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Building feedback into modelling impacts of automated vehicles: Developing a consensus model and quantitative tool

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Abstract

System dynamics offers a rigorous approach to modelling the sometimes-surprising dynamics endogenous in complex systems and is ideal for gaining insight into potential impacts of automation in transport. Researchers from Europe and the U.S. are developing a consensus model, starting from an impact assessment framework presented at TRA 2018 and published shortly thereafter. This paper reports on a 2019 group model building workshop, which collated the intelligence of a diverse international group of modelling, transport and liveability/equity experts, focusing on socioeconomic impacts of highly automated vehicles, from household and public authority standpoints. Subsequent work developed a general framework from which detailed system dynamics models can be created for specific research questions. The ultimate goal is to develop a quantitative tool that can help planners and policy-makers understand how highly automated vehicles may fit within the transport system, and to begin to explore consequences of potential actions under various scenarios.

Keywords: system dynamics; automated vehicles; impact assessment; scenario planning; causal loop structures; feedback

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1. Introduction

Over the past few years, researchers from Europe, Japan and the U.S. have together created and revised a framework for assessing the multi-faceted impacts that may arise from automated vehicle (AV) deployment (Innamaa et al. 2018). The EU-US-Japan Trilateral Sub-Working Group for Impact Assessment, under the Trilateral Working Group for Automation in Road Transportation, has begun to use system dynamics to gain further insights into potential impacts, the linkages between them, and to investigate change over time. This approach will also allow members of the group to create quantitative, working models, thus operationalizing the framework.

The application of system dynamics modelling to transport problems is not new. Examples from the literature include Struben & Sterman (2008), examining the transition from internal combustion engines to alternative fuels, and the work of Pfaffenbichler, Emberger, & Shepherd (2010) to develop the Metropolitan Activity Relocation Simulator (MARS) model for the interaction of transport and land use. Shepherd (2014) has a review of system dynamics models applied to transportation, and most recently, Harrison, Shepherd, Chen, & Barnard (2019) presented a paper focusing on the factors affecting uptake of connected and automated vehicles.

The trilateral group's work using system dynamics kicked off with review of several possible scenarios of deployment of shared highly automated vehicles (SAE Level 4) at a special interest session (SIS89) at the 2018 Intelligent Transportation Systems World Congress in Copenhagen. Level 4 AVs can operate without a driver as long as they remain within a certain operational design domain, such as that defined by a particular geo-fenced area or lane or by certain road characteristics and other conditions, such as clear weather (SAE International, 2018). Level 4 was chosen because (a) it is likely to be technically feasible and (b) as there is no need for a driver, it could lead to significant impacts on mobility and land use that lend themselves to analysis using system dynamics. The emphasis on shared mobility is similar to scenarios developed in Rämä et al. (2017) and Grio et al. (2019).

Members of the trilateral group, as well as other invited researchers in the field, then built on the World Congress results during a group model building workshop in Leeds UK, in April 2019. This workshop was held in conjunction with the 2nd Annual Workshop on System Dynamics in Transportation Modelling, hosted by the University of Leeds Institute for Transport Studies and sponsored by the Transport Special Interest Group of the International System Dynamics Society.

The workshop in Leeds focused on the socioeconomic impacts of automation, with particular emphasis on (1) questions of equity and disparate impact on different groups of travellers, (2) mobility, and (3) wellbeing and quality of life. One breakout group focused on individual mobility while the other considered societal issues, such as the role of public authorities and liveability of cities. Participants considered a scenario in which highly automated vehicles operate within a geo-fenced area of approximately 5 by 5 kilometres, where such vehicles are available for trips to local destinations and as first-mile/last-mile service to a commuter train station. These AVs represent more than 50 percent of vehicles within the area but operate within mixed traffic. While personally-owned AVs are available in the scenario, most people use vehicles owned by a publically-available fleet, reserving a vehicle for each desired trip.

This emphasis on a system dynamics approach used in the Leeds workshop brings a comprehensive feedback lens to impact assessment for automation. Assessing automation's impacts is a challenging endeavour that the trilateral impact assessment sub-group and many others have been tackling for several years (e.g., Smith et al., 2015; Milakis, van Arem, and van Wee, 2017). Beginning with a group model building exercise allowed the group to efficiently collate the intelligence of a diverse international group of modelling, transport and liveability/equity experts to kick off the next phase of work.

This paper presents the results of the workshop in Leeds and subsequent work towards a high-level consensus framework for understanding the key actors within the system, their goals and principal interactions, and the impacts of the introduction of AVs. Researchers can use this framework to pursue quantitative tools to address their particular research questions.

2. Workshopresults

A number of factors surfaced at the Leeds workshop that could affect how such a system based on shared AVs in a restricted area would work, and how the travel behaviour of people living in the area could be affected by it. Factors included:

The importance of quality of travel: This category includes a sense of safety (Would you send yourself? Your children?). It also includes whether the traveller has the opportunity to do something else while travelling, which may be more important on longer trips than on these trips within this 5 by 5 km area. Additionally, when considering ride-sharing opportunities, although multiple travellers sharing a journey could lower each traveller's monetary cost, the additional time required to pick up and drop off the passengers, as well as the loss of personal space, could offset any benefits. Finally, in a situation with lower travel costs, there could be delays due to possible additional congestion or lack of vehicle availability arising from induced additional travel demand.

Attractiveness and usability: The attractiveness of an AV option is relative to that of the alternative modes available for the journey that is to be taken. Within the geo-fenced area, competitively priced shared AVs could affect the use of other modes. For instance, they could encourage people away from car ownership, and, separately, change the attractiveness of active travel (walking or cycling). However, the operational design domain of the AV, and use of active travel, can both depend on weather. Looking at a broader geographic scale, options for trips outside of the geo-fenced area (i.e. to the final journey destination) influence travel behaviour within; for example, the level of service on the commuter rail line serving the zone, the availability of highways, or the presence of a comprehensive regional cycle path could affect wider travel behaviour. Turning our attention to equity, there could be challenges in ensuring that all have access to the AV service. Social exclusion is a risk. For example, price structure and operational design domain could mean that some people do not have access to the service.

Cost and business model: It is important to distinguish operator cost from traveller cost. In addition, the pricing structure chosen by the operator or system manager affects perceived cost for travellers, which in turn affects travel behaviour. Additionally, some people currently use their personally owned vehicles to convey a part of their identity or social status. How will automakers, and travellers, react to the growth of fleet-based travel, which could be seen as threatening the use of personally owned vehicles? Finally, AVs will add some costs to travel at the same time that they remove others, and these may be incurred directly by a different actor. For example, new costs could include control room infrastructure and remote monitors, although higher vehicle utilization may reduce the total ownership cost that must be built into the price charged. As AV technology is still developing, the costs of facilities and services are as yet unknown.

System management: The design, management and governance of the overall transport system will be complex and require collaboration among multiple actors. With mixed traffic (automated and non-automated), mixed ownership models (shared and private), as well as pedestrians and cyclists within the geo-fenced area, who will be responsible for setting and maintaining guidelines and standards? What will be the roles of the public and private sectors, and will these vary inside and outside of the AV's operational design domain? How will fairness in traffic management be defined, and ensured? Legal and regulatory structures, such as who is responsible for an AV's behaviour around impaired road users and even the minimum age for traveling alone, are likely to vary nationally and possibly regionally, and can also depend on how technology eventually develops.

Land use: A large fleet will likely be needed to maintain reasonable service at peak times. Where will vehicles park to minimize wait times and will the public accept their presence waiting, for instance, near their homes? Will vehicles travel around empty instead of parking? What will be the effect of AVs on allocation of road space, and curb access, among competing uses? Additionally, AVs can lead to changes in land value which can affect equity.

Other findings that came out of the workshop were related to expected challenges in the development of our consensus understanding of these issues. For example, on a practical note, the group noted that relevant terminology and concepts differ slightly among the participating countries, such as "ride-hailing", "vehicle-sharing", "trips" and "Mobility-as-a-Service" (MaaS). SAE guidance (SAE International, 2018) on terminology has recently been published and could be helpful. Travellers may change how they use vehicles in ways that are difficult to imagine now. New travel patterns and new en route activities may emerge. Some of these can be explored via testing several scenarios, though some may simply be outside of what we can reasonably imagine, as, for instance, all the uses of the modern Web could not have been foretold at the beginning of the Internet era.

3. Building a consensus impact assessment model

The April 2019 workshop identified the factors above to address further, and began linking them into a causal loop structure. Fig. 1 shows a high-level schematic. Because not all of the polarities of the links are defined, and the feedback loops are not yet identified, this is not a formal causal loop diagram.

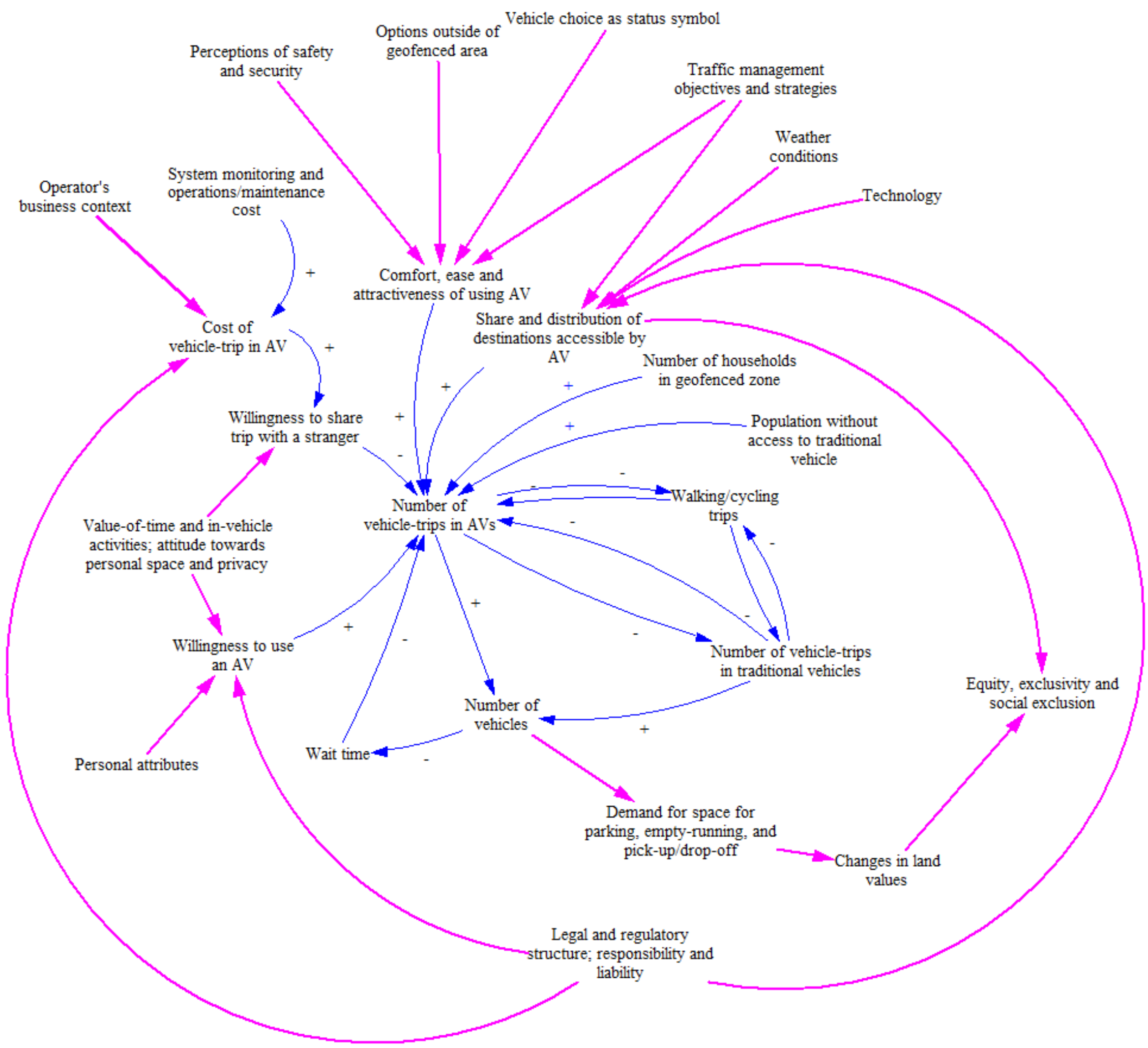

Fig. 1 High-level schematic of the causal loop structure developed at the April 2019 workshop (source: authors)

Arrows in Fig. 1 indicate a link between a pair of items; links shown are not exhaustive but indicate the principal proposed impacts. Thin blue arrows have a clear proposed polarity. In accordance with accepted system dynamics notation, a plus sign means that the link is positive (or "reinforcing"): increasing the first item, all else equal, will lead to an increase in the second item, and decreasing the first item will, all else equal, lead to a decrease in the second. A minus sign means that the link is negative (or "balancing"): an increase in the first item leads to a decrease in the second, and vice-versa. Around the outside of the diagram linked with thicker pink arrows there are the as-yet less-fully-defined groups of factors that can impact the system with a polarity that can be determined once the factor is better defined. For example, "traffic management objectives and strategies" is a placeholder for a more in-depth discussion that will lead to precise variables, with clear polarity, which can then be modelled and simulated. Similarly, "technology" will need to be defined more precisely as a level of technological capacity, in a measurable manner. Additionally, as further development goes forward, relevant feedback loops will be identified, most likely working one at a time with smaller pieces of the larger system shown in Fig. 1.

During the summer and early autumn of 2019, the authors and other members of the trilateral group revised this model to focus at a higher level, creating a framework that will be useful for a broader range of research questions (Fig. 2). Although our attention remains on AVs, in order to understand the wider context the framework identifies the major generic roles within the transportation system and considers how they interact within the context of both traditional and new modes. Roles include the end users of transportation, the entities that control availability of transportation to end users, and the infrastructure and technology providers. Following on from this, we have identified agents within the system with specific relevance to AVs, and suggest the short- and long-term goals of the agents in each role, as well as how automation may affect the agents in ways relevant to their goals.

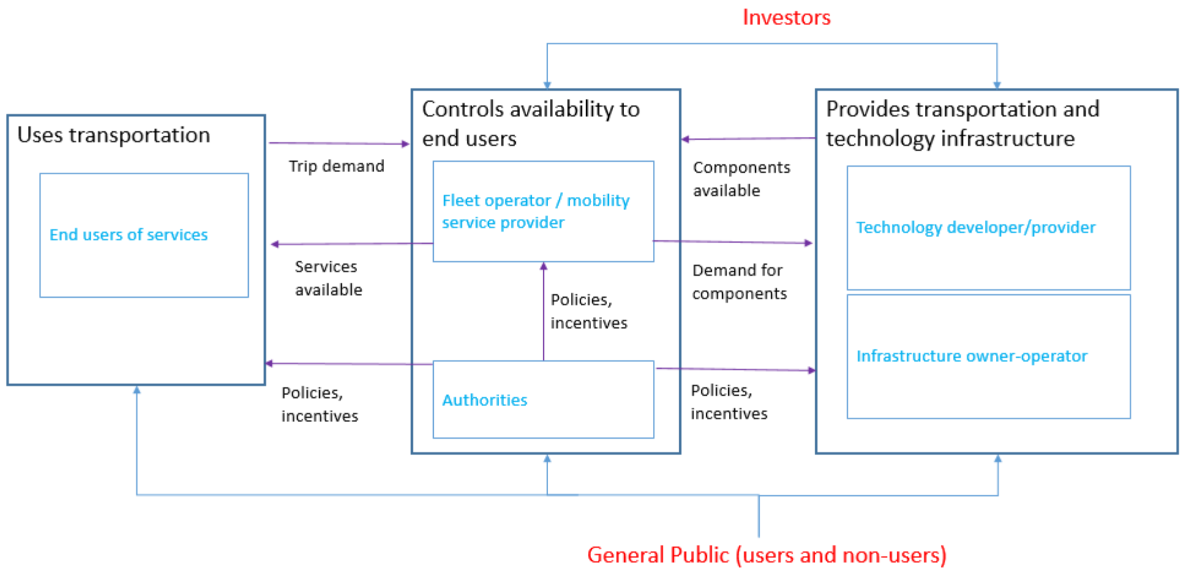

Fig. 2 Diagram of major roles and how they influence each other (source: authors)

The end users of services create demand for either personal, business or freight (parcel delivery) travel, by deciding how much, when and how to travel, or, in the case of freight, which parcel trips to create. A long-term goal is to preserve asset value, such as monetary or other perceived value of property or local services for a resident. End users are constrained by budgets of time, money and effort. These budgets, and the effort to use a particular mode of travel, may vary significantly by person, based on location, economic status, and cognitive or physical ability to use a mode. User choice sets in terms of transport modes are determined by the users' capabilities and desires, tempered by the options that are commercially available for desired trips, as well as by any rules laid down by the authority role. Examples of end users, with short- and long-term objectives, are shown in Table 1, which also provides some relevant potential impacts of automation.

Table 1 End users: examples and objectives

Agent	Short -term objectives	Long-term objectives	Potential automation impacts
Private individual	Make safe trips using the most appropriate mode of travel. In the mid-term, fulfil mobility needs in a safer, faster, more comfortable and/or more sustainable manner	Preserve asset value	• Reduced in-vehicle value of time • Increased comfort • New options for non-motorists • Changes in land use

Agent	Short -term objectives	Long-term objectives	Potential automation impacts
Business	Travel to meet clients or attend appointments on time and at lowest cost	Maintain reputation	• Opportunity to continue working whilst travelling – better use of time and potential to cover longer distances
Freight (shipper)	Optimize shipping cost and performance	Efficient, sustainable and reliable flows for the goods that they transport	New delivery options

In a traditional sense, the fleet operator and mobility service providers acquire (and dispose of) and/or offer vehicles and other technologies to satisfy the travel demand of the end-user. These are provided according to a business model, which could include, for example, contracting for trips, matching providers and customers, or managing payments. They influence user choice sets via the mobility services that they make available. Constraints include funding, policies from others and public sentiment. The long-term goal is to maintain financial sustainability. Examples of fleet operators, with short- and long-term objectives, are shown in Table 2.

Table 2 Fleet operators / Mobility Service Providers: examples and objectives

Agent	Short-term objectives	Long-term objectives	Potential automation impacts
Public transport operator	Maximize service within budget provided	Sustainable operations	• Change in cost structure (e.g. smaller vehicles may be more economical) • New roles for personnel
Private on-demand mobility services	Gain customers	Add value to the business, to either sustain or sell it	• Change in cost structure may lead to increase in demand • Competition via value chain migration (e.g., automaker running own fleet as way to commercialize automated vehicles directly)
Freight (carrier)	Timely and cost-effective delivery	Sustainable operations	• Change in cost structure (e.g. smaller vehicles may be more economical) • New roles for personnel
Traveller using own car (e.g. the traveller is also the operator of a fleet of one vehicle)	Reach destination safely, conveniently, and on time	• Preserve asset value • Fulfil their mobility needs with less money and effort and higher quality • Maintain social status	• Change in cost structure • Increased availability of other options

Authorities may be local (such as a city), regional, national, or trans-national in scope. They design and implement policies to meet the wider needs of their societies. Although transport and traffic policy are most relevant, there may be cross-sectoral such as those affecting environment, public health, and land use which also affect the transport system. In certain operational design domains, such as in an industrial park or a university campus, the authority may be a private entity. Authorities manage the incentives and disincentives that affect others' choices. They are constrained by funding, law/regulation, policy goals from others and public sentiment. Their long-term goal is to maintain support of the public and other stakeholders, and they may also be concerned with finding a sustainable way to manage liability and insurance issues as well as externalities from other roles. Examples of authorities, with short- and long-term objectives, are shown in Table 3.

Table 3 Authority: example and objectives

Agent	Short-term objectives	Long-term objectives	Potential automation impacts
Department of transportation in a U.S. state	Maintain and manage a multimodal transportation system (roads; public transit)	Maintain support of elected officials and the general public	• Changes in highway use affecting safety and congestion • New transport options
University campus administration	Reduce traffic and improve pedestrian safety	Serve as innovation testbed	• New options for meeting users' mobility needs • Changes in traffic patterns

The technology developer or provider could be a vehicle-maker or a supplier of technologies to vehicle-makers, fleet operators or end users. This role develops or purchases technologies, and produces at scale to accepted standards. This ranges from traditional vehicle components through to enabling technologies (e.g., Internet of Things platform, mobile phone app). Developers establish a business model to profit from the demand for mobility, such as by selling or leasing vehicles or licensing technology. They influence user choice sets via the components of a mobility service that they make available, or the assets that they make available directly to end users who provide their own services. Examples of technology developers, with short- and long-term objectives, are shown in Table 4.

Table 4 Technology developers: examples and objectives

Agent	Short-term objectives	Long-term objectives	Potential automation impacts
Auto manufacturer	Sell or lease vehicles; maintain service relationship	Develop future vehicles that consumers will want	• Value chain migration • Shorter product update cycles • Changes in skills required • Changes in customer mix and sales channels
Technology consolidator, such as internet of things platform	Gain users	Add value to the business, to either sustain or sell it	New data to be monetized

The infrastructure owner-operator provides infrastructure-side needs for travel. These are typically roads, but also include communications equipment such as traffic signals, roadside units for cooperative vehicles, sensors and similar, as well as traffic management centres. They are constrained by funding, law and public sentiment, and their long-term goal is financial sustainability and, in some cases, profitability. Examples of infrastructure owner-operators, with short- and long-term objectives, are shown in Table 5.

Table 5 Infrastructure owner-operators: examples and objectives

Agent	Short-term objectives	Long-term objectives	Potential automation impacts
Public-sector highway authority	Operate a safe and efficient road	Maintain sustainable use of budget through capital planning and asset management	Changes in highway capacity, demand, emissions and safety performance
Concessionaire (e.g. private road operator in public-private partnership)	Operate a safe and efficient road	Fulfill contract obligations at lowest cost	Changes in highway capacity, demand, emissions and safety performance

Agent	Short-term objectives	Long-term objectives	Potential automation impacts
Refueling/recharging provider	Provide power or fuel to vehicles	Make capital investments that will pay off	Changing refueling/recharging needs; for example, due to changes to powertrain and vehicle design
Parking infrastructure operator	Gain economic benefit (direct or indirect) through managing parking availability	Maintain appropriate parking availability	• Changing demand for parking due to new vehicle use patterns • Changing land values

4. Next steps

In late 2019 and 2020, members of the trilateral group will build out the details of portions of the model, then use quantitative simulation to test the impact of these factors on key operational parameters, such as the numbers of different types of vehicles and the number of trips by various competing modes. Rather than providing detailed (and inaccurate) forecasts far into the future, the objective is to create a model that can run fast to gain insight into the potential impacts of automation on system attributes such as congestion and mode choice, under a variety of deployment and policy scenarios, and playing out on the various baseline transport and governance contexts in the participating countries. This will demonstrate the value of a systems perspective in planning for AVs and provide a tool upon which others can build.

This approach significantly advances the objective of refining the original trilateral framework into a tool that a regional or municipal planner could use to develop insight into how a highly automated vehicle system in mixed traffic may work in several decades, and even to begin to explore the consequences of potential actions that one could take now.

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