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Modelling Rebound Effects in System Dynamics

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Abstract

The induction of demand by increasing the efficiency of a production or consumption process is known as the rebound effect. Feedback loops in System Dynamics can be used to conceptualize the structure of this complex phenomenon and also for communicating model-based insights. In passenger transport, the rebound effect can be induced through increased cost efficiency (direct economic rebound) and/or increase in speed (time rebound). In this paper we review and compare two models on environmental effects of passenger transport—including a model on the role of information and communication technology. We highlight the feedback mechanisms used to deal with the rebound effect (price, efficiency, and time rebound).

1. Introduction

Energy efficiency helps devices provide the same services using less energy, and thus can be a solution for reducing greenhouse gas emissions. However, it can also induce more demand if the energy saved leads to a lower price of a service. The induction of demand by increasing efficiency is known as the rebound effect. To better understand the complexity of rebound effects of investments in efficiency, dynamic models have to be used. System Dynamics provides an approach to conceptualizing the structure of such complex phenomena and communicating model-based insights [13, 23, 25]. We will use the domain of passenger transport as an example.

In passenger transport, the rebound can be induced through increases in fuel efficiency or other improvements reducing the variable cost per person-kilometre (direct economic rebound) and/or increase in speed of modes (time rebound). In this paper we review and compare two models on environmental effects of passenger transport, including a model on the impact of information and communication technology (ICT) on transport. We highlight the feedback mechanisms used in both models to deal with the different types of rebound effect (direct economic and time rebound).

Brief definitions of the concepts of rebound effects, elasticity of demand, System Dynamics, causal loop diagrams are presented first.

Rebound effects can be categorized as follows [14, 24] (See [12] for a very brief history of rebound analysis):

- Direct economic rebound effects: When cheaper energy (or energy efficiency improvement in using energy-intensive goods) induces price reductions that trigger an increase in the demand for the cheaper good.
- Indirect economic rebound effects (income rebound): If the consumer saves money on one good (because it is used more efficiently and its price goes down) her disposable income is higher than the income she can spend—because she didn't use the money for the purpose, she can use it for something else.

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- Economy-wide rebound effects, which appear when declining energy prices induce a reduction in the prices of intermediate and final goods throughout the economy, and cause structural changes in production patterns and consumption habits.
- Time rebound effects, which is based on time efficiency in consumption: If a consumer can consume a product or service in less time, she tends to demand more of it.

In this paper we only address the direct economic rebound and time rebound. If the efficiency increase is enabled by ICT, both direct and indirect rebound effects are subsumed under the so-called third-order effects of ICT [10].

The size of the economic rebound effect depends on demand elasticity. Economic elasticity of demand with regard to price, or price elasticity of demand (PED) is defined as the percentage change in demand divided by the percentage change in price. Elasticity of demand is one way of modelling rebound effects (See [16] for an overview of price elasticities of transport demand).

Use efficiency can be expressed via price as an input for calculating price elasticity of demand. If for example a vehicle is used more efficiently by transporting more persons at a time, the cost per person kilometer is lower, which can lead to an increase in demand.

System Dynamics is a computer-aided systems modeling approach based on cause-and-effect analysis and feedback loop structures, used for to theory building, policy analysis and strategic decision support [13, 23, 25]. A feedback loop is a closed path of causal influences and information, forming a circular-causal loop of information and action. If the tendency in the loop is to reinforce the initial action, the loop is called a positive or reinforcing feedback loop; if the tendency is to oppose the initial action, the loop is called a negative, counteracting, or balancing feedback loop [23].

Feedback loops in System Dynamics are represented using causal loop diagram (CLD). In a CLD, relationships between variables, as shown in Fig. 1, are depicted using arrows with a positive (+) or negative (-) sign placed besides the arrowhead to indicate link polarity. A positive link polarity implies that "if a cause increases, the effect increases above what it would otherwise have been" and vice versa [25]. Similarly, a negative link polarity "means that if the cause increases, the effect decreases below what it would otherwise have been" and vice versa [25]. A CLD (as a qualitative technique) can be translated into stocks (accumulations or levels) in the system and their inflows and outflows (rates) [25, ch. 6]. Mathematically, a system of difference equations (similar to differential equations but with a fixed time step) formulates relationships between stocks and flows and supports quantitative modeling in System Dynamics [23, 25].

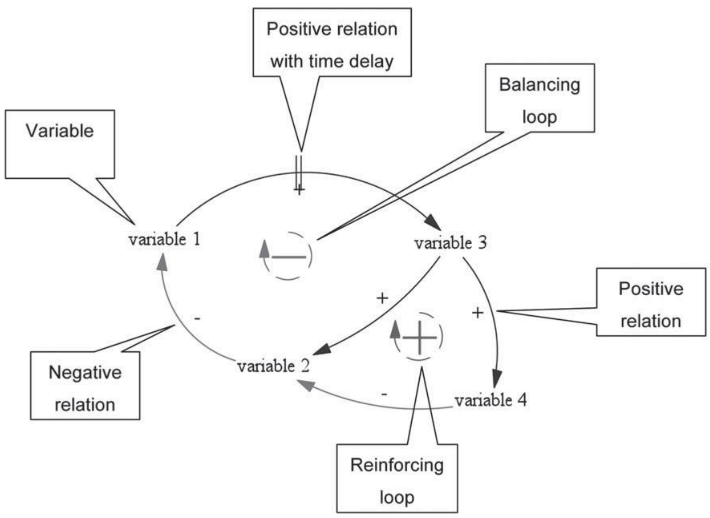

Fig. 1: Elements of causal loop diagrams (taken from [22])

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2. Selected models

Two models from literature have been chosen to illustrate how rebound effect is modelled using System Dynamics feedback loops. The first model (Model 1) models the dynamics of how information and communication technology (ICT) positively or negatively affects the passenger transport demand and modal split. The second model (Model 2) models the dynamics of how pollution-saving technologies positively or negatively affect the tourist transport demand and greenhouse gas emissions.

Feedback loops related to Model 1 and Model 2 (as shown in Fig. 2 and Fig. 3 respectively), which are used to the rebound effects, are presented and discussed in the following sections.

3. Model 1: Future Impacts of ICT on Environmental Sustainability—Submodel of Passenger Transport (IPTS Study)

In 2002, the European Commission's Institute for Prospective Technological Studies (IPTS) commissioned a study to explore the current and future environmental effects of ICT to a consortium led by the Institute for Futures Studies and Technology Assessment (IZT), Berlin, Germany. The aim of the study was to estimate positive and negative effects of the ICT on environmental indicators with a time horizon of 20 years. The method applied was to develop future scenarios, build a model based on the System Dynamics approach, validate the model and use it to run quantitative simulations of the scenarios. The results were published in 2003 and 2004 in five interim reports [1-5] (the 4th interim report [4] describes the model and data used), one final report [6] and several articles [7-10].

In the passenger transport submodel of the IPTS study (called Model 1 here), the goal was to calculate the volume of passenger transport demand (in passenger-kilometres, pkm, for different transport modes) changing over time due to the causal mechanisms and dynamics modelled in terms of stocks and flows. Fig. 2a shows a high-level conceptual model for the passenger transport submodel in the IPTS study [4, 9]. Fig. 2b presents the three main feedback loops in this model: cost efficiency loop, resource scarcity loop, and mode shift loop.

Each loop exists twice (symmetrically) because of the two modes chosen here for illustration, i.e., mode A and B.

Fig. 2b is not a pure CLD, since it includes parts of the stock-and-flow diagram to better describe the central mechanism of shifting transport demand between traffic modes. This mechanism is illustrated here for only two modes of transport, Mode A and Mode B (which can be thought of, e.g., private car and public bus). In the IPTS model, this mechanism was generalized to n modes based on multimodal passenger transport models developed by Hilty [17, 18]. Five traffic modes were differentiated in the IPTS model: Private car (PCar), bus and coach (BusC), tram and metro (TraM), train, and air. In addition, three modes of "virtual mobility" including home-based telework, virtual meetings, and teleshopping were represented, which was a new feature developed for this project.

Two types of rebound effect were modelled in Model 1 with regard to passenger transport [9]: (1) Direct economic rebound effects, and (2) Time rebound effects (based on travel time budget).

The following subsections present how these two categories of rebound effects were addressed in Model 1.

3.1. Direct economic rebound effects in Model 1

The direct economic rebound effects in Model 1 are represented via demand elasticities for passenger transport. The IPTS study considered the rebound induced by the price level of each

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passenger transport mode: besides changes of market prices (e.g., the oil price), which are external to the mode, higher efficiency (e.g., fuel efficiency of vehicles) can lead to lower prices per pkm (direct rebound effect), which will create more demand according to empirical elasticity parameters. Table 1 presents the elasticity parameters for five traffic modes and for three virtual mobility modes that were used as input to the model. As shown in Fig. 2b the elasticity parameter of each mode together with per-pkm price of the mode are controlling the inflow rate of transport volume associated with the mode.

Elasticity is defined as a %-change in demand divided by a %-change in price. It will not be realized immediately, i.e., if the price changes, in that moment no change occurs in demand, but gradually over the years. Empirical studies of elasticity of demand therefore usually distinguish between “short term” and “long term” elasticity. The IPTS model expresses the temporal aspect of elasticity by adding a time constant to each elasticity value: The time values mentioned in Table 1—for example “5 a”— indicates that it takes five years until the adaptation to the price change is realized. Note that all adaptations in the IPTS model including the elasticity-based adaptation of demand (also the shift between modes based on relative speed and time deficit, which will be discussed later) are not immediate in Model 1, but controlled by time constants.

Description	Elasticity Parameters
Economic elasticity of PCar traffic demand with regard to fuel prices	-0.3 (5 a)
Economic elasticity of BusC traffic demand with regard to BusC charges	-0.3 (5 a)
Economic elasticity of TraM traffic demand with regard to TraM charges	-0.3 (5 a)
Economic elasticity of train traffic demand with regard to train charges	-0.3 (5 a)
Economic elasticity of air traffic demand with regard to air fares	-1.5 (5 a)
Economic elasticity of home-based telework with regard to the cost of buying and running the equipment needed	-0.1 (2 a)
Economic elasticity of virtual meetings with regard to the cost of buying and running the equipment needed	-0.3 (2 a)
Economic elasticity of teleshopping with regard to the cost of buying and running the equipment needed	-0.01 (2 a)

Table 1. Elasticity parameters in the IPTS study, passenger transport [4]. Note: An elasticity value of -0.5 means that demand will decrease by 10% if prices increase by 20% (or that the demand will increase by 10% if prices are 20% lower).

Direct economic rebound effects in Model 1 are represented via the following feedback loops (see Fig. 2): cost efficiency loop and resource scarcity loop.

a) *Cost efficiency loop:*

Traffic volume (pkm) for each mode—modeled as a stock—is controlled by an inflow rate depending of the elasticity parameter and the per-pkm fuel price associated with the mode. (For simplicity, fuel is used here a pars pro toto for the sum of all resources needed to produce a pkm which cause variable cost; these resources may vary depending of the mode of transport.)

The elasticity parameter represents “classical” elasticity of demand with regard to price (in the IPTS model: the “PED” submodel included for each mode). Because the fuel price per pkm does not only depend on the fuel price per liter but also on the efficiency with which the fuel is used (“Efficiency of A with regard to fuel”), the price of 1 pkm is affected by efficiency and will, depending on the elasticity, influence the demand (traffic volume). The efficiency can increase by technical measures (e.g., more efficient vehicles) or by better utilization of vehicles (more people in the vehicle means more pkm per vehicle-km). It is possible that more volume increases efficiency for several reasons (the “(+)”). However, for each concrete transport mode, one has to account for the specific causal link between volume and fuel efficiency and how fuel efficiency affects the price the user finally has to pay.

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b) Resource scarcity loop:

Fuel (or any other resource needed to produce a pkm) may change in price if the total demand for this resource changes, depending on how supply reacts to demand in the market. Besides fuels, we may think of road pricing, which reflects the resource “infrastructure capacity” that is used to produce transport. Increasing use of any limited resource will at some point lead to an increase in price, which is reflected in this feedback loop. Again, it depends on the mode how this causal relationship is modeled in detail.

3.2. Time rebound effect in Model 1

In addition to direct economic rebound, the IPTS study (Model 1) included time rebound, another type of rebound effect based on time efficiency in consumption. Especially in passenger transport, time is a scarce resource and may affect behavior more than money. Model 1 (like Model 2) belongs to a class of models which abstain from converting time to money (which would be a straightforward approach in economic modeling) and keep financial budgets and time budgets of users separate. The time rebound effect was considered crucial in the IPTS study, because a core characteristic of ICT is the potential to accelerate processes.

Time rebound effects in Model 1 are modeled via the following mechanisms, as shown Fig. 2:

- Travel time budget mechanism
- Mode shift loop

These mechanisms work with time (not money as it is the case for cost efficiency loop and resource scarcity loop); a central variable is the speed of transport of each mode.

a) Travel time budget mechanism:

For the transport submodel the time rebound was considered via the so-called constant travel time hypothesis, assuming that the average daily time spent in transport over the whole population is more or less stable [26] (a critique of this hypothesis will be addressed later in this paper). At any point in time, the given travel volumes of all modes and their current speed levels make it possible to compare actual travel time with this time budget. If there is a deficit, this will cause a shift of the modal split from slower to faster modes. If Mode A is currently slower than Mode B, then traffic volume will shift to mode B, with some time constants similar to the ones mentioned for economic elasticity, and also with some limitations of the substitution potential. In the full IPTS model with five modes, this can for example mean that people having to commute over a higher distance will then maybe use a private car instead of the public bus, or that car drivers faced with increasing congestion will switch to the train or metro.

b) Mode shift loop:

As shown in Fig. 2, the mode-shift loop includes a causal link between the volume of each mode and the speed of this mode. This reflects the fact that utilization of each mode has an effect on time. It is important to see that this relationship can be different for each mode. For example, in public transport higher volume can lead to a better service (increased density in time and space) such as a higher frequency and more bus lines, which increases door-to-door speed for the passenger. Whereas in the private car mode, increased volume usually means that speed goes down, especially when congestion occurs. Model 1 makes this difference between “self-accelerating” and “self-limiting” transport modes and can therefore account for complex changes in demand, in particular when also the virtual modes and other effects of ICT come into play.

One of these effects is called the “time utilization effect” in the IPTS study (not represented in Fig 2b, but shown in Fig 2a): Because of mobile work that is possible to some limited, but increasing

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degree due to ICT, the time spent in traffic is not fully counted as transport time, i.e., a part of it is not charged from the travel time budget. Of course, the degree of time utilization is different from mode to mode (higher in public modes than in the private car mode) and changes over time with progress in mobile ICT devices and infrastructures. This is a core feature of the IPTS study. Time utilization effects can create more transport demand and influence the modal split towards public transport.

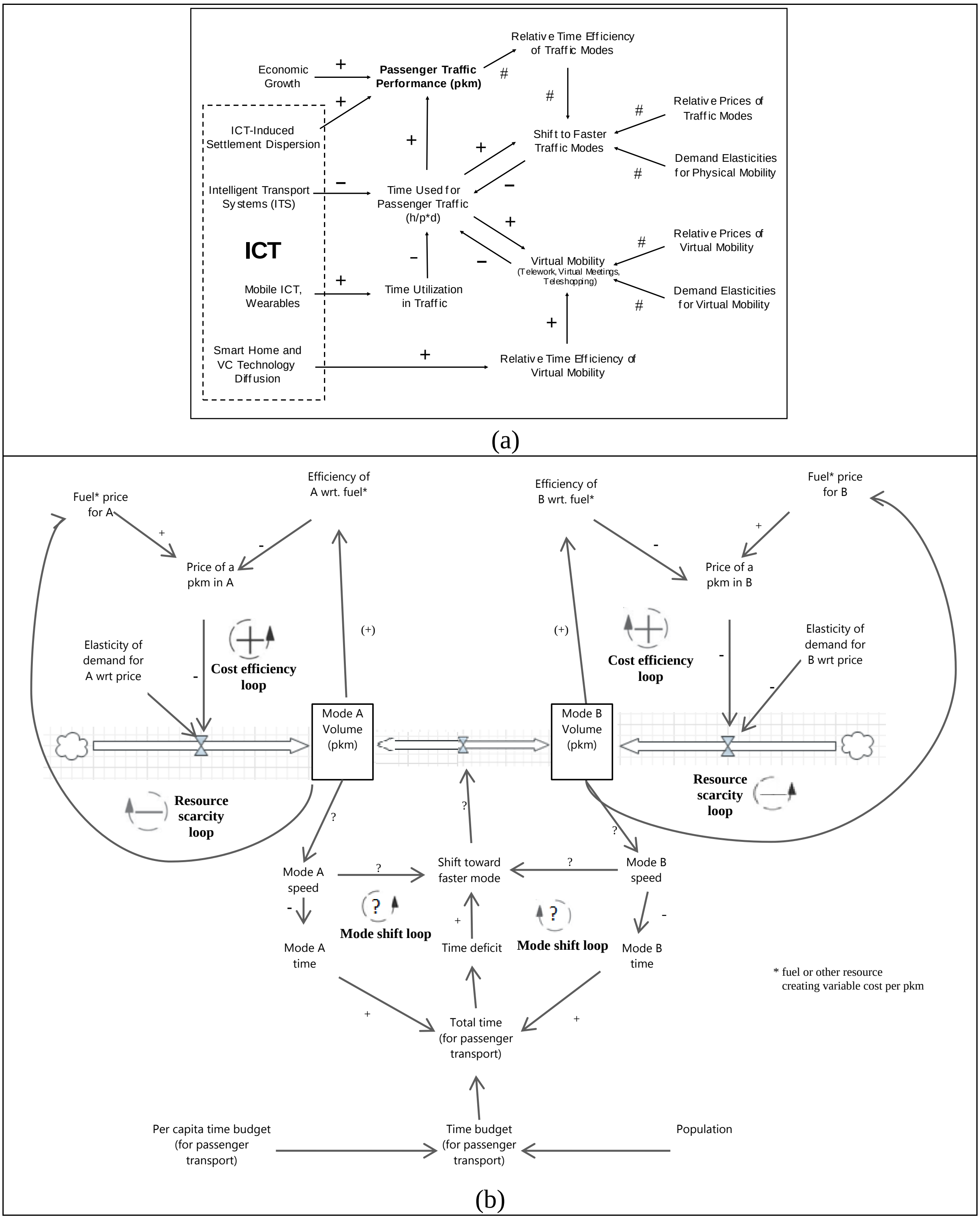

Fig. 2: Causal loop diagram for Model 1: (a) more abstract diagram for the development of passenger transport performance, taken from the IPTS interim report [4]: "ICT has second-order effects when applied passenger traffic (all applications subsumed under Intelligent Transport Systems) and third-order effects in the long term via settlement dispersion, time use in traffic, smart home and videoconferencing technology. The "#" sign is used where the multidimensional variables are involved, leading to complex causal relationships." (b) less abstract diagram focused on main feedback loops

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Two features of Model 1 could not be shown in Fig. 2. First, different modes of transport can share infrastructure, which means that their speeds are coupled to a certain degree (e.g., public buses may be slowed down by congestion caused by private car traffic). This can be expressed in Model 1 by so-called coupling factors for each pair of transport modes. Second, there is an overall reinforcing feedback loop of passenger transport demand which works via settlement dispersion: more traffic volume slowly increases the level of dispersion. It is the level of dispersion which decides how a time deficit is corrected; the correction is in fact a mix between the two possibilities of shifting to a faster mode or reducing the distance covered.

4. Model 2: Tourism Transport, Efficiency, and GHG Emissions

The second model (Model 2) is taken from a study by Peeters [22] on modeling tourism transport demand considering rebound effects of technological efficiency improvement. In a similar way to Model 1, Model 2 has also addressed two types of rebound effects with regard to tourism transport [22]: Direct economic rebound effects and time rebound effects (based on travel time budget).

The following subsections present how these two categories of rebound effects were addressed in Model 2.

4.1. Direct economic rebound effect in Model 2

As shown in Fig. 3a, the direct economic rebound effects are represented via two reinforcing feedback loops in Model 2: Efficiency enhancing loop and emissions loop.

a) Efficiency enhancing loop:

This is the main reinforcing loop, which starts with investment in efficiency enhancing technology. The efficiency reduces energy consumption per seat-kilometer (skm), and thus it reduces cost per skm, which in turn can induce increases in transport volume (pkm) depending on the price elasticity of transport demand (although the economic elasticity is not clearly presented in [22]). More transport generates funds that can be used as more investment in technology improvement, creating a reinforcing loop that improves efficiency.

b) Emissions loop:

The reinforcing loop of efficiency improvement transport volume does not necessarily reduce total emissions due to the increase in transport volume in the reinforcing loop. Which of the two loops of efficiency and emissions has the most impact depends on the specifics of the transport system described by the model [22].

c) Attitude loop:

A third relevant loop in this system is the attitude loop, a balancing loop because an increase in environmental pressure will tend to increase the willingness to invest in pollution-saving technology, which also improves efficiency [22].

4.2. Time rebound effects in Model 2

Model 2, as shown in Fig. 3b, contains three reinforcing feedback loops—travel time loop, cost loop, and mode shift loop—and one balancing loop, i.e., max speed loop. The causal loop diagram in Fig. 3b is based on three basic assumptions drawn from literature (Peeters 2010):

- Tendency to travel longer distances (a significant part of a population has the aspiration to increase their range),
- Travel time budget (on a population level the total amount of time spent for actually traveling from home to destinations and back is more or less constant)

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- Constant share of income (the average amount of money spent on transport per year on a population level is a constant share of income).

a) Travel time loop:

Assuming a constant travel time budget, if people have more money they will be able to travel more kilometers within the constant time budget (This is valid for the whole population, but not for the individual as they can temporarily change the amount of time and money spent on travel.) From ‘‘average distance’’ a reinforcing loop boosts the distances traveled [22].

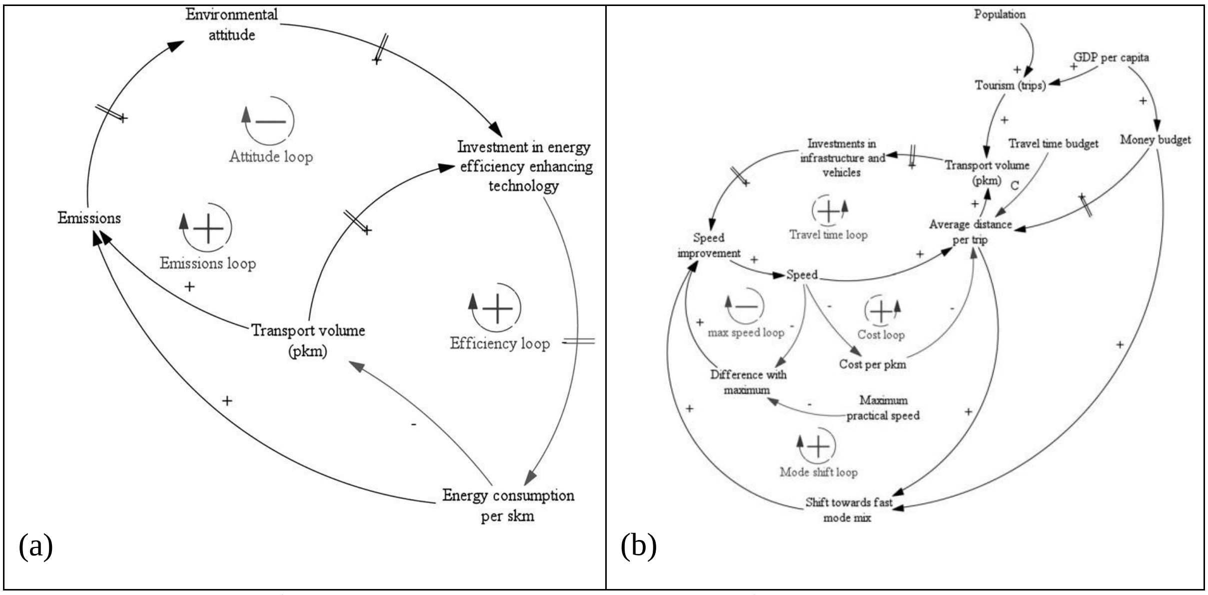

Fig. 3: Causal loop diagram for Model 2 [22]: (a) Pollution-saving loops (b) Basic forces in transport systems (Time delay is indicated by the double strikethrough lines in the arrows.)

b) Mode shift loop:

As shown in Fig. 3b, an increase in money budget and in average travel distance will increase the share of faster modes. Faster transport modes are used over longer distances [22].

c) Cost loop:

This reinforcing loop runs through cost of transport. With an increase in speed, operational costs generally reduce because productivity is increased faster than per hour operational costs, allowing for a higher number of kilometres to be sold [22].

5. Discussion and Future Research

Both Model 1 and Model 2 have employed System Dynamics feedback loops to explore the dynamics of transport volume (in passenger-kilometres, or pkm). A better understanding and calculation of the demand for transport volume is important because energy demand and greenhouse gas emissions are associated with transport volume. Both models showed that efficiency cannot necessarily reduce total emissions if the transport volume increases because of reinforcing feedback loops described above (both time rebound and direct economic rebound).

Both models included similar external variables such as population and the economic growth as drivers of transport demand. (See the upper right part in Fig. 3b and upper left part in Fig 2a)

The efficiency loop modelled in Model 2 (Fig. 3a) includes investment in efficiency enhancing technology. However, investments are not explicitly represented in Model 1.

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Both models have employed the concept of economic elasticity of demand with regard to price. However, Model 1 addressed this in a more explicit way in terms of presenting elasticity parameters for different transport modes.

Both Model 1 and Model 2 in a similar way have used the constant travel time budget assumption to show the dynamics of speed versus demand; higher speed implies using the constant time budget to cover more distance.

Critique of the travel time budget approach:

Both Model 1 and Model 2 have assumed that on a population level the total amount of time spent for actually traveling from home to destinations and back is more or less constant (travel time budget). The idea of a travel time budget—which has been developed since 70s in the field of transport research (e.g., see [15])—has encountered critiques. For instance, Höjer and Mattsson [21] point out weaknesses of this idea and found it "hardly reasonable to presuppose that travel time is constant when planning for future transport systems and urban structures." It would be useful to further investigate the advantages and weaknesses of employing the hypothesis of constant travel time compared to other alternatives. Two points regarding the critique can be considered.

First, the travel time budget approach helps model the scarcity of the resource time. Without a travel time budget, a model could possibly predict that someone who can afford it would travel for more than 24 hours per day.

Second, Model 1 already showed a way how to relax the constant travel time hypothesis without loosing its advantages: the concept of (travel) time utilization, or dual use of time, mitigates some of the problems of this approach. As shown in Fig. 2a, the IPTS study modelled the variable of time utilization in traffic (This variable is not presented in Fig. 2b to make the diagram as simple as possible for the purpose of this paper), which means that if passengers can do something else while traveling, this "something else" makes travel less "time consuming." The IPTS study included certain factors regarding time utilization. For example, an hour on the train while reading is not a full travel time hour. As shown in Fig. 2a, time utilization can create more transport demand and it can influence the modal split via the mechanisms already explained, it has roughly the same effect as an increase in speed.

An alternative approach is to convert time into money, leading to the question of the subjective economic value of time spent on travel. The economic value of travel time has been investigated in empirical studies since the 1970s. As an example, if drivers have the choice to pay a fee to cross a bridge or to accept detour for crossing a bridge without paying a fee, these choices can be related to their income. It is known from such studies that the value people assign to the time spent while driving a car is between 1/3 and 1/2 of their net hourly income [18]. So it is not the same as working, but it is related to income. The advantage of this approach is that time cost could be added to fuel cost and other variable cost, yielding one price for each pkm. It would then be easier to apply demand elasticity data to determine the size of the rebound effect. There would be no specific time rebound, just the economic rebound effects. However, one problem with monetizing time is that the marginal value may increase dramatically; the second hour per day spent in traffic might be much more expensive than the first one, considering this makes the approach less different from the constant travel time budget approach than it may look like.

Quantification of rebound effects

Previous studies on rebound effects have presented the calculation of the magnitude of rebound effects. For example, Borenstein [12], in his microeconomic framework or evaluating energy

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efficiency rebound, provided illustrative calculations for improved auto fuel economy and lighting efficiency and showed that rebound likely reduced the net savings by roughly 10% to 40% from these energy efficiency improvements.

How could such a quantitative analysis be conducted using the models discussed in this paper? Each of the models would have to be run in two versions (so-called competitive models, [19]), an original version and a version with those feedback loops cut which are responsible for rebound effects. The model outputs, such as total energy consumption of passenger transport or total passenger transport volume, could then be compared quantitatively among the two versions. Such a simulation experiment could also be refined to a larger number of model versions by disabling only one type of rebound effect at a time.

To our knowledge, none of the two models discussed in this paper has been used in this way. This is due to the fact that the aim of designing these models has not been to quantify rebound effects, but rather to make predictions in the passenger traffic sector while considering the rebound effects.

6. Conclusions

The two models we discussed both represent the same types of rebound effects in passenger transport. Both are multi-modal transport models, considering the dynamic change of modal split as well. Feedback loops (closed causal chains) are an obvious concept to model rebound effects at a macro-economic level as it is done in System Dynamics (as opposed to use behaviour rules at the micro-economic level in agent-based simulation).

Despite the similarities, the comparison of the two models showed that there can be much variety in the details of modelling rebound effects in passenger transport. Model 1 puts greater emphasis on the different characteristics of transport modes and how they interact, on time utilization and virtual modes, whereas Model 2 explicitly considers investment in technology and environmental attitude as variables in the main feedback loops.

Future research should clarify how these elements can be consistently combined in a model of passenger transport that accounts for the dynamics of rebound effects while considering the various impacts of ICT on transport.

Acknowledgements

The authors would like to thank Empa, KTH (Center for Sustainable Communications), and Vinnova which made this work possible as a part of the first author’s PhD project.

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