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Supporting decision-makers with a web-based system dynamics tool

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Abstract

New mobility technologies and services are emerging rapidly with potentially large effects on future transport behaviour. System dynamics can manage the complexity in such systems and enable analysis of a large amount of dynamic effects over time, ultimately increasing our understanding of different potential futures and assisting in the formation of robust policy strategies. We have developed a system dynamics tool which focuses on capturing the dynamics of the uptake of battery electric vehicles, shared mobility services and connected autonomous vehicles, and how the three fields are interconnected. The tool is accessible through a user-friendly web-based interface. The purpose is to allow for an iterative process in testing the system behaviour under different assumptions and ultimately increasing the policy-makers' understanding about the most influential drivers of change. The ambition is to further develop the model to support decision makers in planning for the future in a robust way.

Keywords:

System Dynamics, Future Mobility, Scenario Planning

Introduction

New mobility technologies and other growing relevant trends interfere with policy makers' ambition to create robust and future-proof plans. More and more city officials come across issues with new mobility services, such as transportation network companies and shared micro-mobility (1,2). Focus is given to new infrastructure and policy that can encourage electrified mobility and accommodate for autonomous vehicles when they appear in large numbers (3). Decisions are made in a transitioning environment, with climate concerns, an ageing population and social isolation being highly discussed topics and influential factors in all stages of planning. Additionally, the COVID-19 crisis and the recovery from it creates an additional layer of uncertainty for most areas in transportation planning, at least in the short-term and mid-term horizons.

It is important for decision makers to find policy combinations that can take advantage of the new technological advancements in mobility and lead to a net positive effect for their area of interest. Positive effects may among others mean less congestion, higher traffic safety, fewer emissions, fewer private vehicles, a more efficient and equitable transport system, all of which contribute to a region's sustainability. These goals are often well articulated in long-term development plans, however the strategic choice of policy measures that will lead to their achievement is less clear.

Successful decisions demand skills that are seldom concentrated in only few people; experience of dealing with transport issues, experience with new technologies, knowledge of the local environment, transport modelling and other technical skills. Thus, a larger number of participants is required to take part in workshops and other strategic meetings to discuss possible solutions and propose new ones, based on the knowledge gained during previous similar occurrences.

There are two main reasons why traditional modelling approaches may be less successful in meeting the demands of this decision process. Firstly, the combination of technological advancements with uncertain development, both in extent and time-wise, create a complex environment with many unknown variables and relationships, that traditional tools are not capable of handling. Not only are the effects of these developments non-linear, but they may even counteract or reinforce one another, not least in different points in time. This behaviour is difficult to simulate with models that are built to use the current situation and assumptions about the linear development of some parameters to predict the future. A more systemic approach is required instead.

Additionally, the standard process of agreeing upon a set of policies to be tested and producing the corresponding results requires resources and is time-consuming. Modelling competence needs to be employed, traditional tools need long times to run and result delivery can also be delayed. Furthermore, the process often lacks transparency; people with non-modelling backgrounds may interpret results in a different way, leading to false assumptions about which factors were most influential and what should the next set of test policies include.

To address these challenges, we have employed the system dynamics method to build a model that can simulate dynamic environments with inter-related components and have developed a web-based interactive interface to enable exploration of results and the underlying model features that have led to them.

The tool focuses on capturing the dynamics of the uptake of battery electric vehicles, shared mobility services and connected autonomous vehicles, and how the three fields are interconnected. The underlying model includes variables regarding technological development, total cost of ownership and adoption behaviour parameters for all technologies. Additionally, there are technology-specific modules, such as range for electric vehicles and safety as well as congestion for autonomous vehicles. The model also includes policy levers, for example emissions taxation and technology subsidies as well as external factors, such as growth in population and GDP. In combination, these components allow the study of new mobility trends and services from a broader, systemic perspective.

The system dynamics tool is accessible through a user-friendly web-based interface. Transparency is a key principle in the interface design as users can access the model structure and explore its components and structure. The purpose is to allow for an iterative process in testing the system behaviour under different assumptions and creating multiple scenarios, ultimately increasing the policy-makers' understanding about the most influential drivers of change.

System dynamics – an overview

System dynamics is an analysis method for exploring complex systems over time, a system in this context meaning any defined set of interconnected components (4). Fundamentally, the system dynamics approach involves going away from simplifying problems by assuming smooth, linear processes for the sake of making numerical predictions, and instead thinking about a problem as a complex result of causes changing over time. To understand or predict the behaviour of one node in a system, system dynamics theory emphasizes the need to understand the whole system, as all system components will be affecting the variable of interest.

The dynamic, cyclical thinking is intuitive as the real world is rarely linear. Yet, feedback effects and other dynamics are often overlooked in modelling analyses which opens up space for systems thinking as a complementary tool for problem-solving (5).

Practically, much of the focus when using a system dynamics approach is laid on mapping the relevant components of a system and the functions that describe the links between cause and effect. Another central element in the system dynamics approach is depicting time-lags between cause and effect, which is particularly relevant when including policy-making in the system, since it is often performed with substantial time-lags. Capturing the causal effects between parameters enables simulation of feedback loops, a key strength of system dynamics modelling (5). A feedback loop is a cyclical effect whereby a change in a parameter ripples through the system, eventually amplifying or reducing the magnitude of the same change over time.

To be able to represent the complexities of large systems, system dynamics modelling is typically performed on a macro level using high levels of abstraction (6). Through a macro lens, inevitably, the level of detail is reduced and variables are often created as average representations of large populations. Consequently, system dynamics modelling can be helpful for understanding complex systems and the but is less useful for accurately predicting numerical outcomes (7).

The model components

Electric vehicles

The electrified mobility portion of the model consists of the following inter-related components:

i) Battery Technology Development

The rate at which electric vehicles technology develops may be faster with public or private investment. The amount invested is related to the sales figures of electric vehicles.

ii) Range and Range Anxiety

Both the actual issue of insufficient range as well as the psychological effect of the fear of insufficient range are modelled, coupled with the available range in the vehicle market and the charging infrastructure in the transport system.

iii) Exposure

The amount of recognition electric vehicles receive through industry marketing, public information campaigns or simply by their increasing presence on the road can together contribute to the enlargement of their potential user base.

iv) Price

The economics of owning and operating an electric vehicle are important for the consumer to decide on purchasing one.

v) Relevant Policy Measures

Policies such as purchase price subsidies or other taxation will form the economic and infrastructure environment that the electric vehicle market will function in.

There is a considerable amount of information on how electrified mobility has been more or less successful in different markets and under various policies, especially compared to the other two technologies that are studied. However, uncertainties remain regarding some of the model components.

How will the battery economics work in practice? The dynamics between the technology advancements and its introduction in the market are dependent on the willingness of car manufacturers to shift a larger portion of their production and sales to electric vehicles. This willingness is at an unknown degree for the time being and there may be a lagging effect that should be introduced in the model.

What mix of public and private charging infrastructure is most efficient? Although both public and private charging infrastructure are considered in the model, there is uncertainty regarding their effect on the decision to purchase an electric vehicle or to even consider it as an alternative to an internal combustion engine vehicle. It is also important to understand the reverse dynamics of the relationship, i.e. how does owning an electric vehicle affect the choice of purchasing a home charger.

How effective will marketing be in the future? With other technological trends appearing in the digital landscape, it is possible that the effect of marketing will change and possibly be different for each individual. Simultaneously, a characteristic of younger generations is that they are more environmentally conscious, which may also affect their response to information campaigns.

What other innovative policy measures may be developed in the future? There are measures such as separate road infrastructure or subsidizing private businesses with electrified fleets that may become more relevant soon. Additionally, the emergence of new digital technologies may enable other innovative measures that we cannot envision today.

Shared mobility

The shared mobility portion of the model consists of the following inter-related components:

i) A replacement trip module that is a simplistic logit choice model to distribute trips among car, public transport and a ride-hailing alternative.

ii) A complementary trip module that calculates the potential of ride-hailing as a first-mile / last-mile solution for public transport.

iii) An exposure module that considers consumer behaviour and marketing efficiency.

Ride-hailing has been introduced in several cities, but its uptake is very dependent on local environment and regional travellers' attributes. Therefore, some other relations need also be modelled and improved upon.

What evaluations do individuals have on different aspects of their trip? There are cultural differences among regions regarding the willingness to walk or cycle to a public transport station and the value of travel time with different modes. Additionally, these evaluations may develop in various ways with new technologies, such as higher autonomy in private vehicles or more amenities in public transport vehicles.

Which other shared mobility modes can become relevant within the current model limitations? The model focuses on trips that are longer than 5 kilometres, which in turn excludes modes that are in principle used for shorter trips. Shared micro-mobility is a rapidly growing area of interest and car-sharing services may become more popular in the future.

How can mobility as a service affect individual choice? There are pilots and a few implementations of MAAS in various parts of the world. These create a reinforcing effect on the available alternatives, as it makes them easier to find, combine and compare to each other. The pricing of the alternatives as well as of the MAAS membership is also decisive.

What infrastructure and pricing policy can encourage or discourage the development of new technologies? There are examples of pricing policies in place that may qualify the more sustainable solutions over those that encourage higher car use and lead to congested cities. Pavement management and differentiated charging, for example in line with caused congestion or emissions, may be a significant advantage for a specific technology.

Connected and autonomous vehicles

The connected autonomous vehicle portion of the model concerns a fully developed technology where no driver is required, either in the car or remotely (Autonomy Level 5). The inter-related components that constitute this portion of the model include:

i) Traffic safety

As more components of vehicles become autonomous, the human factor in driving will be smaller. A high number of traffic accidents are caused by human error. Therefore, a future of autonomy will mean a safer transport system.

ii) Price

The price of autonomous private vehicles will initially be too high for widespread adoption. Technological developments will allow for a larger share of the population to afford an autonomous vehicle.

iii) New potential users

A fully-autonomous vehicle will mean that the client base for private transport will be enlarged. People without driving licenses, minors and other groups that were not able to drive a conventional car, will have the option to purchase an autonomous one, without needing assistance in its use.

Being a technology with minimal existence in the transport system today, autonomous vehicles have a higher degree of uncertainty than the other two technologies. Some of the points of uncertainty can be summarized here.

How will economies of scale function for connected autonomous vehicles? It remains to be seen how the rate at which autonomy is adopted will affect the purchase price of these vehicles. At the moment, it is expected that the initial phase will be quite unstable and those involved will act on a ‘learn-by-doing’ basis.

What effect can delay in regulation have in the technology adoption? There is already legislation in some regions regarding the regulatory environment in which connected and autonomous vehicles will evolve and which already allows self-driving vehicle tests on public roads. It will however take a different size of effort and time span to create a legal framework that can accommodate issues such as data-sharing standardization or liability insurance for car owners.

How will the intermediate situation of combined presence affect the transport system? It is expected that different levels of autonomy will be using public roads simultaneously, as technology will be introduced in a continuous manner. The effects of this mix will mean a loss of efficiency in the system and safety risks in case the technologies are incompatible. Further study of these effects may reveal a counteracting influence, for example on setting the regulation or on the individuals’ willingness to purchase a vehicle of higher autonomy.

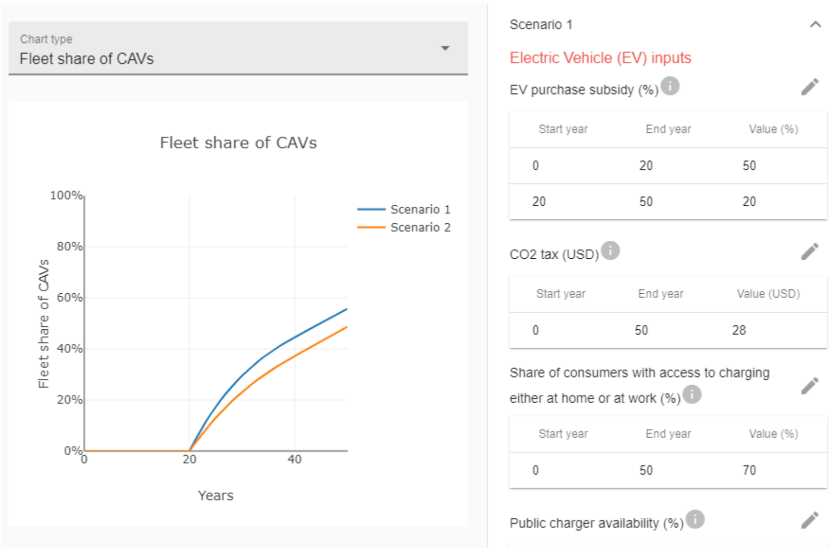
What behavioural change may autonomous mobility bring about? The ability to use in-vehicle travel time for other purposes, such as working, leisure or rest will mean that the evaluation of it will change. This evaluation is one of the key components in current transport models of mode and destination choice and will therefore need to be updated with new information when this becomes available.

The web-based interface

The initial model was built in the system dynamics modelling software Vensim. Although the software has all the required functions and can simulate the complex relationships that are included in the model, it does not provide with a platform that enables quick and user-friendly modifications, especially when the user is not familiar with the entire model and/or the method of system dynamics.

This led us to the decision of developing a web-based interface that can be functional, quick to run models on and easy to use even without technical, modelling or significant mathematical knowledge. This transformation was based on the Python library PySD, which parses a model file from Vensim and translates the result into Python. The model can be executed independently of the Vensim environment.

The visualization of the model input and output was built with the Python library matplotlib. The input part consists of a wide range of variables which the user may modify the value of over time. The output is a selection of variables that are deemed important and can be shown in form of time series. The user may add scenarios with different input combinations, run them in real time and compare the results.



Screenshot of the web-based platform, with example input (right panel) and output (left panel)

Applications

With its ability to capture the complexity of non-linear relationships and the development of future trends not yet widely considered in established transportation models, the tool has been employed in projects where these trends needed to be evaluated more accurately, two of which are presented below.

Motorway future capacity, WSP for Swedish Transport Administration

The circumstances created by future mobility raised the Swedish Transport Administration's interest in the capacity requirements for road 155 in Sweden. After the implementation of three scenarios using traditional demand models, the system dynamics tool was used to predict an additional five where the uptake of electrical and automated vehicles continues uninterruptedly. The output of vehicle kilometres travelled was observed and compared among the scenarios. The quick adaptation of the tool to local characteristics gives in an additional advantage on other methods.

Future ready kerbside, WSP for Uber Australia & New Zealand

Uber is one of the largest ride-hailing services worldwide. The aim of the project was to understand how Uber's service will affect or be affected by their own development and various policies governing kerbside management. The system dynamics tool was used to demonstrate what the potential make-up of the vehicle fleet in 2050 could be – including electric vehicles, automated vehicles and ride sharing – if a number of shared mobility principles are to be held. Model variables such as access to charging points, marketing for technology, costs for different modes of transportation and taxation of fossil fuels were tweaked over a 30-year analysis period and in a series of scenarios. Applying the principles led to a two-fold increase of ride sharing trips after 10 years and nearly double that after 30 years, compared to a baseline case. Furthermore, the fleet electrification rate was higher in the principles scenario, leading to the electric vehicles share being 3 times higher after 10 years, compared to the baseline scenario; the latter recovered in the following years and reduced this number to 2.5 at the end of the period.

Policy-making with the tool

The overall purpose of the tool is to provide the users with a clearer understanding of the concurrent reinforcing and counteracting dynamics of the modelled system and to assist in better informed policy-making that considers a wider range of factors. It can be used in elements of a long-term planning process, the context of which consists of work meetings and co-operative discussions to produce a consensus over the proposed policies. The system dynamics method can handle the amount of complexity in the questions and can combine the different knowledge bases of the participants, as well as the results of previous work. The user-friendliness of the interface assists in the exploration of the underlying model relationships and the rapid testing of combinatory policy ideas in different future scenarios.

Several application areas have been identified for the existing base model. Firstly, it can be used to produce input for future scenarios in transport modelling and increase the confidence in assumptions on vehicle ownership, operating costs and shares of new mobility vehicles, be it electric, shared, autonomous or combinations of these. Policy discussions on the development of new battery charging infrastructure and how to combine it with existing or proposed subsidies for alternative fuel vehicles will also gain from using the tool. The development of public transport and the gains or losses it will experience from the rise of transportation network companies can be discussed as well.

As more information and experience-based knowledge becomes available in the areas of interest, some of the model elasticities may become outdated or insufficient. The strength of a system dynamics model is that it needs relatively low effort to update the existing relationships and to add new relevant variables in the model. This also holds for adding new areas of interest and expanding the model to include more modules, which can be directly or indirectly related to the existing ones.

The base model can be expanded to deal with issues in more application areas. The socioeconomic developments will affect and be affected by new mobility and can thus be a field of expansion. The environmental impact of the new technologies is a topic of interest for most countries and it can be included in the analysis too. Other, more city-level issues can also be the focus of future model versions, such as pavement management and road congestion.

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