Feedback loops in mobility and recommendations on system transformation – the Swiss case

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To accelerate the transformation to a sustainable mobility system, we propose a causal loop diagram to better understand the dynamic behavior of policy interventions and trends. As such, we identified five core agents through a set of expert interviews. By utilizing concept maps and causal loop diagrams we further integrated subcomponents of each agent into a holistic and connected model, enabling the qualitative assessment of feedback loops. We use the example of battery electric vehicles and evaluate policy measures and trends on their potential impact on adoption. In addition, we set the causal loop diagram, trends and niche-innovations into the context of socio-economic system transformation to grasp the full potential in transforming the prevailing private, fossil fuel based, car regime providing recommendations to support this transformation. The causal loop diagram could serve as a basis for in-depth quantitative studies and deepened assessment of feedback loops in transforming mobility systems.

1 Introduction

Mobility is a basic need of the society as it serves as a connection between spatial structures. It enables the connection between home and workplace as well as shopping and leisure trips. These connections drive the industry and social interactions making it an integral part of everyday life. Despite mobility being of utmost importance, it also creates tension and negative effects such as accidents, congestion, emissions (e.g. CO_2, noise) and land use (Docherty et al., 2018; Holz-Rau and Scheiner, 2019). One of the main drivers of these negative effects is the use of private fossil fuel internal combustion engine cars, a technology that was developed more than one century ago and is still considered to be the current prevailing regime, for individual mobility (Bladh, 2018). However, we experience a plethora of societal, technological and environmental trends that set the current mobility system under pressure giving space for opportunities and risks (Corwin et al., 2015; Prognos, 2016). With increasing populations, higher GDP per capita, and continuing urban sprawl, demand for mobility is rising (Holz-Rau and Scheiner, 2019). In light of current environmental threats, and particularly climate change, this poses serious challenges for many countries in the world, as they agreed to reduce their CO_2 footprint at the Paris Agreement in 2015. In line with the convention, the

Fukushima disaster in 2011 and radical changes in the international energy environment, Switzerland responded with its Energy Strategy 2050. Its main goal is to effectively use the potentials of energy efficiency and exploit the potentials of renewable energy technologies (UVEK, 2018). Today, the transport sector is responsible for 31% of Switzerland's CO_2 emissions making it the largest CO_2 emitter, even larger than the industry, which ranks second (20%)(BAFU, 2017).

Within this paper we follow the mission proposed by the Swiss Competence Center for Energy Research in Mobility (SCCER Mobility), which is to "develop the knowledge and technologies essential for the transition of the current fossil fuel based transportation system to a sustainable one, featuring minimal CO_2 output and Primary Energy Demand as well as virtually zero-pollutant emissions" (SCCER Mobility, 2017). In the first phase of SCCER Mobility a profound knowledge base has been created to understand the meaning of system transformation, current trends as well as which components are relevant in the transformation process (Hoppe et al., 2017). Yet, policy measures need to be directed to a certain component within the mobility structure. These components are not isolated fractions but rather entwined in a complex and interacting system that together with various feedback mechanisms lead to an outcome. It is thus crucial to understand the dynamic effects they could exert on the system.

The effect of an intervention on the mobility system is hard to capture without the help of a mental model. Mental models are mostly used in the field of system thinking to understand how causal relationships and feedbacks work within everyday problems (Doyle and Ford, 1998). Such models are visualized through causal loop diagrams (CLD) in system dynamics (SD). SD have gained frequent attention in the recent years, especially the application in modelling the transition pathways or diffusion of alternative powertrain options in the transportation sector (Harrison et al., 2016; Harrison and Thiel, 2017; Pasaoglu et al., 2016). It is argued that SD has a crucial benefit over traditional methods like agent-based modelling, forecasting, optimization, or time series based approaches as it accounts for feedback mechanisms, non-linearity and behavioural aspects (Harrison et al., 2016). The field of application of SD in transportation ranges from powertrain transition forecasts, strategic assessment of policy strategies to modelling interactions with other sectors (e.g. land use models, energy demand, econometrics, etc.). With SD models in transportation, research typically aims to achieve the following targets that can be roughly divided into three segments:

1. Powertrain/fuel transition forecasts (Feng et al., 2019; Pasaoglu et al., 2016; Struben and Sterman, 2008)
2. Strategic assessment of policy strategies (Fiorello et al., 2010; Sayyadi and Awasthi, 2017)
3. Modelling interactions with other approaches (e.g. land use)(Pfaffenbichler et al., 2010; Yao and Chen, 2015)

While the majority of studies apply SD for policy testing a combination of the above mentioned segments is common as well (Gerboni et al., 2017). The multi-level perspective developed by Geels (2002) provides a framework on how to qualitatively discuss and investigate pathways to a sustainable mobility system. Still, to the best of our knowledge, no application of the multi-level perspective to system dynamics has been applied so far, despite the mutual relationship in qualitatively assessing transformation pathways of both methods. Hence, building on the findings of the first phase of SCCER Mobility, we analysed the main components of the Swiss mobility system derived therein and investigated in their role as major interacting agents. Since battery electric vehicles (BEV) are one of the main drivers of change in the current transportation system and recognized as the most promising niche innovation, we want to understand the key factors in how to accelerate the adoption of BEVs to support the sustainable transformation of the Swiss mobility system. The main research questions for this paper is thus the following:

> How to apply system dynamics to the multi-level perspective for the Swiss case to understand key factors in the Swiss mobility transformation with respect to BEVs?

We structured the remainder of the paper as follows: first, we give a short overview of the applied methods in section two. In section three, we apply the multi-level perspective from Geels (2002) on the Swiss mobility system. Here, the relevant agents defining the socio-technical regime are defined by applying concept maps and the system dynamics approach. We then summarize the macro-level developments referred to as megatrends and give a short overview of niche-developments. With the deepened understanding of the mobility regime, trends and niche-developments, we finally investigate two influential trends on their feedback structure within the mobility system. Last, in section four and five, we provide recommendations on the micro-, meso- and macro-level of the transformation process and make a final conclusion.

1.1 Causal loop diagrams in system dynamics

To get a holistic overview of how and why mobility landscape changes and niche-developments like new BEVs influence the whole mobility system and its components, a dynamic and holistic approach is necessary. The methodology of system dynamics (SD) allows to include equation-based connections between components and captures feedback within the system, enabling to test the new mobility services and changing lifestyles on their potential impact. Unlike other modelling approaches that try to examine one part of a system and break it into smaller and smaller pieces, system dynamics looks at the system as a whole. The complexity of interactions and dependencies between components can thus be captured and investigated.

The essential tools in system dynamics are causal loop diagrams (CLD) and stock and flow diagrams (SFD) where the former is applied in qualitative- and the latter in a quantitative framework. These two tools are the central concept of SD theory, whereas in this paper, we will only focus on the use of CLD.

When thinking of any system, causal or feedback loops exist. These direct and indirect links determine the behaviour of the system over time. Yet, our mental models when thinking of such systems with many feedback loops rapidly come to its limits. Therefore, the use of CLDs help us in bringing the mental models to "paper" and visualize the complexity. Within a CLD links are represented by arrows and the agents by variables. The variables are connected with said arrows that could either be a reinforcing (positive) or balancing (negative) dependency. Within a reinforcing loop, an increase in one parameter leads to an increase of another, which would increase exponentially if no other relationships exist. The balancing loop consists of a parameter that – when increased – leads to a decrease of another, until a dynamic equilibrium is reached (Harrison et al., 2016). Variables that only influence another variable but are not influenced by any other variable themselves are referred to as exogenous variables while those who have an influence on and are influenced by another variables are defined as endogenous variables. Figure 1 depicts a simple example

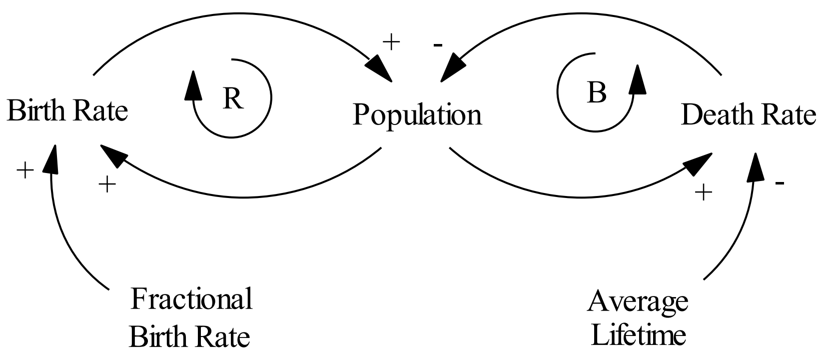

Figure 1: Example causal loop diagram according to (Sterman, 2000).

model with two feedback loops that determine population. The loop on the left is reinforcing. A high fractional birth rate (exogenous) leads to a higher birth rate (endogenous), eventually increasing the population, which in turn increases the birth rate again. In contrast, a higher average lifetime decreases death rate (negative dependency, thus depicted with a minus symbol), which increases population. The higher population yet leads to a higher death rate, which decreases population again, leading to a balancing feedback loop (Sterman, 2000).

While the example above only contains two loops, CLD can grow very fast and easily become confusing instead of providing a good overview of the system at stake. It is thus important to only focus on the main components and sometimes aggregate several sub-components into one single component. Still, CLD are very powerful tools to qualitatively assess the dynamics of a complex system and are especially useful to grasp the feedback structure.

2 Methodology

The transformation of a stable regime to a new and eventually stable regime is a very complex task as it is embedded within an environment of a mix of diverse actors, their feedbacks, rules and established habits. It is thus of high value to utilize a framework to better understand the context in which change happens or needs to happen. The multi-level perspective is considered to be a well-established framework for this task (Chang et al., 2017). It is characterized by three levels that together define how transformation can happen (Figure 2). The core therein is the socio-technical regime "a coherent, highly interrelated and stable structure … characterized by established products and technologies, stocks of knowledge, user practices, expectations, norms, regulations, etc." (Markard and Truffer, 2008, p. 603). Besides the socio-technical regime or so called status-quo, developments on highest level, such as megatrends exert pressure on the regime eventually leading to windows of opportunities for a transformation to happen. These landscape developments are characterized by "a set of factors that influence innovation or transition processes but are hardly (or only in the long run) affected by themselves" (Markard and Truffer, 2008, p. 603). On the niche-level, technological as well as social innovations are described within the framework to disturb the regime by having a "protective space for path-breaking innovations" (Smith and Raven, 2012, p. 1025). Since the multi-level perspective as shown in Figure 2 does not specifically address the mobility sector, we conducted five semi-structured interviews with experts from economy, geography, transport engineering and system dynamics, aiming to find a consensus on the top-tier actors within the mobility system as well as their most relevant sub-components (Hoppe and Michl, 2018). Once we defined the core agents of the mobility regime, we used concept maps to structure the thinking-process of defining what sub-components are embedded within the main agents of the mobility system. The concept map normally starts with a super-ordinate focus question that wants to be answered and then adds sub-ordinate parts in the manner of a hierarchical tree-like structure (Davies, 2011; Novak and Cañas, 2008). Our concept map for the mobility sector can be found in Appendix A1. After deriving the sub-components of the mobility system we performed an extensive literature review on existing CLD in the transport sector. This enabled us to integrate specific components from these CLDs for each agent into a holistic system representing a combination of the socio-technical regime and system dynamics (Harrison et al., 2016; Pfaffenbichler et al., 2008; Shafiei et al., 2015; Struben and Sterman, 2008). Last, experts in the field of mobility validated a first and second draft of the CLD.

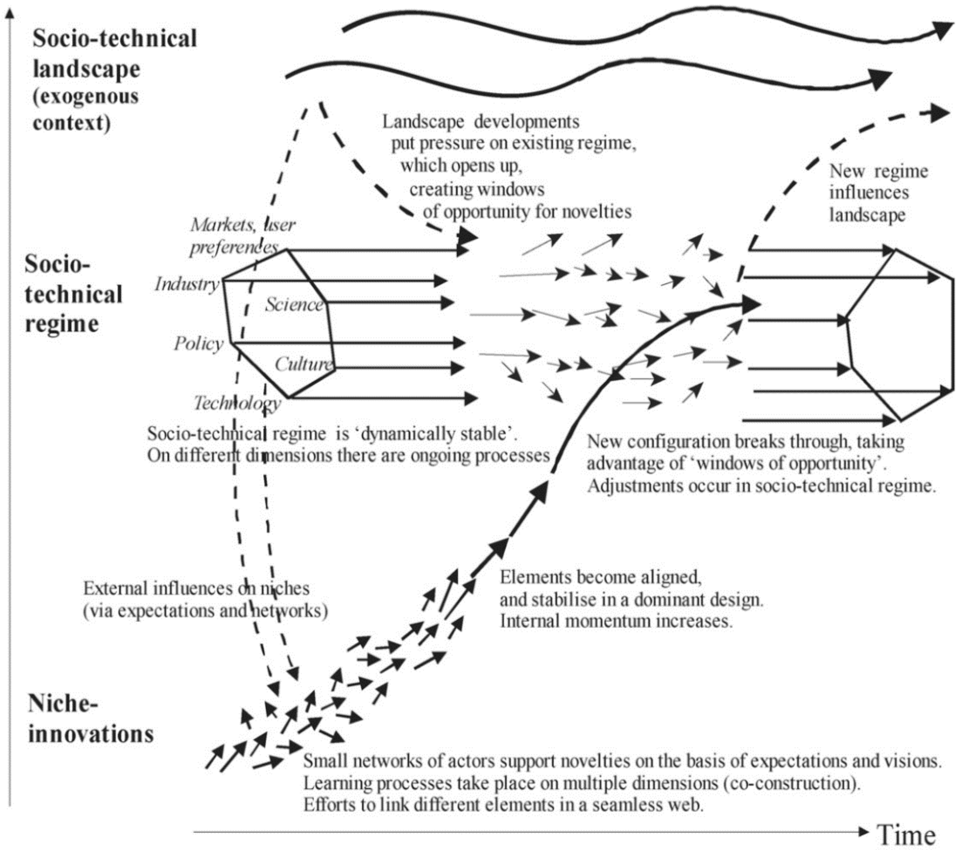

Figure 2: Multi-level perspective on transitions (Geels, 2012).

3 Results

3.1 Socio-technical regime

The Swiss meso-level is dominated by a highly dense and connected public transport network and the use of private fossil-fuel based cars – the current leading regime. Switzerland is considered to have one of the world's most dense rail network (Buehler and Pucher, 2012). Still, 66% of the total daily mobility demand is conducted with private cars in average (BFS and ARE, 2017). Many subaltern regimes (like cycling and walking) exist within the system. The regime is kept stable through the interaction of a set of agents. The main agents have been defined as the government, the economy, society, spatial structures and institutions, which differ from the six dimensions depicted in the multi-level perspective (Figure 2) by representing actual agents instead of dimensions. As such, dynamic relationships in the CLD can be better described. For a first, holistic overview the agents can either have an influence on- or be influenced by another agent. Double-headed arrows depict interactions and the red arrows visualizes where the direct emissions, such as CO_2, come from (Figure 3). For specific mobility related questions, one can then further investigate the sub-components. Examples of the first set of sub-components are shaded in orange. For instance, the actions of society - in regard to the topic in question that is mobility - can be defined through the culture, reasons for mobility and mobility behaviour. In Figure of Appendix A, this hierarchical structure is widened to many sub-components, allowing to get a deeper understanding of the system. Be aware however, that the arrows don't depict causal relationships, (like in the causal loop diagram), but the hierarchy of the component within the main agent. Such structural mapping of a system is crucial to elucidate which components are defining the system and to get a general overview. In this way, a deeper understanding of the whole system and the position of components therein can be achieved. Once the system has reached enough depth for the scope of the study, it can serve as an input for the causal loop diagram.

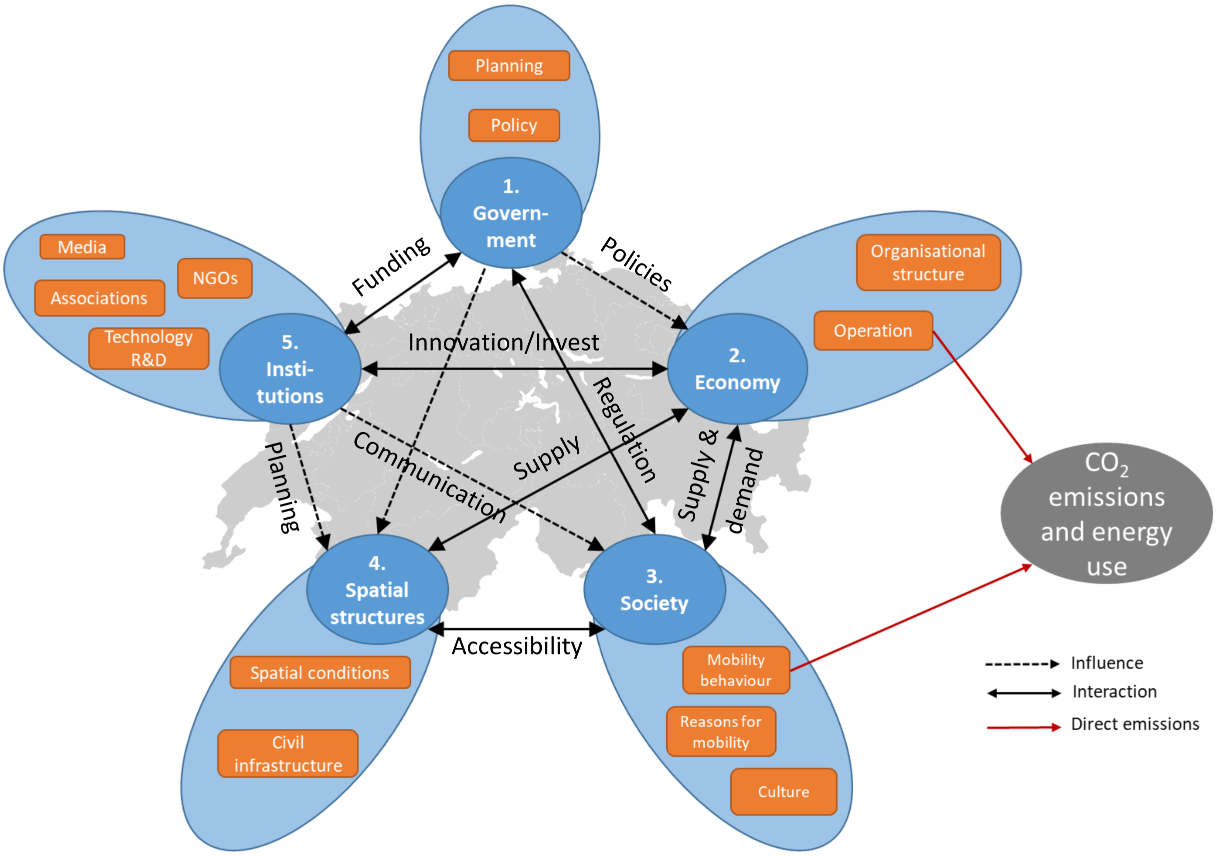

Figure 3: Overview of the five core agents of the mobility system and their influence/interaction.

Mobility behaviour and the connected value chain of the economy lead to CO_2 emissions. Yet, as we see in Figure 7 these components are embedded within a plethora of other components and interactions between the five core agents. Finding the cause and effect relationship is not possible within this structure. To convert these concept maps into a CLD, we applied an agent-based approach similar to Harrison et al. (2016). Note that by "agent-based" we refer to the conceptualised term of a specific group within the whole CLD in contrast to agent-based modelling that models individuals as agents. The five core components, government, economy, society, spatial structure and institutions thus serve as the agents in the CLD and are represented with separate colour each. Figure 4 depicts this CLD with a specific focus on the adoption of BEVs.

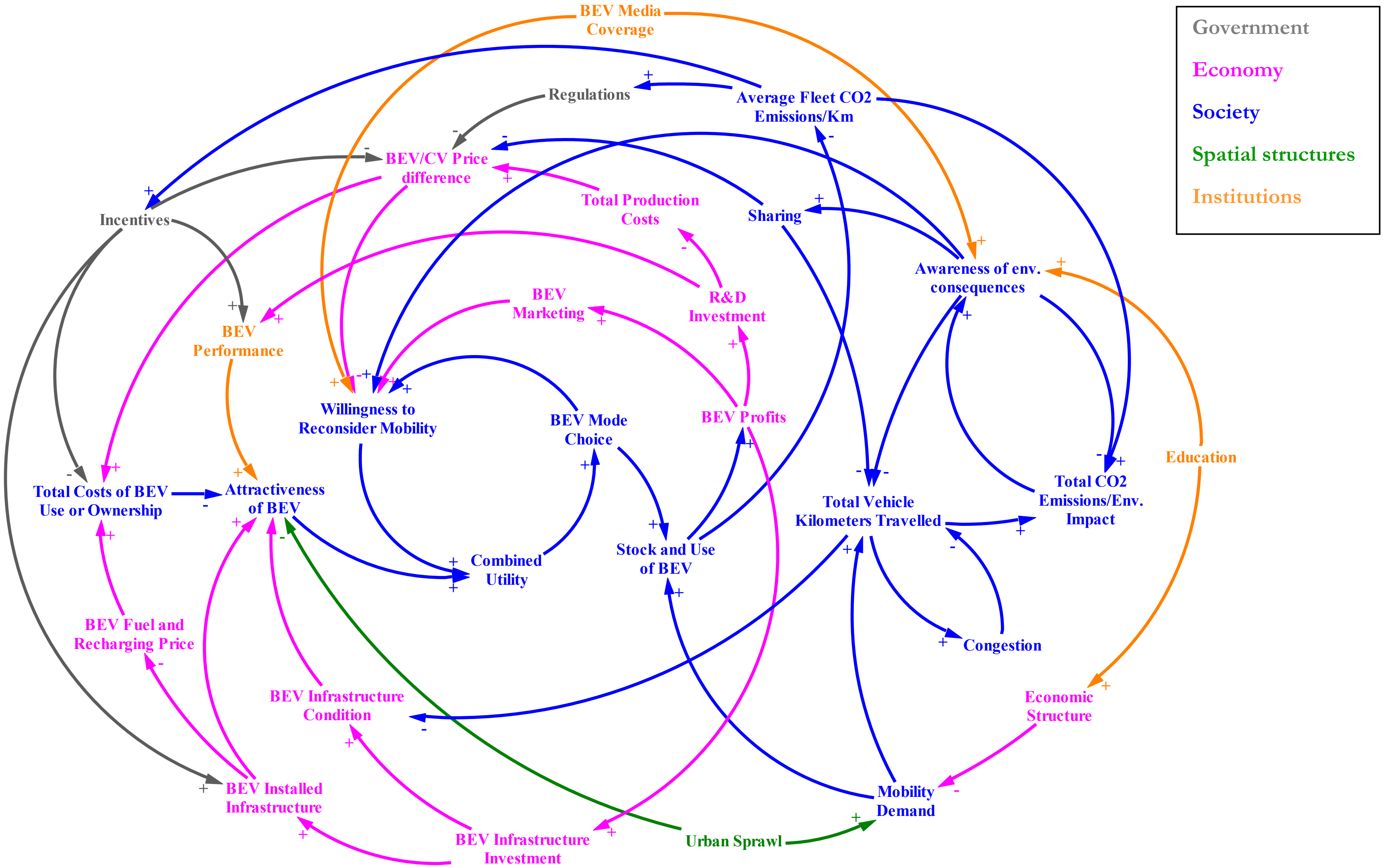

Figure 4: CLD of the Swiss mobility system using the example of BEV. CV stands for conventional vehicle.

3.1.1 The government agent group (grey)

Within the CLD we simplified the government agent group to act through incentives and regulations, which are mostly altering the price for society and costs for economy, respectively. One can either incentivize to buy and use BEVs or discourage the uptake and use of conventional vehicles (CV). As such, only few components are visualized within the CLD but they could have a strong influence on the whole behaviour of the system as steering mechanism through price were found to be very effective (Sierzchula et al., 2014).

One of the most common governmental regulations are taxes and penalties. Many countries around the globe incorporated penalties on new car sales if the fleet average exceeds a certain amount of CO_2 emissions. A prominent example in Europe is the obligation on vehicle manufacturers to achieve an average CO_2 emission performance target for all vehicles they sell in Europe. This target was set to 130 g CO_2/km in 2015 and to 95g CO_2/km in 2021 (European Environment Agency, 2018). As Switzerland is not a vehicle manufacturer but imports most of the cars from Germany, they are directly affected by this obligation.

Within the CLD, regulations affect the BEV/CV price difference, which is a negative relationship since higher regulations lead to lower BEV/CV price differences.

Tax-exemptions are another way to incentivize the uptake of energy efficient cars BEVs. Taxes for automobile owner occur in different ways, for instance as a registration tax, annual circulation tax, road tax or toll roads. A combination of a variety of tax exemptions for electric cars is common and most prominently executed in Norway. In Switzerland, tax-exemptions and other benefits for electric cars vary strongly among cantons. According to a comparison from Touring Club Schweiz (TCS), road tax are calculated using either the total weight, cubic capacity, power and CO_2 emissions or a combination thereof. Huge differences are the result sometimes even leading to a higher road tax for a BEV in comparison to a similar gasoline/diesel car (TCS, 2018). Still, this remains a minority as road taxes are lower for BEVs in most cantons (TCS, 2018). Energy efficient cars can also benefit from cheaper car insurances. The comparison from Comparis (2018) revealed an average cost reduction of 20% for BEVs in contrast to a comparable fossil fuel car. For one insurance company this reduction was even over 50% (Comparis, 2018). Yet, the Swiss government does not influence the car insurance rate nor grants any subsidies for the purchase of electric cars and so far only acts through road tax benefits.

Incentives influence the BEV/CV price difference, the performance of BEVs through research funding, the installed infrastructure and consequently the total costs of BEV use or ownership.

3.1.2 The economy agent group (pink)

The economy is responsible for providing vehicles, services and infrastructure. One of the main decisions within the CLD is the allocation of profits to marketing, R&D investments and infrastructure investments. With more investments in R&D the total production costs can be minimized leading to a lower price for the consumer, which eventually increases the willingness to reconsider mobility. Similarly, more marketing could increase the willingness to reconsider mobility directly. In Switzerland, the auto-lobby is not as strong as in neighbouring countries such as Germany where many car manufactures are present. Yet the car-sellers still interact through marketing, while investments in R&D is mostly done outside of Switzerland.

On the lower end of the CLD, investments in infrastructure (such as road, rail, recharging stations or power production) can improve the network, traffic-flow or its condition leading to more convenience and as such, attractiveness of BEVs. With an increased number of recharging stations as well as power production, prices for BEV could fall and finally reduce the total cost of BEV use or ownership. In addition, the increased amount of charging stations fosters the convenience of BEV leading to a higher attractiveness of these modes. Investments in infrastructure such as charging stations are done by the big car manufacturers in order to maintain a broad network and better convenience of their electric cars for the customers. But also companies invest in their own charging stations for their employees and private interest groups increasingly build charging stations where the network is sparse.

The economic structure refers to the organization of the company (refer to Figure 7) that could influence the mobility behaviour (e.g. distribution of working sites determine commuting characteristics). With a more sensible focus on the possible feedback effects on mobility, actual mobility demand could be reduced.

3.1.3 The society agent group (blue)

Many important decisions, such as mode choice or travel demand have to be made by the society. With 13 components they thus represent the biggest group within the CLD followed closely by the economy (10 components).

Mobility demand can be understood as the summary of all commuting, business, shopping and leisure trips undertaken by the society. With an increased mobility demand that origins from population growth and increased distances travelled, the stock and use of BEV will rise, as well as the total vehicle kilometres travelled (VKT). With this increased use of BEV the average fleet CO_2 emissions/km will fall, eventually determining the amount of regulations and incentives deployed by the government. The reduced CO_2 emissions of the car-fleet further reduce the total CO_2 emissions. In contrast, an increased VKT increases the total CO_2 emissions, finally increasing the awareness of environmental consequences that could lead to more sustainable mobility behaviour. The average Swiss citizen drives 24 kilometres per day with a car, where the majority of this distance driven are due to leisure activities (44%), followed by commuting (24%)(BFS and ARE, 2017).

A crucial part within the CLD is the combined utility that defines BEV mode choice. It stems from the idea that a certain technology (electric vehicle) or service (carsharing) first needs to enter into the decision making process through being confronted with this novelty or niche. This is referred to as the willingness to reconsider mobility within the CLD and originates from Struben and Sterman (2008). Together with the total cost of BEV use or ownership that increases the attractiveness of BEV if reduced, the combined utility is computed. Finally, choice to purchase or use a BEV determines the percentage of stock and use of this mode among all mode options.

3.1.4 The spatial structures agent group (green)

While only urban sprawl is visualized as a component of the spatial structures within the CLD it could have a strong impact on mobility demand and the attractiveness of certain modes such as BEV. Additional subcomponents of spatial structures such as the availability of leisure facilities on a regional context or the distribution of charging infrastructure are not described within this holistic CLD in order to retain lucidity of the model. Yet, they could be addressed when going deeper into specific feedback loops of the CLD.

3.1.5 The institutions agent group (orange)

Three major components characterizing the institutional agents are described within the CLD. The only endogenous component is the BEV performance, which stems from the research activities of institutions that receive funding from the government or economy. With an increased performance of a variety of attributes including; safety, quality and efficiency, the attractiveness of the mode in question will rise.

Another important institutional component is the media coverage for a specific vehicle or vehicle service. Especially with the increasing trend of digitalisation and social media consumption, the influence of the media cannot be neglected. Major press or free of charge newspapers shape the perception of mobility technologies, decreasing or increasing the willingness to reconsider mobility. Furthermore, the awareness of environmental consequences could be affected as well.

The last institutional component is education, which could influence the awareness of environmental consequences and the economic structure of companies and administrations, as for instance, increased home-office, sustainable mobility management and sufficiency principles.

3.2 Socio-technical landscape and niches – current mobility related trends

The socio-technical landscape describes the changing frame conditions for the socio-technical regime on a macro level. It can be referred to as the factors that have an impact on the functioning of a variety of innovation and interaction processes without being affected by the outcome of these new establishments in the short- to medium-term (Markard and Truffer, 2008). Widely known examples of such factors (referred to as trends or megatrends) are climate change, ageing of society, fossil fuel demand of developing countries or changing lifestyles. They exert pressure on the current regime by challenging the existing structures, demanding for niche-innovation to change the locked-in path of the regime.

A niche is a space where innovations can originate, such as within start-ups or research institutions. They do not yet contain the stability and continuity of a regime as a critical size is lacking. They could either be in the form of new technology or business models. A prominent example for a niche-technology is electric mobility, which, for the moment, only serves consumers willing to test the new technology (early adopters) yet experience a clear increase in market share, slowly pushing itself into the fossil-fuel car dominated regime.

In mobility, we can identify three main technological niche-developments:

- Electric vehicles
- Autonomous driving
- Mobility as a service (including a variety of sharing services like car-/ridesharing or bikesharing)

New governance models, that foster sustainability in mobility include:

- Flexibility of work-related mobility (home office, tele-communication, coworking spaces)
- Smart regions and urban planning that decrease the need for mobility (sufficiency principles)

Table 1 serves as an overview of current trends and their relevance for mobility as well as their expected change and agent characterization.

Table 1: List of trends and their relevance for mobility and system agents adapted from Hoppe et al. (2017)

Factor	Expected development in the future	Relevance for mobility	Positive/negative change on sustainable mobility	Agent
GDP	⬆ Slight increase - with uncertainty	★ Economic growth and activity lead to commuting	– Slight increase of mobility demand	Economy
Working population	⬆ Slight increase but slowing down (in a medium scenario)	★★ Potential commuters	– Slight increase of mobility demand	Economy
Fuel price	⬆⬆ Moderate increase with volatile dynamic	★ Mode shift depending on the price elasticity	+ Reduced / stabilized car use	Economy

Population	↑↑	Moderate increase (in a medium scenario)	★★	Mobility demand of new inhabitants: work & leisure	− −	Moderate increase of mobility demand	Society
Age group over 65 years old	↑↑↑	Considerable increase	★★	Special mobility needs of the aging population beyond commuting	− −	Moderate increase of leisure mobility	Society
Age group under 24 years old	↔	Lower/constant share of population	★	Lower share of driving licenses	+	Slight decrease of car use	Society
Incomes	↑	Slight increase depending on GDP / competitiveness	★	Increasing travel distance and time	−	Increase of (leisure) mobility	Economy
Land use	↑↑	Urban sprawl	★★★	Regionally differing impact on travel demand and modal choice	− − −	Longer travel distances; increasing use of car or PT depending on infrastructure accessibility	Spatial structures
Regulations on CO_2 emissions and energy consumption	↑↑↑	Considerable increase in strictness of the regulations	★★	Evolution of powertrain and fuels, but system remains car-based	+ −	Single cars more efficient; effects depending on mobility demand (→ rebound effects)	Government
Length and capacity of the road network	↑	Slight increase	★	New roads areas increase attractiveness of car use	−	Slight increase of car use	Economy
Length and capacity of the rail network	↑↑	Moderate increase	★	New and faster connections increase attractiveness of public transport enabling long distance commuting	− −	Moderate increase of public transport use & commuting distances	Economy
Evolution of powertrain and fuel	↑↑	Evolution towards alternative technologies	★★	Innovation will occur, but the system is still based on individual vehicles (cars)	+ −	Constant mobility demand with shift between vehicle categories	Institutions
Sharing economy	↑↑	Moderate increase on supply and demand side	★★	Diffusion of the "mobility as a service" paradigm	+	Shift towards multi-modal mobility with reduction of private car	Society
Digital revolution	↑↑↑	Increase in ICT-based mobility options, e.g. Mobility as a Service (MaaS)	★★★	Change of individual mobility patterns	+	Reduction of individual car use and increase in intermodality / PT use	Institutions/ Economy

	↑↑ Further development in teleworking options	★★ Potential increase in remote work	+ Reduction of car use and mobility demand in general	Economy
	↑ ICT based organisation of road transport	★ Efficiency increase of roads with partly automated driving	– Increase of car use	Economy
Disruptive technologies - driverless cars	↑↑↑ Expected market entrance in a decade	★★★ Change of mobility culture on the level of individuals and society	– – Increase of individualized moblity and of individual vehicles use	Institutions/ Economy

3.3 Feedback loops within the Swiss mobility system

As we have seen in the previous section, a variety of trends are creating windows of opportunity for niches to flourish. Yet before rushing to displace an old system with new ones, it is important to investigate the possible feedback mechanisms that such a change would bring in order to be better prepared for possible unintended feedbacks. As shown in Table 1, the trend for urban sprawl and MaaS show the strongest influence on the mobility system. Hence, we investigate the effect of these two highly influential trends on the adoption of BEVs with the help of the CLD (Figure 4).

3.3.1 Urban sprawl

The Swiss citizens are increasingly living in the surroundings of the centres and suburbs (ARE, 2016). Hence, travel distances are expected to increase as people live outside of the city but work within the city (Christiansen and Loftsgarden, 2011). In the CLD urban sprawl would increase, creating an increased mobility demand, which in turn increases total vehicle kilometres travelled and as such, impacts total CO_2 emissions. On the other hand, an increased urban sprawl could increase and decrease the attractiveness of BEVs in many ways. For example, living in sub-urban and rural oriented regions provides more opportunities to install a private charging station as private garages and parking lots are typically less available within cities, increasing the attractiveness of BEVs. Contrary, the longer average distance to go to work could increase range anxiety and therefore decrease the attractiveness of BEVs. With a decreased attractiveness of BEV, the combined utility also decreases leading to a reduced purchase of BEV, which in turn increases average fleet CO_2 emissions that increase the total CO_2 emissions again. However, the increased average fleet CO_2 emissions are likely to trigger more strict regulations that increase the price of conventional fossil-fuel based vehicles (CV), reducing the price difference between BEV and CV consequently could increase the willingness to reconsider mobility. Simultaneously, the total cost of BEV ownership could be reduced through increased incentives and reduced BEV/CV price difference enhancing the attractiveness of BEV. Now, the increased willingness to reconsider mobility and attractiveness of BEV could lead to a higher combined utility and as such, a higher share of BEV purchase. This example calculation thus reveals a balancing feedback loop. Still, the strengths of each feedback loop is unknown and would need further research to be able to tell which one would dominate the system.

3.3.2 Fostering the sharing economy – increase in Mobility as a Service (MaaS)

The increased use of ICT-base technology such as MaaS is expected to have a high impact on the mobility system by offering an appealing alternative to the private car (Hoerler et al., 2019). Such alternatives could include carsharing, bikesharing, tram, bus, train as well as on-demand services (taxi) and are booked through a single mobile phone app (Lyons et al., 2019). MaaS knows plenty of different definitions, whereas we adopted the following term by Heikkilä (2014, p. 8): "MaaS is a system, in which a comprehensive range of mobility services are provided to customers by mobility operators" with mobility operators being a "company, which buys mobility services from service producers, combines them as a service supply and provides the services to customers".

An increased use of MaaS, could reduce the total vehicle kilometres travelled by providing attractive alternatives to the private car, consequently reducing the total CO_2 emissions. Furthermore, reduced vehicle kilometres also reduce congestion, which in turn increases vehicle kilometres again, representing a balancing feedback loop. A further feedback or rebound effect stems from the "freed" parking lots increasing the attractiveness of using the car again (Mounce and Nelson, 2019). It is thus important to use the "freed" space to enhance quality of life, by e.g., converting the space into pedestrian walkways or parking for slow modes. MaaS could decrease the need for a high-range BEV by offering a simple and easy-to-use alternative (e.g. carsharing) for the rare cases a small BEV would not be sufficient for a specific trip (Hoerler et al., 2021). Since occasional use of MaaS in combination of owning a small BEV could decrease overall mobility costs compared to owning a large, high-range BEV, the attractiveness of BEVs could increase. Another opportunity represents the use of BEVs within carsharing services which could increase the willingness to consider buying a BEV through an easy first access to this new technology (Schlüter and Weyer, 2019).

MaaS could thus have the potential for two sustainable mobility effects, one in reducing vehicle kilometres and another in increasing the share of BEV usage, both leading to a reduction of total CO_2 emissions.

4 Recommended actions on the micro-, meso- and macro-level

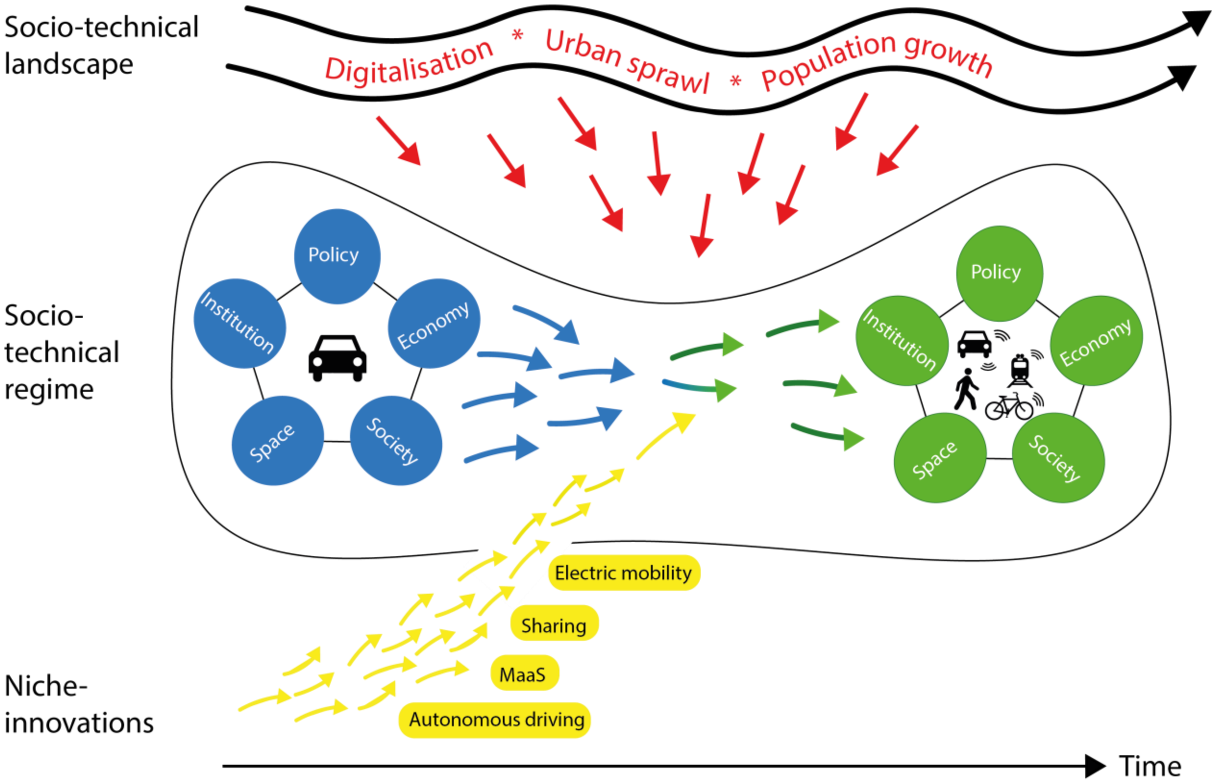

Figure 6: Multi-level perspective on the Swiss mobility system, adapted from Geels (2012).

The Swiss mobility system is undergoing a transformation process. While we have seen several landscape developments (megatrends) that weaken the bonds of the prevailing regime, emerging niche-innovations increasingly take roots into the mass market, displacing the old ones. As such, change is slowly but continuously happening. In light of the increasing adverse effects of climate change we need to accelerate this transformation. In this chapter, recommendations are given for the three levels as defined in Figure 6.

4.1 Niche-innovations (micro-level)

Niche-innovations need a protected space for development as they would not survive within the mass market due to costs generally being too high for being competitive. It is thus encouraged to create mobility-related funds and initiatives that support niches financially, providing an environment for testing and allow feedbacks for the continuous improvement of the innovation. Such niche-innovations have been found to be MaaS, free-floating carsharing, commuting mobility management and electric, autonomous vehicles. While Switzerland is generally considered to be a favorable place for innovations to flourish (Hollanders and Es-Sadki, 2018), overcoming the initial hurdles of growth and establishing a customer base is a difficult task. Often, the technology is developed and ready, yet doesn't find a high enough demand to sustain itself. Stronger public-private partnerships, where e.g. public administrations commit themselves to sustainable mobility such as incorporating a carsharing system or supporting new forms of services like MaaS could help these niches to grow. Additionally, Hoerler et al. (2019) and Hoerler and Hoppe (2019) suggest that there is still a strong openness gap between the commuters and transport-related stakeholders (such as administrations, industry, planning & research, policy etc.) in using sharing services like car-/ridesharing and bikesharing as the stakeholders showed a much higher openness. Building user-friendly options that take the considerations of the society into account are key in rising the openness to these modes.

4.2 Socio-technical regime (meso-level)

Figure 6 illustrates the transformation process that the current socio-technical regime needs to undergo. In order to grasp the windows of opportunities that arise from megatrends and niche-innovations, the five core agents need to work closely together. As we have seen in the previous sections, these agents are interconnected, having influence and being influenced by each other as well as creating a variety of feedback loops that determine the final outcome of interventions. To make use of niche-innovations like BEVs the combined utility of these modes need to rise. To achieve that, an increased marketing from the economic sector, combined with information campaigns by the government and research activities could trigger an increased presence in the media, leading to a higher willingness to consider such vehicles. On the other hand, the availability of overnight charging could significantly increase the attractiveness of BEVs (Patt et al., 2019) and therefore the utility of BEVs. The still prevalent range anxiety is especially present in suburban and rural areas, where trip lengths are typically longer. MaaS and carsharing services could be a potential solution in this regard, since trips where the range of the BEV is not sufficient could be covered by these services. The service provider could thus engage in a public-private cooperation in order to define the hotspots for carsharing stations (or in the case of free-floating carsharing secured parking lots) and complement the public transport network. With a well-defined network, access to the services can be raised, increasing the attractiveness of these new mobility services. Lastly - and probably most importantly – financial support from initiatives and public administrations could reduce the total costs for users, increasing the attractiveness again. Together with an increased willingness to reconsider mobility and the increased attractiveness of BEVs and these services the combined utility will rise, eventually leading to a higher adoption rate.

Similar pathways can be defined for other innovations like autonomous driving. The interplay between strong economic actors, functioning as supporters and partners of niche-innovations, governmental incentives and regulations, the involvement of the public, consideration of spatial characteristics and guidelines from research institutions shape the sustainable transformation of the Swiss transport sector.

4.3 Socio-technical landscape (macro-level)

Macro-level developments such as digitalization, urban sprawl and population growth need to be detected, understood and incorporated into the agenda of the transformation process. They exert pressure on prevailing old systems, in this case fossil-fuel based private cars, facilitating the breakthrough of niche-innovations. How these landscape developments actually influence the core agents needs to be investigated by research. Digitalization for example enabled new forms of social interactions, working structures and the way we live our lives. Such changing lifestyles also change the interaction with other agents within the transport system. How and if these lifestyles actually contribute to more sustainability needs to be investigated in order to continuously steer the transformation into the planned direction.

5 Conclusion

Switzerland agreed to reduce CO_2 emissions in line with the Paris agreement in 2015 and to increase energy efficiency within transport by the Swiss energy strategy in 2017 (UVEK, 2018). Within this paper we established an overview of system agents relevant for this transformation process, how they interact with each other and provided recommendations on how to make use of existing trends and emerging niche-innovations.

We described five core agents that define the prevailing car-dominated mobility regime with the help of causal loop diagrams (CLD). Within this diagram, various important feedback loops are present, most notably the reinforcing effect of financial incentives by the government and investment into marketing and infrastructure by the economy. The society's choice of mode strongly depends on these actions as well as on the increasing willingness to reconsider mobility through increasing customer base of sustainable mode options. Institutions, the like of media and research associations, also shape the perception of the respective mode and thus willingness to reconsider ones mobility. Education, which falls under the institutional agent, could accelerate the transformation through increasing the awareness of environmental consequences as well as new and sustainable working structures (e.g. home office, mobility management within companies). Lastly, the ongoing trend of urban sprawl increases mobility demand yet offers the possibility to adopt more sustainable mode options like BEVs by fostering charging stations that are easier to install in private garages and parking lots usually present in more dispersed environments compared to the core city.

This work could serve as a basis for qualitatively investigating policies on their potential effect on the diffusion of new and sustainable mobility offers as well as final CO_2 emissions. It also provides an overview of how a system transformation needs to consider the windows of opportunities that stem from megatrends and niche-innovations. Even though our focus was set on Switzerland, the model parameter and interactions are generalizable to other countries as well due to its holistic and qualitative nature. While no quantitative system dynamics model has been applied in this study, the current CLD could be used in future research to define a set of important feedback loops for an in-depth quantitative analysis.

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Appendix A

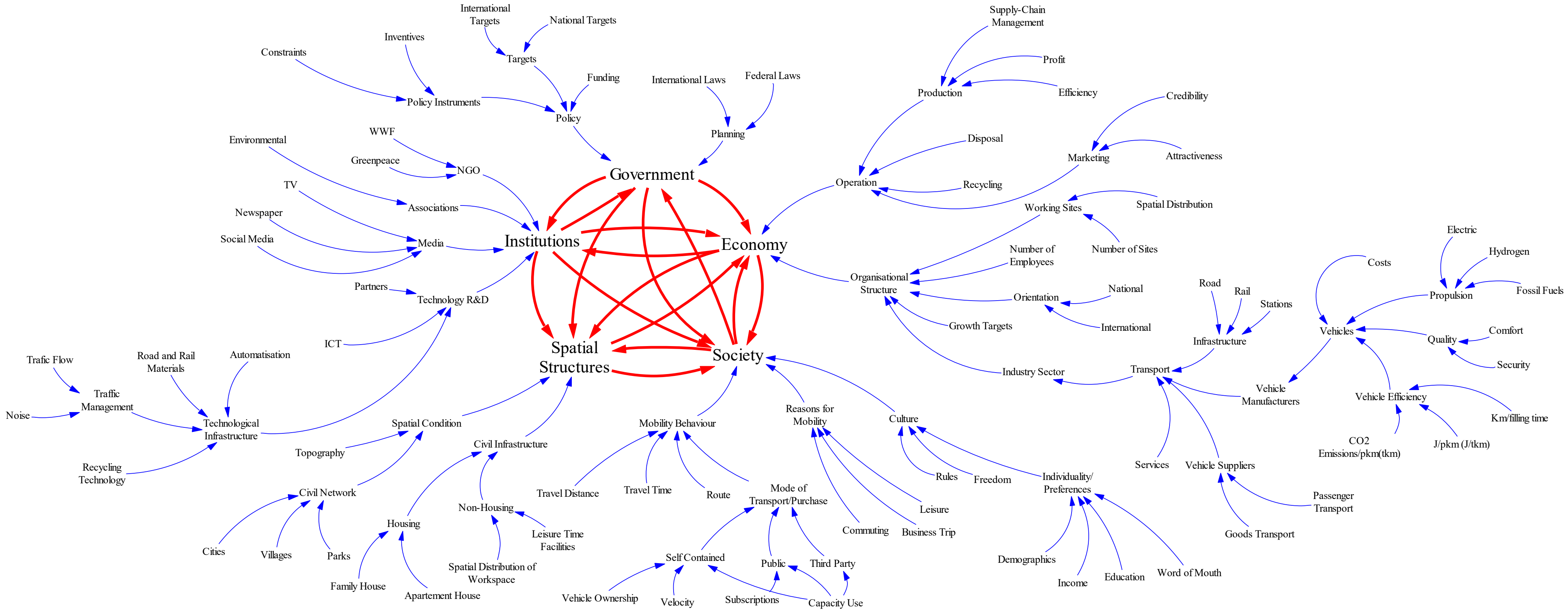

Figure 7: Hierarchical concept map of the mobility system, depicting the subcomponents of the five core agents.

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