading to also higher parking costs (Maxwell *et al*. 2011).

Another aspect is telecommuting which is often considered as an important tool to reduce the environmental impact of transport. One study (Matthews and Williams 2005 cited in IET 2010) found that telecommuting reduces the vehicle use by 50-70 %. But there are a number of rebound effects that may result from it, such as people moving further from their work place and thus contributing to urban sprawl, additional non-commuting trips and increasing the household energy use (IET 2010).

Rebound effects in urban traffic may be decreased by introducing congestion charging schemes, higher parking prices and alternative transport modes, including improved public transport system. Another tool in city planning is land use change: “compact” or “polycentric” cities reduce journey distances and frequencies and as result reduce the rebound effects by decreasing the need to travel (Maxwell *et al*. 2011).

7 Final Discussion and Conclusions

This report presents work that has been done in the LeMO project, work that has had the goal to provide knowledge of the rebound effects of big data in transport. The issue at stake is to reduce negative impacts of big data use in transport. The project has chosen to use environmental impacts as a category of undesired impacts and addressed this through rebound effects. This framing puts limits on the assessment of environmental impacts, as rebound effects are to a large degree applied in connection with energy-efficiency improvements, and the implementation of technology providing this. There are other aspects of big data use in transport that can cause environmental impacts that are not often addressed via rebound effects. Human health impacts of pollutants and material resource depletion are two examples.

Having these limitations in mind the report gives the reader an introduction to the concept of rebound effects and it´s use in addressing some important environmental impacts connected to big data in transport. The difference between direct and indirect rebound effects should now be clear, as well as society-wide rebound effects.

As the concept of rebound effects originated and is mainly used in connection with energy use and the unexpected consequences of energy-efficiency measures, resulting in overly optimistic expectations of energy reductions, this is also the main focus in this report. However, we have made efforts to also include other environmental impacts, in addition to energy use.

We have not found other work that specifically address rebound effects from the use of big data in transport. To deal with this issue, we have therefore proposed two different approaches for how to rebound effects can be assessed. Used in combination, they could provide guidance for how the main forms of rebound effects can be identified and thus taken into account when studying big data use in transport. It is out hope that this is a useful outcome of the task that could assist the remaining work in the LeMO project. It should be taken into consideration particularly during the case studies in the project. We suggest that during each case study, questions should be asked about rebound effects, both potential and real effects. When implementation of big data in transport are motivated by expectations of environmental improvements, e.g. as energy savings, critical questions should be asked about rebound effects of the actions. This could provide valuable knowledge also of the strategies for mitigating the rebound effects of big data use in transport.

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