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Autonomous Cars – The next Revolution in Mobility

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Autonomous cars are predicted to make the jump from science and research to factory floors and consumers in the next few years. Accordingly, an increasing interest in this new form of mobility exists. Established car manufacturers as well as new players, above all Google, invest in the development of autonomous cars. Governments offer supportive measures and adapt their legal framework to prepare their countries for this new and promising industry. The next revolution in mobility is in the air.

Autonomous cars are the planned subject of this dissertation. In different scenarios the probable and possible consequences and effects of this new technology on tomorrow's mobility will be studied. Research questions are how autonomous cars can integrate with established forms of transport and how their arrival will change mobility demand and behaviour. By using the agent-based transport micro-simulation tool MATSim, these questions shall be investigated quantitatively.

The agent-based character of MATSim requires knowledge about the potential added value of autonomous cars on the individual level of single traffic participants. An important part of the planned dissertation is therefore a survey of this issue. The main goal of this survey is the quantification of the added value of autonomous cars. Additionally, the survey participants' expectations, acceptance and requirements toward autonomous cars shall be studied.

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Introduction

Autonomous Cars (ACs) are expected to make the jump from science and R&D-departments to industry and consumers in the next few years (Silberg, 2013), (Howard, 2013), (Mui, 2013), (Lutin et al., 2013). Accordingly, a continuously growing interest in this topic exists. Established car manufacturers and new players, above all Google, invest heavily in this new form of mobility (Ewing, 2013), (Gallagher and Brockman, 2013). Governments try to position their economies and legal frameworks so their countries might profit from this new technology (Marks, 2012), (Kelly, 2012), (Bertel, 2013), (Reuters, 2013). ACs are expected to become nothing less than the next revolution of mobility.

If ACs become a part of our life, they have the potential to disruptively revolutionize the way people move and to significantly improve their quality of life (Fagnant and Kockelman, 2014a), (Lutin et al., 2013), (Silberg, 2013), (The Economist, 2013), (Hars, 2010), (Bilton, 2013). In ACs, public, private and commercial transport join to offer a new experience of traveling:
Car sharing companies can provide ACs for the price of today's public transport systems, while offering the individual experience and door-to-door service today associated with private cars. ACs combine this with the opportunity to work privately or enjoy entertainment while moving which is a feature of today's commercial transport offerings like taxi or limousine services. For those who are still willing to own private cars, these cars have the potential to outperform their traditional role of private transport. They can serve as personal delivery robots. While the owner is at work, they can for example autonomously pick up online ordered groceries. Additionally, ACs promise a new unprecedented autonomy and mobility for those not able or willing to drive, the elderly, the children and the disabled.

Research Question

These possible fundamental changes in mobility are of growing interest to the scientific community. Many effects of ACs on mobility have been suggested. Examples are shorter commute times or a reduced number of cars (Mui, 2013), (The Economist, 2013), (Yang, 2013). So far however, only few of these effects have been subject to scientific investigation and fewer even have been attempted to be quantified by transport science (Section *State of the Art - State of Research*).
The goal of this thesis is to quantitatively investigate some of these effects. MATSim[1], an agent-based transport micro-simulation, will be used as the main tool to achieve this goal. MATSim combines the modelling of large scale transport scenarios with the simulation of individual vehicles and traffic participants (Section *State of the Art - Methodology*). MATSim therefore allows the quantitative investigation of autonomously operating cars embedded in a large scale, realistic environment with individuals adapting their mobility behaviour dynamically. Based on the results the quantitative effects of AC's on tomorrow's mobility and society can be estimated (Section *Detailed Research Plan* and Section *Relevance for Science and Economy*).

State of the Art

History

The idea of autonomous vehicles is almost 75 years old (Kornhauser, 2013a). Despite obvious advantages, they never achieved a major breakthrough. The main reason was that all past solutions required immense adaptations of the environment. Examples are copper-wires along the streets or fenced-off pathways clear of any unexpected objects and possible obstacles. Such expensive adaptations of the environment suffer from the chicken-and-egg-problem[2], which prevented any

[1] See http://matsim.org/, accessed on June 19th, 2014
[2] A large demand is required to justify large scale investments, while large scale investments are required to generate a large demand.

implementation beyond small, occasional projects. Nevertheless, in their niche autonomous vehicles in clearly defined environments, so called Personal Rapid Transit (PRT) systems, are a well-established concept (Anderson, 1974).
Since a few years however, modern IT and sensor technology provide for the first time in history the technical means to create truly autonomous cars (for example at ETH Zurich (Lamon et al., 2006), at the National University of Singapore together with MIT (Chong et al., 2011) or at Google (Urmson, 2014b)). These cars drive autonomously and freely in uncertain, open environments created for humans. This new kind of AC, which is a giant leap from PRT in controlled and restricted environments, is the subject of this thesis. The take-off event for these new ACs was the first DARPA Grand Challenge in 2004 (Bilger, 2013). The challenge and its follow up events in 2005 and 2007 (DARPA, 2014) attracted large media attention. ACs suddenly found themselves in the focus of interest of various technical institutes (e.g. (Scaramuzza et al., 2010), (Chong et al., 2011)) and of major enterprises with well-funded R&D-divisions (Burns, 2013). Very recently, that is in the last one or two years, governments started to explicitly considering ACs as a possible new strategic industry too. They started to provide the necessary legal framework to test and use ACs on their streets, for example in the US (Fagnant and Kockelman, 2014a), in Japan (Bertel, 2013) and in Europe (Marks, 2012), (Reuters, 2013).
In contrast to these technical, economic and political developments, ACs are still only arriving in transport research. Only recently, conferences (e.g. the TRB Road Vehicle Workshops since 2012 (Shladover et al., 2014)) and scientific publications (e.g. (Burns et al., 2013), (Lutin et al., 2013), (Fagnant and Kockelman, 2014b)) on this subject started to appear more frequently. Definitely a gap as ACs have the potential to revolutionize the way people move as drastic as about 130 years ago the upgrade from horse-powered carriages to motorized cars with horse-powers (Silberg, 2013).

State of Research

As mentioned above, until recently, ACs got only marginal attention from the transport science community. Therefore only limited scientific literature is available so far and a research need exists as explicitly stated by for example Fagnant and Kockelman (2014a).

A topic already under some investigation is the potential of ACs in a car sharing context. There the focus often lies on the possible reduction of the total car fleet.
Recent studies by Kornhauser (2013b) and by Ford (2012) investigate for example the effect of a fleet of ACs organized in a car sharing system and used as “aTaxis”. They investigate the potential of such a fleet in terms of cost- and km-reduction for a community of commuters to a nearby city. They find the aTaxis to be highly profitable.
Burns et al. (2013) investigated the case for typical US-commuters, for a shared, driverless fleet in Manhattan, and for a community for elderly in Florida. By combining an analytical and a simulation model, they found that ACs enable “better mobility experiences at radically lower cost” for all three cases.
Frazzoli et al. are interested in the potential of ACs for mobility-on-demand systems (e.g. (Pavone et al., 2012), (Spieser et al., 2014)). In (Spieser et al., 2014) they could for example show that an Automated Mobility-on-Demand system could “meet the personal mobility need of the entire population […] with a fleet whose size is approximately 1/3 of the total number of passenger vehicles currently in operation.”
Another example for an investigation of ACs from a transport research perspective is a study by Fagnant and Kockelman (2014b). They find that in an urban environment “a system of SAVs [Shared Autonomous Vehicles] may well save members ten times the number of cars”.
In all cases, the lack of a suitable transport simulation tool able to simulate autonomous cars is identifiable. Fagnant and Kockelman (2014b) even explicitly identify this as a further research need.

Open Research Questions

Possible, currently open research questions on ACs from a transport research perspective are listed below. Similar listings of open research questions can be found in for example (Hars, 2010) or (Fagnant and Kockelman, 2014b).

- *Car Fleet Size:* What is the expected effect of ACs on the total car fleet size? While privately owned delivery robots indicate an increase, car sharing and special purpose car fleets suggest a drastic decrease (e.g. (Yang, 2013), (Silberg, 2013)).
- *Car Productivity:* Car productivity (total driven kilometers per car-life) is expected to increase with the arrival of ACs (e.g. (Lutin et al., 2013)). How much will it increase? What does this mean in terms of cost per kilometre driven? What is the future price of transport services (trucks and taxis) with no driver and increased car productivity?
- *"Last mile"-Potential:* On the "last mile" of other, established transport systems (for example public transport or station-based car sharing) are ACs expected to appear first (e.g. (Yang, 2013)). What are the potentials and possible effects?
- *Road Capacity Increase:* ACs are expected to be much better drivers than humans (e.g. no distraction, shorter reaction time, safer driving style) (e.g. (Yang, 2013), (Silberg, 2013), (Lutin et al., 2013), (Chacon et al., 2012)). As one effect, ACs need for example much less space on the road and (de-)accelerate faster at obstacles. This raises the road capacity, which is expected to manifest in a shift in the form of the fundamental diagram. How much of an increase can be expected? Are investments in more road capacities still sensible and justifiable?
- *Commuting Behaviour and Congestion:* With the arrival of ACs, a decrease in traffic variability and a more evenly distributed traffic demand are expected (e.g. (Silberg, 2013), (Lutin et al., 2013), (Burns, 2013)). Are any such effects confirmable and supportable with traffic demand simulations?
- *Policy Reviews:* The advent of ACs requires new, adapted traffic policies and laws. What are possible policies? For example what would be the effect of a ban of manual cars from highways during peak hours? From which AC share in the total car fleet are such policies feasible and sensible?
- *Logistics:* In intra-logistics, automated guided vehicles (AGVs) are an established and proven mean of transport. With AC-technology these vehicles may leave the warehouses and transport goods autonomously on the roads (Flämig, 2014). What are possible (positive and negative) consequences of such a development for logistics?
- *Other:* Further research ideas are for example the investigation of the E-Car potential of ACs or of the possible changes in parking. With ACs, how many parking opportunities are needed when and where?

Methodology

MATSim

MATSim is an open-source software project providing "a framework to implement large-scale agent-based transport simulations." (MATSim, 2014) Its modular design facilitates extensions and the integration of new implementations. The three main contributors to MATSim are the Institute of Land and Sea Transport Systems[3] (ILS) of the Technical University Berlin, the IVT-ETHZ, and the private company Senozon[4].

MATSim typically simulates one day *scenarios*. A scenario normally consists of a road and rail *network*, of *facilities* and of a *population* of agents. Typically one *agent* represents one traffic participant with a

[3] See http://www.ils.tu-berlin.de/, accessed on June 19th, 2014
[4] See http://senozon.com/, accessed on June 19th, 2014

one day plan of *activities* and *trips*. This is complemented with public transport, which is represented by a fleet of *vehicles* and a *schedule* defining the lines and the driving times. (Balmer, 2007), (Rieser, 2010)
In the simulation, agents execute their daily plan. This means they do their planned activities at facilities and if, during the day, they need to switch facilities they move on the network. For the movement, that is the actual traffic simulation, an event-based queue model is used. After the simulation, each agent rates its executed plan with a utility function and has the opportunity to change the plan and / or any routes. Using an evolutionary optimization approach over many simulated days, agents optimize their plans and routes until a user equilibrium is reached.
The simulation output is a list of *events* which then can be analysed. Recorded in the events are for example for each agent any starting or finishing of an activity or any movement in the network.

Survey

The agents in MATSim need a set of values for the utility function, with which they rate the executed plans. These values are positive and negative utilities from activities and trips plus, optionally, more detailed utilities like for example the utility of being too early or too late for an activity. For trips these utilities correspond to the generalized costs of the trips.

The standard tool to identify such utilities are stated choice surveys, which are especially suited for investigations of hypothetical markets (Axhausen, 1996).
In a stated choice survey participants are confronted with a series of decision problems. A decision problem consists of different alternatives from which the participants have to choose one. This weighing of different alternatives represents the real decision process. Based on the results individual and aggregated traffic decisions can be modelled and the relative utilities of different alternatives can be found (Axhausen, 1996), (Louviere et al., 2010), (König et al., 2004).

Detailed Research Plan

Objectives and Goals

In the recent literature and news many different numbers are used to promote or discredit ACs, often with unclear sources. In this thesis the phenomenon of ACs will be quantitatively studied by applying state-of-the-art transport simulation. The goal of the thesis is therefore to give a coherent picture of what the advent of ACs might mean for transport in Switzerland and other developed countries.

Work Packages and Tasks

WP1: Literature Research

The goal of *WP1: Literature Research* is an in depth knowledge of the current state-of-the-art in the field of traffic research on ACs as well as to identify the key actors in the field (institutes as well as individual researchers). As part of the work package, an overview of past and present research done by other groups and by the IVT shall be developed and open research questions shall be identified. The result of WP1 is this research plan.

WP2: Scenario Development

The goal of *WP2: Scenario Development* is a base scenario for MATSim which can be used for the further studies. The base scenario will be a multi-modal Zurich scenario (network, facilities and base population). The base scenario will be of a generic character as the specific research questions are formulated and investigated later in *WP5: Autonomous Cars*.
The WP consists of the development and calibration of this scenario as it is not yet available for 2010 at the IVT. Currently at the IVT however, the development of a coherent and comprehensive

Switzerland scenario is on-going. This scenario will include a new, updated population and a multimodal network based on Open Street Map[5]. The WP2 base scenario will be developed from this Switzerland scenario.

WP3: MATSim-Servants

For the simulation of ACs in MATSim, the simulation framework needs to newly include unmanned cars participating in traffic. The goal of *WP3: MATSim-Servants* is the required extension of MATSim. For the extension, the introduction of assistive agents called "Servants" is planned. These Servants will exist only in a restricted number in MATSim and have the purpose of serving the current MATSim-Agents. While not serving, the Servants behave according to strategies. These strategies can be, for example, of a redistributing character in a car sharing context or of a task-fulfilling character in a delivery robot context. As Servants do not have day plans but rather constantly adapt to the agents' wishes and/or follow strategies, they require the ability for on-the-fly planning. Here the work by Dobler (2013) on within-day replanning in MATSim and the work by Maciejewski and Nagel (2013) on taxi simulations in MATSim will serve as starting points.

In a car sharing context, the Servants can be called by agents to carry them from A to B, similar to the MATSim taxi simulations by Maciejewski and Nagel (2013) and the MATSim car sharing studies by Balac and Ciari (2014). On the way to B, they might pick up several other agents, who wait within a certain detour-distance and who want to get to somewhere close to B too (collaborative mobility, following the MATSim work of Dubernet and Axhausen (2012)). When not serving, they reposition and park themselves following redistributing strategies. It is hypothesized that such strategies are dependent on the current traffic situation, the form of the street network and on the number of Servants available. Different strategies might be studied and optimized similarly to the parking search strategies by Waraich et al. (2012).
In a personal delivery context, the Servants can be used traditionally as normal cars by agents. Only the utility will be different, as to be determined in *WP4: Survey*. When not moving an agent however, Servants can for example park autonomously or serve as personal delivery robots. In these situations, a strategy approach as in the car sharing context might be applicable. If the Servants are shared by several members of a group (e.g. family), the according MATSim agents will have to coordinate as in the work by Dubernet and Axhausen (2012).

The vehicle-concept introduced to MATSim by Rieser (2010) can serve as a starting point for Servants. But nevertheless, Servants mean a technical and conceptual paradigm change for MATSim. Technical because agents without the typical, predefined day-plan will then participate in the simulation. Conceptual because two different entity types (agents and Servants) are optimizing differently and to a different extent. The work planned in WP3 is therefore ambitious but also sought-after as mentioned in section *State of the Art - State of Research*.

WP4: Survey

WP4: Survey consists of a survey on the topic of ACs. The main goal of this survey is the identification of the expected utility of driving with an autonomous car. A stated choice questionnaire serves as a traditional and suitable tool for this task (Section *State of the Art - Methodology*). These utilities are needed for a correct implementation of ACs in MATSim.
Additionally, given the apparent arrival of ACs, the survey will include questions concerning the expectations, the acceptance and the requirements of ACs. In this context, interesting research questions are for example what would get the people to change to an autonomous car? How attractive are ACs for people? How ready are they for such a change? What would facilitate such a change? What are the main concerns? What do they expect from these cars?

[5] See http://www.openstreetmap.org/, accessed on June 19th, 2014

Few similar surveys have already been conducted in America (e.g. (Silberg, 2013), (Vallet, 2013)). For Europe and Switzerland in particular however, no similar surveys are currently known to the author.

WP5: Autonomous Cars

In *WP5: Autonomous Cars*, concrete research questions on ACs are developed and investigated. Possible research questions which serve as a starting point for this WP are listed in section *State of the Art - Open Research Questions*. When developing the concrete research questions on ACs, the research by other groups and the results of the previous WPs will be considered.
The defined research questions will be investigated in different scenarios. Three possible examples for such scenarios, two extreme and one moderate, are sketched here.

1. *Extreme Scenario "Growth":* If the concept of private ownership of cars survives the dawn of ACs and even proliferates with cars used as private delivery robots, the number of cars and driven kilometres per capita are expected to drastically increase in the future: As children, elderly and disabled are allowed respectively enabled to drive on their own, the number of cars is expected to increase. As cars can be used as private delivery robots, the number of kilometres driven per capita is expected to increase.
2. *Extreme Scenario "Sharing":* ACs have the potential to eventually bring the concept of car sharing to a major breakthrough. With ACs serving as taxis without the cost of a driver, car sharing programs may become much cheaper and more convenient than any form of private ownership of cars. This leads to the economic, ecologic and social benefits frequently attributed to car sharing, such as reduced car fleet, special purpose cars and increased car productivity (e.g. (Hars, 2010), (Yang, 2013), (Silberg, 2013)).
3. *Moderate Scenario "Balance":* It is to assume that some moderate scenario between the two extremes above will eventually become reality. Cost- and eco-sensitive and/or urban consumers might rather opt for car-sharing suitable for a "green", "city" lifestyle. Traditional, rural and/or less cost-sensitive consumers on the other hand might afford the luxury of a privately owned, all-time-available car usable as a private delivery robot.

WP6: Dissertation

WP6: Dissertation covers the actual writing of the dissertation. The dissertation brings together the results from the previous work packages to a coherent whole.

Relevance for Science and Economy

The chances for ACs to become part of everyday life have never been as promising as today. Estimates by involved stakeholders reach from as early as 2020 for the appearance of commercially available ACs (Burns, 2013). Only recently, Google presented its first purely autonomous prototype (Urmson, 2014a) and in Singapore, light-weight ACs are currently deployed for field tests (Tan, 2014). In short, the question of appearance of ACs on our streets seems to be more one of a *when* than one of an *if*.

If ACs become part of everyday life however, Switzerland, its society, law makers, politicians and its economy have to decide how to position itself and how to react on this development. Such decisions need an information base which must be provided by science. Recent technological advancements, for example smartphones, show how quickly and euphoric such new products are embraced by people today - a development to be expected for ACs too (Strong, 2013). Transport science has to do the necessary research proactively and visionary (Fagnant and Kockelman, 2014a). It has to develop the (simulation) tools needed. It has to be ready to provide answers when the questions arise in public.
With this proposed dissertation, a first step shall be done to build the according expertise in Switzerland, at ETH Zurich, at the Institute for Transport Planning and Systems.

Time Schedule

	SS 14	FS 14	SS 15	FS 15	SS 16	FS 16
Literature Research						
Scenario Development						
MATSim - Minions						
Survey						
Autonomous Cars						
Dissertation						

SS: Spring Semester (February to August); FS: Fall Semester (September to January)

Literature

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