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# Environmental rebound effects of high-speed transport technologies: a case study of climate change rebound effects of a future underground maglev train system

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**Abstract**

The implementation of new high-speed transport technologies re-shapes the demand balance between transport modes and rebound effects may occur. In this paper first a definition of environmental rebound effects of high-speed transport is presented and various cases are discussed. Second, a method is developed to determine and quantify the environmental rebound effects employing life cycle assessment. The method is illustrated in a case study by investigating the greenhouse gas emissions of a frequently discussed future underground maglev train system for Switzerland.

The environmental rebound effect expresses the size of environmental impact changes due to demand corrections in relation to the plain substitution effect. The latter expresses efficiency substitution effects due to the substitution of existing transport services with a high-speed transport service; i.e. passenger-kilometre performance remains constant in a world with and without the new transport service. Demand corrections are determined employing the notion of the constant travel time budget, assuming that if travel speed increases, the time saved will be exclusively used to travel more and further.

In order to quantify the environmental rebound effect we determined the environmental efficiency – including operation, energy supply, vehicle supply and infrastructure supply – for all important transport services of the current passenger transport system as well as for the new transport technology. In addition, we generated and quantified a set of cornerstone scenarios to address possible changes in mobility patterns and technological options of passenger car transport at the time when the new high-speed transport technology would be in operation.

The results show an increase of per capita environmental impact for all considered scenarios even without accounting for additional transport demand due to time saving effects. All scenarios show additional environmental impacts due to rebound effects on top of pure substitution effects.

The case study demonstrates that taking into account demand changes, i.e. rebound effects is essential to evaluate emerging transport technologies. New technologies allowing for higher travel speed, even if energy-efficient on a passenger-kilometre basis, might lead to higher environmental impacts. This is ignored by the traditional approach of environmental transport assessment, which compares environmental efficiency of each transport mode separately. The presented approach allows to better understand the consequences of new transport services, and facilitates the assessment of future transport technologies on the level of the transport system as a whole.


*Keywords:* Life cycle assessment; Rebound effects; High-speed transport; Maglev technology; Sustainable consumption; Travel time budget; Swissmetro; Cornerstone scenarios; Climate change; System delimitation; Prospective life cycle assessment; Induced impacts

## 1. Introduction

In all industrialized countries, transport demand continues to increase [1] and roads are becoming more congested [2]. This also is the case for Switzerland [3]. Alongside the

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growing construction of new roads, often alternative transport services and the construction of new infrastructure for public transport are proposed to meet the continuously increasing demand. Public transport is often promoted as being the preferable option over the construction of new roads for individual motoring as it has a lower space demand and higher energy-efficiency per seat kilometre [4]. Therefore, new mass transport systems are being constructed in large cities [5,6]. At the regional scale Europe has seen the emergence of new high-speed train systems [7]. A frequently discussed alternative high-speed train technology is so-called maglev (magnetic levitation) trains [8,9], which cannot use existing rail systems and are based on completely new infrastructures. Examples are the German Transrapid that started first commercial service in January 2004 in Shanghai (China) [10,11] and the proposed Swissmetro [12,13].

Environmental aspects of new transport technologies are frequently addressed using life cycle assessment (LCA). LCA, a tool facilitating a ‘‘cradle-to-grave’’ analysis of the consumption of resources and emissions, is particularly useful to detect and account for trade-offs [14], e.g. the shifting of environmental burdens from vehicle use to transport infrastructure. LCA studies on transport technology compare the environmental efficiency of existing transport services with new alternatives. Such an approach is applicable for (a) an intra-modal comparison such as the introduction of new propulsion system and fuel types [15–17] and/or (b) an inter-modal comparison (e.g. bus vs. rail) [4], provided a complete substitution of one mode (e.g. rail) by another mode (e.g. bus) takes place.

As high-speed maglev trains go in hand with completely new infrastructure, they in fact constitute a new transport mode. Therefore, they re-shape the demand balance between existing transport modes.

Consequently, determining and comparing the environmental efficiency, i.e. the emissions per passenger-kilometre, of different transport modes is not sufficient. In addition, one should assess transport alternatives on a transport system level, taking into account environmental consequences of changes in the modal split induced by the introduction of a new technology. Most important is the so-called rebound effects.

Traditionally, the concept of rebound effect is associated with energy use and the question how energy-efficiency improvements affect energy consumption [18,19]. The classical rebound effect describes changes in total resource use due to increased efficiency in the use of that specific resource [20]. For example, Haas and Biermayr [21] report demand increases of 30% for heating services induced by the increased energy-efficiency of the retrofitted heating systems in eight multi-family dwellings in Austria. Rebound effects also can be expected to occur when hybrid vehicles enter the market, however, such effects could not be identified up to present [22,23].

In recent years, the discussion on rebound effects and sustainable consumption recognizes the time dimension (see Jalas [24] for a brief overview). Similar to the classical rebound effect, the rebound effect in time describes changes in total resource use due to increased efficiency in time use, which in turn influences the use of resources in general. For example, Binswanger [25] theorizes – based on the household production function approach [26,27] – that if there is a time saving innovation in transport technology (faster cars, faster public transport, etc.) people will travel longer distances, since a certain distance can be traveled at lower opportunity costs. In contrast to the classical rebound, therefore, rebound in time is ruled by the allocation of a fixed and limited resource (time), whilst the classical rebound is ruled by the elasticity of demand to changes in efficiency (not to be confused with changes in price).

The goal of this research is to define environmental rebound effects (ERE) and develop a method to investigate and quantify ERE caused by the introduction of time saving transport innovations. The method is illustrated in a case study of an intensely debated future high-speed underground maglev train system for Switzerland.

The paper is organized as follows. In Section 2, we outline the methods used and the concept to determine and quantify ERE. Section 3 describes the main characteristics of the current transport system and the possible maglev enhancement. In Section 4, we present and discuss the results. Final conclusions are drawn in Section 5.

## 2. Methods

### 2.1. Environmental rebound effect

The environmental rebound effect describes changes in the environmental performance of a transport system due to the introduction of a time saving innovation in the transport sector.

Following the concept introduced by Haas and Biermayr [21], we distinguish two types of environmental impact changes, describing the difference in mobility patterns of an average traveler's behaviour in a transport system with high-speed transport ($A_1$) and a transport system without high-speed transport ($A_0$):

- Environmental impact changes ($\Delta EI_{cp}$) expressing exclusively the efficiency substitution effects of selected transport service with high-speed transport; i.e. whilst the average traveler substitutes existing transport services with Swissmetro the total kilometric performance of the transport system remains constant, (cp = ceteris paribus). $\Delta EI_{cp} < 0$ indicate a higher environmental efficiency of the new transport service compared with the substituted service(s).
- Environmental impact changes $\Delta EI_{dc}$ expressing efficiency substitution effects and including environmental impacts due to demand corrections (dc). The latter describes the environmental impacts of the activities that occupy the time that is saved by using a high-speed transport service instead of a conventional service. If demand does not change, then $\Delta EI_{dc} = \Delta EI_{cp}$

Environmental impact changes are calculated as follows:

$$\Delta EI_{\mathrm{dc}} = EI_{1,\mathrm{dc}} - EI_0 \tag{1}$$

and

$$\Delta EI_{\mathrm{cp}} = EI_{1,\mathrm{cp}} - EI_0 \tag{2}$$

with

- $EI_0$: environmental impact of a transport network without high-speed transport;
- $EI_{1,dc}$: environmental impact of a transport network with high-speed transport accounting for both efficiency substitution effects as well as environmental impacts of the activities that occupies the time that is saved by using a high-speed transport service instead of a conventional service;
- $EI_{1,cp}$: environmental impact of a transport network with high-speed transport accounting solely for efficiency substitution effects.

The rebound effect – expressing the size of environmental impacts due to demand corrections in relation to the plain substitution impact (ceteris paribus) – then is defined as:

$$\mathrm{ERE} = 1 - \frac{\Delta EI_{\mathrm{dc}}}{\Delta EI_{\mathrm{cp}}} \tag{3}$$

It should be noted that the environmental rebound effect of high-speed transport services – determined by employing life cycle assessment – is limited to the quantification of direct induced changes due to time savings. Consequences of changes on the macro level, e.g. expected changes in the regional development are neglected. Such changes are likely to change production patterns in distant sectors and hence conflict with the LCA's ceteris paribus restriction [28]. Second order effects, which may be of opposite sign and are probably smaller than the first-order effects [18], are difficult to quantify and hence may be neglected for quantified LCA studies.

### 2.2. Quantification of demand corrections and constant travel time budget

Ideally, for the quantification of demand corrections a distinction between a "time substitution" effect (as a certain distance can be traveled quicker, people may drive longer distances within the same time) and "time income" effect (as a certain distance can be traveled quicker people gain more time that they can spend for other activities) may be introduced.

In order to allow for decomposition into substitution and income effects empirical information on how people use time and what they do when they gain extra time would be required [29]. In absence of empirical data, however, we apply the constant travel time budget hypothesis [30,31] as a first approximation.

Under the assumption of constant travel time budgets (TTB), on average, people will allocate a fixed amount of their daily time to travel. This implies that time allocation is absolutely inelastic as far as travel is involved and ignores a possible saturation level for a given service.

Consequently, if travel speed increases, the time saved will be exclusively used to travel more or further. Assumption of TTB means that all time gains will be adsorbed by the time substitution effect and that the time income effect be zero. The TTB only holds for all travel by all modes. The sum of the daily per capita travel time, TT, over all modes of transport, $i$, which satisfy daily transport demands, $TD_i$, at mean speed, $v_i$, must equal the TTB [1]:

$$\sum_i TT_i = \sum_i \frac{TD_i}{v_i} = \mathrm{TTB} \tag{4}$$

### 2.3. Prospective life cycle assessment

In order to determine the environmental impacts and impact changes of the passenger transport system and account for uncertainties in the future development of mobility patterns and technological changes, prospective life cycle assessment is proposed, featuring a structured approach of scenario analysis [4].

The functional unit is defined as "average daily mobility of an average traveler". The mobility is expressed as the daily demand of various transport services. In order to fulfil his mobility demand, a traveler utilizes several transport services: cars, motorbikes, local public transport, coaches, trains, and aircrafts. Environmental impacts for all these transport services and the new high-speed transport technology must be determined by pursuing a life cycle approach, taking into account environmental interventions due to (a) vehicle travel, (b) pre-combustion, (c) vehicle supply (manufacturing, maintenance and disposal of vehicles), and (d) transport infrastructure supply (construction, maintenance and operation and disposal) [32].

Uncertainties with respect to possible future changes in travelers' behaviour and future technology developments (and market penetration of these technologies) are addressed with so-called cornerstone scenarios [33]. Scenario modelling as introduced by Spielmann et al. [4] – particularly designed for applications for the inventory matrix method [34] – can be employed to determine a set of highly consistent and diverse (cornerstone) scenarios.

The environmental impact per traveler and day, EI, for the current mobility pattern and for each scenario $S$ is determined by matching emissions $EE_i$ with transport demand $TD_i$ (pkm) for each transport service $i$:

$$EI^S = \sum_{i=1}^{n} TD_i^S EE_i^S = \sum_{i=1}^{n} TT_i^S v_i EE_i^S \tag{5}$$

The revealed environmental impact changes $\Delta EI^S_{\mathrm{dc}}$ and theoretical environmental impact changes $\Delta EI^S_{\mathrm{cp}}$ for each scenario $S$ are derived as follows:

$$\Delta EI^S_{\mathrm{dc}} = EI^S_{1,\mathrm{dc}} - EI^S_0 = \sum_i \left( TD_i^{S_{A1_{\mathrm{dc}}}} - TD_i^{S_{A0}} \right) EE_i^S \tag{6}$$

$$\Delta EI^S_{cp} = EI^S_{1,cp} - EI^S_0 = \sum_i \left( TD_i^{S_{A1cp}} - TD_i^{S_{A0}} \right) EE^S_i \qquad (7)$$

where, $TD_i$ is the daily transport demand (pkm) of a certain transport service $i$, and $EE_i$ is the environmental efficiency (kg/pkm) of transport service $i$.

### *2.4. Classification of environmental rebound effects*

Depending on the sign and magnitude of results of Eq. (3), we identify and classify five types of environmental rebound effects (ERE). A graphical representation is given in Fig. 1.

(1) Classical rebound effect ($0 < ERE < 2$): benefits due to environmental efficiency gains ($\Delta EI_{cp} < 0$) are partially offset by increased transport demand due to time savings. Two cases may be differentiated. In case 1a, a rebound effect occurs, however, the system performance $\Delta EI_{cp} < \Delta EI_{dc} < 0$ is still better than in the base case $EI_0$, representing the environmental impact of the conventional transport service modal split ($0 < ERE < 1$). This effect occurs for all point set of $\Delta EI_{cp}$ and $\Delta EI_{dc}$ located in area A in quadrant I (e.g. dot 1). In case 2, $\Delta EI_{dc} > 0$; i.e. the system performs worse than the base case, because of the strong rebound effect ($1 < ERE < 2$). This effect occurs for all point set of $\Delta EI_{cp}$ and $\Delta EI_{dc}$ located in area A in quadrant II (e.g. dot 1b).

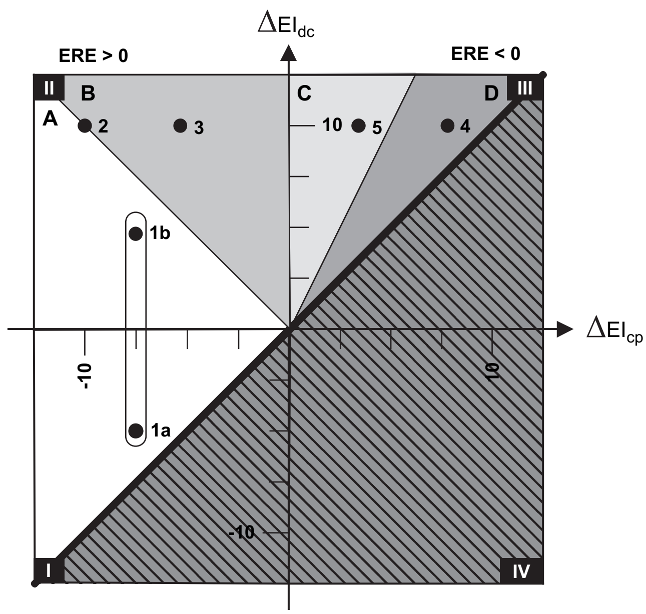


Fig. 1. Graphical representation of various types of rebound effects. The graph is divided in four quadrants (I–IV). The *y*-axis and *x*-axis represents scores of $\Delta EI_{dc}$ and the $\Delta EI_{cp}$, respectively. The bisector represents the set of points where $\Delta EI_{dc} = \Delta EI_{cp}$, i.e. $RER = 0$. Points below the bisector (shaded area) are not valid, since $\Delta EI_{dc} < \Delta EI_{cp}$. Depending on magnitude and sign of ERE, five different types of ERE are identified located in the four labeled areas A–D and on the bisector of quadrant. Each dot illustrates one type of rebound effect and the area in/or line on which a dot is located represents all possible point sets for this type of rebound effect. For instance, dot 3 ($\Delta EI_{dc} = 10$, $\Delta EI_{cp} = -5$) representing a so-called backfire effect ($ERE > 2$): According to Eq. (1), $ERE = 1-(10/(-5)) = 3$.

(2) Compensational rebound effect ($ERE = 2$): in this specific case benefits due to environmental efficiency gains ($\Delta EI_{cp} < 0$) are exactly compensated by increased transport demand due to time savings; i.e. the transport system shows the same performance independently whether the new technology is introduced or not. This effect occurs for all point set of $\Delta EI_{cp}$ and $\Delta EI_{dc}$ located on the bisector of quadrant II (e.g. dot 2).

(3) Backfire effect ($ERE > 2$): environmental efficiency gains ($\Delta EI_{cp} < 0$) are outweighed by environmental impacts caused by induced transport demand due to time savings ($|\Delta EI_{cp}| < |\Delta EI_{dc}|$ with $\Delta EI_{dc} > 0$); i.e. the transport system shows a worth performance as a consequence of the introduction of the new technology, although the new technology shows a better performance than the substituted service(s). This effect occurs for all point set of $\Delta EI_{cp}$ and $\Delta EI_{dc}$ located in area B (e.g. dot 3).

(4) Amplifying effect ($0 > ERE > -1$): the new high-speed transport technology has higher environmental impacts than the substituted service(s). Thus, if $0 < \Delta EI_{cp} < \Delta EI_{dc}$ there is an additional environmental impact on top of the substitution effect, due to demand corrections. A simple amplifying effect is defined as a case where the share of $\Delta EI_{cp}$ dominates the environmental rebound effect, i.e. $(\Delta EI_{dc} - \Delta EI_{cp}) < \Delta EI_{cp}$. This effect occurs for all point set of $\Delta EI_{cp}$ and $\Delta EI_{dc}$ located in area D (e.g. dot 4).

(5) Leverage effect ($ERE \leq -1$): this is an extreme case of the amplifying effect, occurring if $(\Delta EI_{dc} - \Delta EI_{cp}) \geq \Delta EI_{cp}$; i.e. that the environmental impacts of additional transport demand are higher than environmental impacts of pure substitution. This effect occurs for all point set of $\Delta EI_{cp}$ and $\Delta EI_{dc}$ located in area C (e.g. dot 5).

Clearly, if $\Delta EI_{dc}$ and $\Delta EI_{cp}$ are of the same magnitude no rebound effect is observed and hence $ERE = 0$.

## 3. Case study

### *3.1. Goal and scope*

The overall goal of the case study is to illustrate and test the above described approach in a real world case study. The new transport technology is the ‘‘Swissmetro’’ (SM), promoted as a ‘‘new-generation maglev’’ [13]. The Swissmetro transport system would be entirely operated in underground partial vacuum tunnels; reducing two critical local environmental impacts of transportation: noise emissions and land use. Additional energy savings in the operation phase of Swissmetro – compared to ‘conventional’ maglev technology without partial vacuum operation – can be expected due to the reduced resistance. However, these efficiency advantages in the operation phase will be counteracted by higher operation speed and additional energy requirements for partial vacuum and more sophisticated infrastructure [12].

The Swissmetro rail network is limited to Switzerland with stations situated in Geneva, Lausanne, Bern, Luzerne, St. Gallen, Basel, Zurich and Lugano [35], and is assumed to be in operation in the year 2040. South–north extensions and east–west extensions are 200 and 350 km, respectively.

The functional unit is defined as "average daily mobility of an average Swiss traveler". The mobility is expressed as the daily demand of various transport services. In order to fulfil his mobility demand, a Swiss traveler utilizes several motorised transport services: cars, motorbikes, local public transport (including: tram, diesel buses and trolleybuses), coaches, trains (including regional and intercity trains), aircrafts. For non-motorised transport services (pedestrians and bicycles) zero emissions can be assumed.

Cumulative environmental emissions are determined for $CO_2$, $CH_4$ and $N_2O$ emissions which are further aggregated to a single score, so-called climate change emissions [36].

As outlined in Section 2, environmental impacts of the current and future mobility of an average Swiss traveler are determined by the environmental efficiency of transport services and the demand for each of these services. Uncertainties due to future changes in efficiencies of transport services and demand patterns are addressed in four cornerstone scenarios.

### 3.2. Scenario description

The various steps of scenario development are described elsewhere [4]. In Table 1 the developed scenarios are summarised. For each scenario a label and a brief storyline is given.

Table 1
Cornerstone scenarios and referring story lines

| Scenario label | Storyline |
|---|---|
| Individual diversity | State regulation is reduced to a minimum and no environmental taxes are enforceable. Fuel prices are low. No changes in the mobility lifestyle are expected. The individual behaves spontaneously and selfish to realize a variety of interests and satisfy his wishes. For car use the load factor decrease below the current average. |
| Moderate regulation | Higher fuel prices are imposed to set incentives for technology efficiency improvements. Environmental awareness is low, resulting in a considerabe decline of human powered mobility (walking, cycling) for leisure activities. Time savings in leisure mobility are used for additional commuting and shopping mobility. The modal split is shifting to a higher share of car use. |
| Sufficiency | Environmental progress is achieved by new means of state regulation e.g. promoting locally focused leisure activities and human powered mobility to reduce the amount of motorised transport. For commuting trips, public transport options are preferred to individual car use. Efficiency measure with respect to new car technologies are of less importance. |
| World in change | Mobility patterns are the same as in scenario "Sufficiency". In addition, environmental efficiency is increasing as a consequence of high taxes and high fuel prices for individual car use. |

### 3.3. Scenarios quantification

The starting point for the quantification of the scenarios is a comprehensive analysis of the current situation. Scenarios addressing uncertainties in possible future mobility patters are first developed for a transport system without Swissmetro. In a second step, scenarios for a transport system with Swissmetro are derived by applying substitution factors, expressing to what extent conventional transport services are substituted by Swissmetro.

#### 3.3.1. Environmental efficiency scores of transport services

For conventional transport services, cumulative greenhouse gas emissions (comprising $CO_2$, $CH_4$ and $N_2O$ emissions) are derived from Spielmann et al. [37]. Cumulative emissions comprise emissions from vehicle travel, fuel/electricity supply, vehicle manufacturing, maintenance and disposal as well as transport infrastructure construction, operation, maintenance and disposal. The general assumption and methodological choices have been presented elsewhere [32,38]. The data represent Swiss average conditions for the year 2000. For road transport vehicles the presented figures for vehicle travel are based on Ref. [39] and represent Swiss conditions in 2005. Inventory data for Swissmetro are obtained from Baumgartner et al. [12]. In Table 2 the greenhouse gas efficiency scores for all transport services considered are summarised.

For the calculation of Swissmetro and train efficiency scores, we used the UCTE electricity mix [40]. The rationale behind this choice is that we assume the privatisation of the electricity market in Europe by the time Swissmetro will be in operation. The environmental efficiency score of Swissmetro is dominated by the transport component fuel/electricity supply. The latter comprises the cumulative greenhouse gas emissions due to the supply of electricity for the actual operation of the Swissmetro vehicles as well as for the supply of vacuum. However, infrastructure expenditures contribute to about 26% of the total score for Swissmetro. A comparison of the efficiency of Swissmetro with other transport services reveals that Swissmetro obviously can compete with air transport whilst it scores considerably worse than rail transport.

As stated in Ref. [4], in a prospective LCA, it is sufficient to apply scenario analysis to those unit processes that exhibit considerable time dependency and that are environmentally important. This is particular the case for private cars, which currently dominate the climate change emissions of passenger transport in Switzerland [39] and for which the future technology mix is uncertain. For the remaining conventional modes of transport, life cycle inventory data representing the current Swiss conditions are employed.

Scenarios for the technology changes in the future passenger car fleet are based on the outcomes of a comprehensive study analysing the environmental efficiency and market penetration of different powertrain concepts (conventional internal combustion engine (ICE) and fuel cell (FC)) as well as various fuels (crude oil, natural gas, nuclear power, biomass and solar irradiation) [41,42]. Röder [41] calculated the greenhouse gas emissions for 16 scenarios of possible future passenger car

Table 2
Climate change emissions and average speed of modeled transport services

| No. | Transport service | Average speed ($v$)[a] km/h | Transport component | | | | Total emission |
|---|---|---|---|---|---|---|---|
| | | | Vehicle travel | Fuel/electricity supply chain[b] | Vehicle supply[c] | Transport infrastructure supply[d] | |
| | | | g/$CO_2$ eq./pkm | | | | |
| 1 | Pedestrian | 3.8 | 0 | 0 | 0 | 0 | 0 |
| 2 | Bicycle | 12 | 0 | 0 | 0 | 0 | 0 |
| 3 | Car | 42.5 | 127 | 30 | 32 | 10 | 199 |
| 4 | Motorbike | 33.1 | 91 | 23 | 6 | 10 | 130 |
| 6 | Coach | 65 | 38 | 7 | 0 | 4 | 49 |
| 8 | Aircraft[e] | 220 | 143 | 23 | 1 | 93 | 259 |
| 5 | Urban public road transport[f] | 17 | 79 | 14 | 7 | 6 | 107 |
| 7 | Train UCTE mix[g,h] | 59 | 0 | 13 | 1 | 17 | 32 |
| 9 | Swissmetro[h,i] | 280 | 0 | 102 | 3 | 37 | 142 |

[a] If not explicitly stated, speed ($v$) is calculated from travel time and travel demand (distance) data as available from (ARE and SFSO 2000).
[b] Well to tank supply of fuels (e.g. diesel and petrol for passenger cars), or electricity supply chains, including mining activities for primary energy carriers.
[c] Vehicle supply comprises vehicle manufacturing, maintenance and disposal.
[d] Transport infrastructure supply comprises construction, operation, maintenance and disposal of transport infrastructure.
[e] Speed ($v$) is derived from calculations made for a trip Zurich−Geneva, including time expenditures for check-in.
[f] Diesel bus (80%), Trolley (8%) and Tram (12%).
[g] Intercity (75%), Regional train (25%).
[h] Electricity mix according to (Frischknecht, 2003).
[i] Speed is taken from (Baumgartner, Tietje et al. 2000) and including time expenditures for check-in.

fleet composition in Switzerland by combining LCA and an energy optimisation model.

The results of this study are complemented with road infrastructure data as available from Spielmann et al. [37] and transformed to the concept of scenario modelling [4]. In Table 3 the employed emission factors and the underlying technology are summarised.

Table 3
Technology mix and emission factors for future passenger cars in four cornerstone scenarios

| Scenario label | Passenger car technology and emission factors (car technology mix[a], fuel type[b], vehicle technology[c], market share) |
|---|---|
| Individual diversity | Small cars: (advanced gasoline; ICE, 100%); Compact cars: (advanced gasoline; ICE, 100%); Mid-class cars: (advanced gasoline; ICE, 100%). Emission factor: 170 g $CO_2$ eq./pkm (average load: 1.2 p). |
| Moderate regulation | Small cars: (Diesel, FC, 100%); Compact cars: (Diesel, FC, 100%); Mid-class cars: (EtOH from Wheat, ICE, 74%) and (MeOH from scarp wood, FC, 23%). Emission factor: 88 g CO2 eq./pkm (average load: 1.59 p) |
| Sufficiency | Small cars: (MeOH from NG, ICE, 100%); Compact cars: (MeOH from NG, ICE, 100%) Mid-class cars: (MeOH from NG, ICE, 100%). Emission factor: 117 g CO2 eq./pkm (average load: 1.59 p) |
| World in change | Small cars (CH2 from NG and nuclear), FC, 63%) and (MeOH from scrap wood, FC, 35%); Compact cars: (MeOH from scrap wood, FC, 93%) and (CNG, ICE, 7%). Emission factor: 39 g CO2 eq./pkm (average load: 1.59 p). |

[a] Differentiated with respect to engine size: 20% small cars (1400 $cm^3$), 55% compact cars (1400−2000 $cm^3$), 25% middle class cars (>2000 $cm^3$).
[b] Fuel types: CH2: compressed hydrogen; CNG: compressed natural gas; EtOH: ethanol; MeOH: methanol; NG: natural gas.
[c] Vehicle technology: FC: fuel cell; ICE: internal combustion engine.

### 3.3.2. Mobility pattern of Swiss traveler

Mobility patterns for the current situation are achieved by an in-depth analysis of the data files of the Swiss survey on travel behaviour [43]. According to this analysis we obtain a travel time budget of 92 min per day and traveler (mobile persons older than six years). In addition to $n = 9$ different transport services (see Table 1), we distinguish $m = 4$ different mobility categories: commuting mobility (CM), leisure mobility (LM), shopping mobility (ShM) and business mobility (BM).

Possible future mobility patterns are derived by adjusting the modal split based on the lifestyle changes summarised in Table 1. This process is performed for each scenario $S$ in two steps: (1) adjusting travel time (TT) with respect towards purpose of travel ($j$), while considering the fixed travel time budget (TTB) constraint (92 $\text{min d}^{-1}\text{p}^{-1}$) and (2) modification of the modal split $\mu_{i,j}$ within each category of transport purpose ($j$).

$$\sum TD_i^S = \sum_{i=1}^{n} \sum_{j=1}^{m} v_{i,j} TT_{i,j} = \sum_{i=1}^{n} v_i \sum_{j=1}^{m} TT_j \mu_{i,j} \quad (8)$$

where, $n$ denotes the number of transport services and $m$ runs over the four travel types (CM, LM, ShM, BM). The speed for each transport service ($v_i$) is assumed to be constant for each purpose of travel.

In Table 4, time expenditures of a Swiss traveller for the four cornerstone scenarios differentiated with respect to transport services and mobility purpose are presented.

Table 4
Time expenditures of a Swiss traveler (min $d^{-1}$) for the selected four cornerstone scenarios differentiated with respect to transport service and mobility purpose

| Scenario | Individual diversity without SM | | | | | Moderate regulation without SM | | | | | Sufficency and world in change without SM | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Purpose of mobility | CM | LM | ShM | BM | Total *M* | CM | LM | ShM | BM | Total *M* | CM | LM | ShM | BM | Total *M* |
| Pedestrian | 5.8 | 20.6 | 4.6 | 0.7 | 31.7 | 6.9 | 12.8 | 4.5 | 0.7 | 24.9 | 6.9 | 23.0 | 3.8 | 0.7 | 34.4 |
| Bicycle | 1.5 | 2.7 | 0.5 | 0.1 | 4.8 | 1.8 | 2.2 | 0.7 | 0.1 | 4.8 | 4.7 | 7.5 | 0.7 | 0.1 | 13.1 |
| Car | 10.8 | 18.0 | 6.0 | 3.6 | 38.4 | 14.3 | 18.5 | 9.8 | 3.7 | 46.4 | 7.0 | 10.7 | 2.6 | 3.4 | 23.7 |
| Motorbike | 0.3 | 0.4 | 0.1 | 0.1 | 0.9 | 0.4 | 0.3 | 0.1 | 0.1 | 0.9 | 0.4 | 0.4 | 0.1 | 0.1 | 0.9 |
| Urban public road transport | 2.6 | 1.9 | 0.9 | 0.3 | 5.7 | 2.4 | 1.5 | 1.2 | 0.3 | 5.4 | 3.1 | 1.9 | 0.6 | 0.3 | 5.8 |
| Coach | 0.1 | 0.4 | 0.0 | 0.0 | 0.5 | 0.1 | 0.3 | 0.0 | 0.0 | 0.5 | 0.1 | 0.4 | 0.0 | 0.0 | 0.5 |
| Train | 2.2 | 2.0 | 0.5 | 0.3 | 5.0 | 1.9 | 1.6 | 0.7 | 0.1 | 4.3 | 5.5 | 2.0 | 0.3 | 0.4 | 8.3 |
| Aircraft | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Others | 1.2 | 2.3 | 0.2 | 1.1 | 4.9 | 1.4 | 1.9 | 0.3 | 1.1 | 4.7 | 1.4 | 2.3 | 0.1 | 1.1 | 5.0 |
| Total travel time, TT | 24.6 | 48.4 | 12.8 | 6.2 | 92.0 | 29.2 | 39.2 | 17.4 | 6.2 | 92.0 | 29.2 | 48.4 | 8.2 | 6.2 | 92.0 |

### *3.3.3. Changes due to the introduction of Swissmetro*

In order to quantify the consequence of the introduction of Swissmetro for each scenario information about the substitution effects determined by Abay [44] of Swissmetro are employed. Abay [44] – based on a stated preference analysis – argues that due to the introduction of Swissmetro, a reduction of 50% of the transport demand of intercity trains will occur. Currently, intercity trains account for 75% of the total rail transport volume. Thus, assuming that this will hold in the future and assuming an increase of regional rail transport due to Swissmetro of 10%, about 35% of the total rail transport will be substituted by Swissmetro. A substitution factor SF = 35%, expresses the fact that on average a traveler will reduce his transport demand (pkm) for conventional trains by 35%.

For road transport, Abay [44] calculated a reduction in road traffic volume of 9.2% for the highway link Zurich–Bern. As we conduct this study for a comprehensive Swissmetro network we extrapolate this figure to the entire Swiss highway network. For the calculation of the substitution factor with respect to time, we assume that 38% of the car traffic (vkm) is performed on highways and taken into account a speed effect assuming that the average speed on highways is approximately twice as high as on the remaining roads [39]. As a result, we obtain a substitution factor SF = 2%. Finally, we assume a complete substitution of 100% for all domestic air transport. Based on these assumptions the transport demand of Swissmetro for alternative $A_{1,\mathrm{cp}}$ is determined by the sum of the substituted travel demand for rail, car and air transport services. In order to determine the demand-corrected mobility patterns for Alternative $A_{1,\mathrm{dc}}$, the resulting total time savings $t_{\mathrm{save}}$ due to the substitution effect have to be calculated as follows:

$$t_{\mathrm{save}} = \sum_i \left[ TT_i - \left( TT_i \frac{v_i}{v_{\mathrm{SM}}} \right) \right] SF_{i \to \mathrm{SM}} \tag{9}$$

where the total travel time of Swissmetro is

$$TT_{\mathrm{SM}} = \sum_i TT_i \frac{v_i}{v_{\mathrm{SM}}} SF_{i \to \mathrm{SM}} \tag{10}$$

Average speed assumed for the various transport services are presented in Table 2.

The time savings are allocated to the conventional transport services according to the modal split as determined for the corresponding service scenario without Swissmetro.

Table 5 illustrates the transport demand of a Swiss traveler differentiated with respect to various transport services. A comparison between scenario "Individual Diversity" with scenario "Moderate Regulation" reveals a considerable increase in individual car transport and decreased rail transport as well as human powered mobility such as walking and biking. In turn, in scenarios "World in Change" and "Sufficiency"

Table 5
Transport demand of a Swiss traveler (km $d^{-1}$) for the selected cornerstone scenarios and alternatives differentiated with respect to transport service

| Scenario | Individual diversity | | | Moderate regulation | | | Sufficiency and world in change | | |
|---|---|---|---|---|---|---|---|---|---|
| Option | $A_0$ | $A_{1,\mathrm{cp}}$ | $A_{1,\mathrm{dc}}$ | $A_0$ | $A_{1,\mathrm{cp}}$ | $A_{1,\mathrm{dc}}$ | $A_0$ | $A_{1,\mathrm{cp}}$ | $A_{1,\mathrm{dc}}$ |
| Pedestrian | 2.01 | 2.01 | 2.05 | 1.58 | 1.58 | 1.61 | 2.18 | 2.18 | 2.24 |
| Bicycle | 0.97 | 0.97 | 0.99 | 0.96 | 0.96 | 0.98 | 2.62 | 2.62 | 2.70 |
| Car | 27.63 | 27.08 | 27.69 | 33.41 | 32.74 | 33.46 | 17.10 | 16.75 | 17.26 |
| Motorbike | 0.50 | 0.50 | 0.51 | 0.52 | 0.52 | 0.53 | 0.52 | 0.52 | 0.53 |
| Urban public road transport | 1.65 | 1.65 | 1.69 | 1.57 | 1.57 | 1.60 | 1.70 | 1.70 | 1.75 |
| Coach | 0.58 | 0.58 | 0.59 | 0.51 | 0.51 | 0.52 | 0.60 | 0.60 | 0.61 |
| Train | 5.01 | 3.26 | 3.37 | 4.34 | 2.82 | 2.91 | 8.32 | 5.41 | 5.65 |
| Aircraft | 0.22 | 0.00 | 0.00 | 0.19 | 0.00 | 0.00 | 0.22 | 0.00 | 0.00 |
| Swissmetro | 0.00 | 2.52 | 2.52 | 0.00 | 2.38 | 2.38 | 0.00 | 3.48 | 3.48 |
| Total travel demand | 38.57 | 38.57 | 39.42 | 43.07 | 43.07 | 44.00 | 33.26 | 33.26 | 34.23 |

car transport decreases and rail transport increases. The introduction of Swissmetro does not change the total transport demand for alternative $A_{1,cp}$. As a consequence of the application of the notion of constant travel time budget and the time savings due to Swissmetro introduction, we observe a slight increase of the total transport demand for each scenario for alternative $A_{1,dc}$. The highest increase is observed for the scenarios ‘‘World in Change’’ and ‘‘Sufficiency’’. As both scenarios are characterised by a high share of rail transport in a world without Swissmetro, a fixed 35% substitution will result in a higher penetration of Swissmetro as for scenarios characterised by a low share of rail transport in alternative $A_0$.

## 4. Results and discussion

In Fig. 2 the climate change scores per traveler and day for all scenarios and options are presented. The environmental scores of the three options show the same pattern in each scenario ($EI_{1,dc} > EI_{1,cp} > EI_0$), with only marginal differences between the three options. In contrast the differences between the four scenarios – due to changes in the mobility lifestyle and the technological improvements for passenger cars – are more pronounced.

The ranking of scenario scores demonstrates the interplay of sufficiency and efficiency. Considerable sufficiency improvements – resulting in lower transport demand per capita – in scenario ‘‘Sufficiency’’ outbalance higher efficiencies of the car mix in scenario ‘‘Moderate Regulation’’. In turn, these high car efficiencies are sufficient to outbalance the slightly higher travel demand of scenario ‘‘Moderate Regulation’’ compared to scenario ‘‘Individual Diversity’’. However, the enormous difference between these two scenarios is also a consequence of the assumed lower load factor for passenger cars in scenario ‘‘Individual Diversity’’.

As demonstrated in Fig. 2, for all considered scenarios the introduction of Swissmetro will increase the per capita environmental impact ($\Delta EI_{cp} > 0$) even without accounting for additional transport demand due to time saving effects. This indicates that environmental benefits gained from the substitution of air transport with Swissmetro, are outweighed by environmental burdens imposed on the system by the substitution of car and train transport with Swissmetro (Table 2). Obviously, substitution effects ($\Delta EI_{cp}$) show the opposite ranking as observed for the total scenario scores.

The scenarios with the lowest absolute emission (‘‘Sufficiency’’ and ‘‘World in Change’’) show the highest values of $\Delta EI_{cp}$. This is the consequence of the high difference in efficiency of Swissmetro and rail transport, which is extensively substituted by Swissmetro. The slight difference in the environmental impacts for ‘‘Sufficiency’’ and ‘‘World in Change’’ is a consequence of the higher efficiency of cars which are substituted by Swissmetro in scenario ‘‘World in Change’’.

Lowest values for $\Delta EI_{cp}$ are observed for scenario ‘‘Individual Diversity’’. Due to low environmental efficiency in this scenario, a substitution from car transport results in only marginal differences between alternative $A_0$ and $A_{1,cp}$. Moreover, the share of rail transport is comparatively low, resulting in a low absolute substitution of rail transport with Swissmetro.

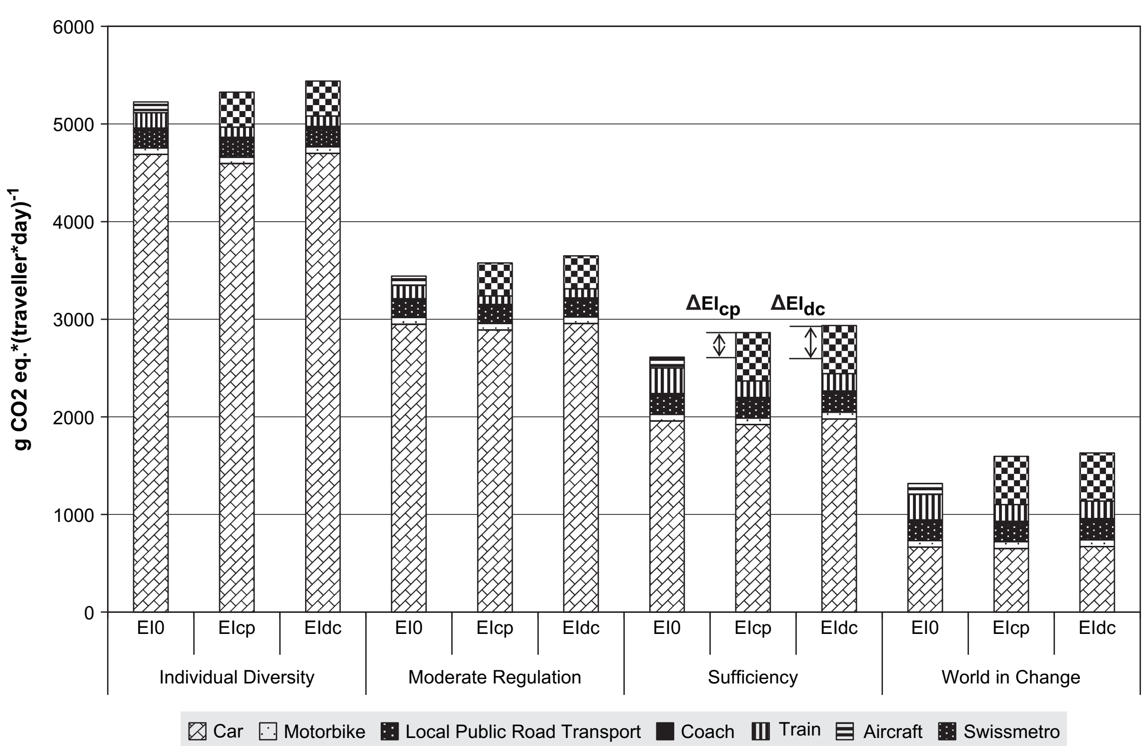


Fig. 2. Absolute environmental impacts (Climate change scores) per traveler and day for all scenarios and alternatives.

As a consequence of the application of the notion of constant travel time budget, all scenarios show additional environmental impacts due to time rebound effects on top of pure substitution effects.

In Fig. 3 the results of the case study are illustrated according to Fig. 1. For all considered scenarios, the environmental rebound effect has a negative sign and indicates the size of environmental impacts due to demand corrections in relation to the plain substitution impact (ceteris paribus).

An environmental rebound effect, $ERE < -1$ indicates that the environmental impacts of additional transport demand are higher than environmental impacts of pure substitution. This is the case for scenario ‘‘Individual Diversity’’ with $ERE = -1.14$. For the remaining scenarios the environmental rebound effect is in the range between $0 > ERE > -1$ implying that substitution effects are more important. The lowest rebound is obtained for the scenario ‘‘World in Change’’ with an environmental rebound effect that is only 0.11 of the environmental impact induced by the plain substitution. Scenarios ‘‘Moderate Regulation’’ and ‘‘Sufficiency’’ show a ERE of −0.53 and −0.29, respectively.

The absolute magnitude of environmental impacts due to demand corrections ($\Delta EI_{dc} - \Delta EI_{cp}$) is determined by the magnitude of time savings and environmental efficiency of transport services used for the additional transport activities. Scenario ‘‘World in Change’’ – characterised by the highest time savings – shows the smallest increase of environmental burdens ($\Delta EI_{dc} - \Delta EI_{cp}$). Thus, it is the high efficiency of the transport services used for additional transport activities that guarantee a low environmental rebound effect. For scenario ‘‘Sufficiency’’ characterised by the same time savings, the lower efficiency in car transport (factor 3.0) results in a considerably higher environmental rebound effect.

## 5. Conclusions

In this paper, a general method to define and quantify environmental rebound effects of time saving transport innovations has been developed and demonstrated in a Swiss case study. The foundation of the quantification of the environmental rebound effect is a comprehensive environmental assessment of the new transport technology as well as possible developments of existing transport services. For high-speed transport technologies that require a completely new vehicle concepts as well as transport infrastructure, a life cycle approach – taking into account all transport components, i.e. vehicle operation, fuel/electricity supply as well as vehicle and infrastructure supply [32] – is essential. Previous studies have revealed considerable environmental contributions due to infrastructure supply (e.g. Ref. [12]). Furthermore, the implementation of a new high-speed transport network is a comprehensive task, involving several planning phase and a long construction phase. Thus, another important feature of the presented approach is the integration of scenario modelling to address uncertainties in technological developments of existing transport services and changes in mobility patterns that may occur at the time the new transport technology is in operation, independently whether the new transport technology is implemented or not. The proposed integration of scenario modelling is mere briefly mentioned in this paper; however, a comprehensive description is available from Spielmann [4].

Environmental impact changes due to the introduction of new transport services are quantified employing the notion of constant travel time budget (TTB), which states that on average, people will allocate a fixed amount of their daily time to travel. It should be noted, that the fixed TTB hypothesis is not

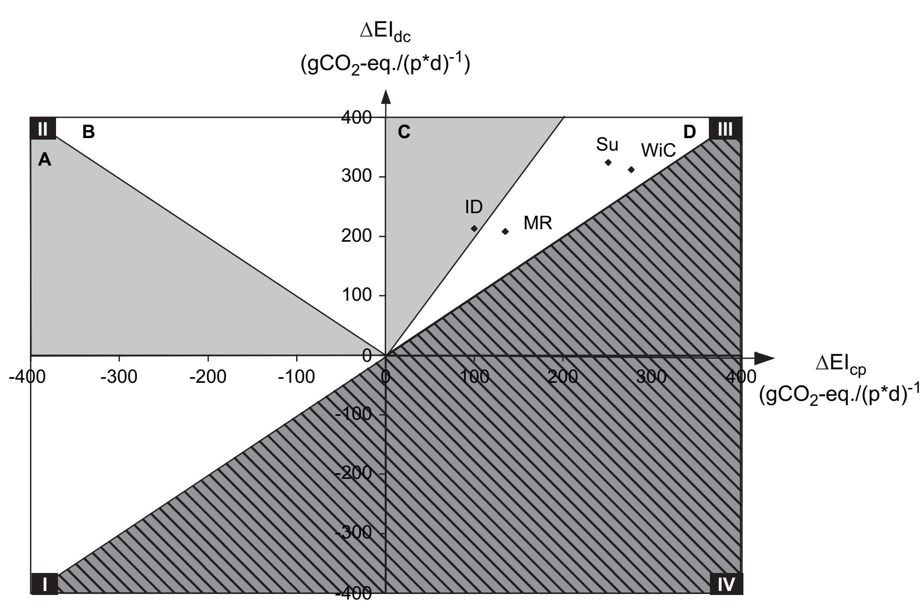


Fig. 3. Graphical representation of environmental impact changes. As illustrated in Fig. 1 the results indicate an amplifying effect for scenarios ‘‘Moderate Regulation’’, ‘‘Sufficiency’’ and ‘‘World in Change’’ (point set located in area D). For scenario ‘‘Individual Diversity’’, with the point set located in area C a leverage effect is observed.

a commonly accepted hypothesis [29,45,46]. Monetary budget constraints are not directly addressed in this research; however, they are implicitly incorporated in the substitution factors for rail and car transport which are obtained from a stated preference analysis.

Consequently, the calculated environmental rebound effects includes exclusively environmental impacts of further transport services occupying the entire time that is saved by using a high-speed transport service instead of a conventional service.

Keeping in mind the methodological constraints outlined above, two major conclusions can be drawn from the case study.

- First, the introduction of Swissmetro always results in higher environmental impact per capita in all considered scenarios, unaffected by uncertainties about the future development of the passenger transport system. This higher impact occurs even without accounting for additional transport demand due to time saving effects, since efficiency gains due to the substitution of low-efficiency air transport services are outweighed by the substitution of high-efficiency rail and car transport.
- Second, there is a rebound effect, which amplifies the above higher environmental impact. The size of this environmental rebound effect varies between 11% and 114%. Besides the magnitude of time saving, the size of the environmental rebound effect is determined by the efficiency of transport services used for additional transport activities. We assumed that additional transport demand does not alter the modal split. If the saved time were used differently, this would affect the magnitude of the environmental rebound effect. For instance, an increase of leisure trips on motor bikes would increase the size of the environmental rebound effect. Thus, an important impact factor to be considered in future research on the effects of environmental rebound effects due to new, faster transport service – besides the quantification of the actual amount of saved time – is the modal split of mobility activities performed within the extra time.

The case study demonstrates that taking into account demand changes, i.e. rebound effects is essential to evaluate emerging transport technologies. New technologies allowing for higher travel speed, even if energy-efficient on a passenger-kilometre basis, might lead to higher environmental impacts. This is ignored by the traditional approach, which compares environmental efficiency of each transport service individual.

Clearly, time rebound effects are only one type of potential rebound effects that may occur if a new transport technology is implemented (see Ref. [47] for an overview). Thus, future research may focus on quantifying synergies and interplay of time rebound effects and other types of rebound effects, for instance monetary rebound effects (see Ref. [48]).

In our case, Swissmetro will be more expensive than the substituted means of transport and thereby limit the consumption of further goods and services. Under the notion of the constant travel time budget, this would imply that the average Swiss traveler either reduces consumption of non-transport services or chooses cheaper transport services. In the latter case, one could assume that the saved time is used for human powered mobility and hence the calculated time rebound effect would be reduced. In order to incorporate the first effect, a further extension of the scope is required; e.g. instead of an average Swiss traveler one would investigate Swiss households.

As far as indirect or second order effects are considered, various options are possible and may be investigated separately, for each scenario either by sensitivity analysis or performing calculations for sub-scenarios. For instance, a high substitution of train transport with Swissmetro may result in the closure of certain transport services and hence in a further substitution of train services (snowball effect). In contrast, a substitution of car use with Swissmetro may result in a reduction of car ownership and hence a lower performance of car transportation.

The approach employed in this paper is well suited to enhance our understanding of the consequences of the introduction of new emerging transport services and thus to facilitate the assessment of future transport technologies on the level of the transport system as a whole. It allows for further extensions with respect to the incorporation of other types of rebound effects as well as for a systematic investigation of indirect rebound effects.

As stated by Hertwich [49] the identification of co-benefits and negative side effects of technical or policy measures is a bread-and-butter issue for life cycle assessment. Seen in this light the assessment of potential rebound effects as addressed in this paper tackles a crucial issue of current LCA research which recently has gained increasing attention [47,48].

The incorporation of rebound effects as presented in this paper contributes to the development of refined LCA methods for system delimitation and thereby is related to the issue of consequential LCA, presenting a market based approach to system delimitation opposed to the classical delimitation based on physically interrelated flows [50].

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