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Dynamic adaptive policymaking for the sustainable city: The case of automated taxis

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ABSTRACT

By 2050, about two-thirds of the world's people are expected to live in urban areas. But, the economic viability and sustainability of city centers is threatened by problems related to transport, such as pollution, congestion, and parking. Much has been written about automated vehicles and demand responsive transport. The combination of these potentially disruptive developments could reduce these problems. However, implementation is held back by uncertainties, including public acceptance, liability, and privacy. So, their potential to reduce urban transport problems may not be fully realized. We propose an adaptive approach to implementation that takes some actions right away and creates a framework for future actions that allows for adaptations over time as knowledge about performance and acceptance of the new system (called 'automated taxis') accumulates and critical events for implementation take place. The adaptive approach is illustrated in the context of a hypothetical large city.

Introduction

Modern cities are increasingly confronted with growing externalities of road traffic – congestion, fatalities, consumption of scarce space, use of energy, and emissions. To a large extent, these problems can be attributed to an inefficient use of user-owned vehicles and to driver errors. However, recent technological developments provide an opportunity to reduce these externalities significantly, while improving the driver and passenger experience. The general impacts of developments in information and communications technology on transport are summarized by Banister and Stead (2004). In this paper, we focus on technological developments that can contribute to these benefits—in particular, automated vehicles (AVs) that require no drivers (because they can maneuver independently in real traffic situations using on-board sensors, cameras, maps, and associated software), and smartphones (for travelers to request rides from wherever they may be, and to pay for the rides).

'Automated taxis' (ATs), as we are calling this emerging new mode of local passenger transport, is based on the definition of 'real-time ridesharing' of Chan and Shaheen (2012) and an extension of the definition of 'ride-sourcing' of Chen (2015). It is also called "autonomous taxis" (Bischoff and Maciejewski, 2016), "self-driving taxis" (Correia et al., 2016), an 'automated universal taxi system' or 'dial-a-pod' (Enoch, 2015). It provides customers with O-D transportation in an automated vehicle,

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in real time, at their desired departure time. Ride-matching software automatically matches cars to riders, and notifies the rider's smartphone. Payments are charged directly to the rider's credit card, which is stored electronically. GPS devices automatically guide the car. Automated taxi companies operate in a similar way to traditional taxi companies; the main distinction is that technology takes over the trip reservation, dispatching, and taxi driving tasks.

Widespread implementation of ATs could potentially lead to significant economic, environmental, and social benefits (Fagnant and Kockelman, 2015a,b; International Transport Forum, 2015; McEvoy, 2015). Among the economic benefits are a dramatic reduction in traffic accidents, reduction in traffic congestion, and savings in parking costs and land use. Among the likely environmental benefits are reductions in emissions and fuel consumption. And, among the privately realized benefits are travel time reductions, and savings in the cost of vehicles, fuel, insurance, and parking. All vehicle driving tasks are executed automatically by the automated vehicles. Hence, traveling could also become more comfortable and more convenient compared to today's driving. However, there may be some disbenefits as well. The introduction of ATs might lead to small increases in vehicle miles traveled (Gucwa, 2014; Childress et al., 2015), and significant increases if cities scale down or eliminate their public transport systems (International Transport Forum, 2015). Also, their introduction is likely to cause significant labor issues, as there will be no more employment for taxi drivers. Anderson et al. (2016) describe the "promise and perils of autonomous vehicle technology". Chapter 2 of their report discusses these 'promises and perils' in terms of the social costs of driving, the effects of AVs on safety, congestion, mobility for those unable to drive, land use, energy and emissions, costs, and 'disadvantages' (e.g., increased vehicle miles traveled, loss of parking income, effect on public transit, effect on jobs, and effect on automobile insurance companies).

Transport policymakers and automakers in various countries are becoming increasingly interested in the large-scale implementation of automated vehicles. And, many shared driving organizations (e.g., Uber and Lyft) are interested in using their vehicles as ATs (see, for example, Goddin, 2015). However, the automated vehicles they would use are still in the preliminary testing and experimentation phase. Although the potential benefits of ATs are large, implementation is slow due to a variety of 'deep uncertainties', primarily related to the use of automated vehicles. Until now, the development of automated vehicles has been strongly technology driven. Their performance has been assessed only in experiments under strictly controlled conditions, implying limited real-world validity. Further technology development and assessment of its impacts are strongly related to the societal conditions that have to be fulfilled for implementation. For instance, it is often argued that users will be hesitant to use automated vehicles, since there is no human driver in the driver's seat. Another issue involves legal regulations. It will be necessary to change vehicle licensing and certification rules, and rules regarding liability and third-party insurance for ATs. There are also issues about data privacy and electronic security. These types of issues generate major uncertainties surrounding the feasibility of implementation. Policymaking is often characterized by a 'wait and see' or reactive attitude in response to uncertainties. This relatively uninvolved approach could slow down the development of ATs and fail to advance general transport policy goals. Hence, there is a need for a policy course toward ATs that recognizes the existence of uncertainties without neglecting the possibilities and responsibilities of public authorities with respect to general transport policy goals. In this paper, such a course is presented by focusing on identifying and handling relevant uncertainties within the context of policymaking. This approach involves a flexible or adaptive policy, which allows adaptations in time as knowledge about automated vehicles and ATs proceeds and critical events for implementation take place. Some policymaking organizations have already realized the need for policy guidance in the face of uncertainties, and are proposing adaptive approaches. For example, the U.S. National Highway Traffic Safety Administration recently proposed building flexibility and adaptability into their testing protocols for AVs (National Highway Traffic Safety Administration, 2016). And the European Union has called for "a step-by-step 'learning-by-experience' approach" for cooperation among the Member States in the field of connected and automated driving (European Union, 2016).

A framework for policy analysis

In general, policymaking concerns making choices regarding a system in order to change the system outcomes in a desired way (see Fig. 1) (Walker, 2000). At the heart of this view is the system comprising the policy domain, in our case the urban passenger transport system. It is important (1) to define its boundaries, and (2) to define its structure (that is, the elements and relationships among them (R)). In general, a transport system can be defined by distinguishing physical components of transportation and their mutual interactions (van de Riet, 1998). These physical components include the

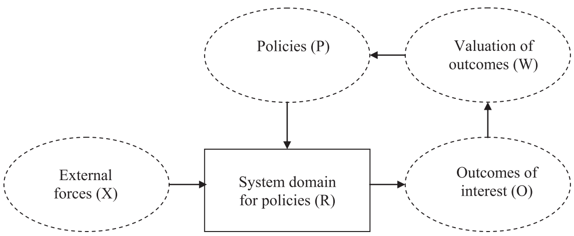


Fig. 1. A framework for policymaking (Walker, 2000).

subjects of transportation (people), the means of transportation (vehicles), and infrastructure. The results of these interactions (the system outputs) are called *outcomes of interest (O)*. Outcomes of interest refer to the characteristics of the system that are considered relevant criteria for the evaluation of policy measures. For urban transport policies, these criteria involve, for instance, the level of emissions by motor vehicles, the number of road casualties, and the level of congestion on the road network (van der Loop et al., 2003). The *valuation of outcomes (W)* refers to the (relative) importance (weights) given to the outcomes by crucial stakeholders, including policymakers. It involves how stakeholders value the results of the changes in the system, such as improved traffic efficiency, fewer fatalities, reduced emissions, and improved travel time reliability.

Two types of forces act on the system: *external forces (X)* and *policies (P)*. Both types of forces are developments outside the system that can affect the structure of the system (and, hence, the outcomes of interest to policymakers and other stakeholders). *External forces* refer to forces that are not controllable by the policymaker but may influence the system significantly – i.e. exogenous influences. External forces on the transport system include demographic, economic, spatial, social, and technological developments (Button and Taylor, 2002; van Wee, 2002). *Policies* are the set of forces within the control of the policymakers related to the system. In other words, a policy is a set of actions taken to control the system, to help solve problems within it or caused by it, or to help obtain benefits from it. In speaking about national policies, the problems and benefits generally relate to broad national goals. For instance, in the Netherlands, the national transport policy goals are to make the Netherlands competitive, accessible, livable and safe (Netherlands Ministry of Infrastructure and Environment, 2012).

Based on this framework for policymaking, a classification of uncertainties and their levels can be made (Walker et al., 2003). Fig. 2 present this framework. Applied to transport, transport policy analysis problems can be characterized by different levels of uncertainty about the external forces (X), the transport system and transport system models, the outcomes of interest (O) and valuations of the outcomes. Level 1 uncertainty is often treated through a simple sensitivity analysis of transport model parameters, where the impacts of small perturbations of model input parameters on the outcomes of a model are assessed. Level 2 uncertainty is any uncertainty that can be described adequately in statistical terms. In the case of uncertainty about the future, Level 2 uncertainty is often captured in the form of either a (single) forecast (usually trend based) with a confidence interval or multiple forecasts ('scenarios') with associated probabilities.

The long-term related Level 3 and Level 4 uncertainties cannot be dealt with through the use of probabilities and cannot be reduced by gathering more information, but are basically unknowable and unpredictable at the present time. And these higher levels of uncertainty can involve uncertainties about all aspects of a transport policy analysis problem — external or internal developments, the appropriate (future) system model, the parameterization of the model, the model outcomes, and the valuation of the outcomes by (future) stakeholders. There is a growing literature on assessing the costs and benefits of automated vehicles and automated taxis. However, the implicit assumption usually made is that they are dealing with Level 3 uncertainties. The core of their approach is the assumption that the future can be specified well enough to identify policies that will produce favorable outcomes in one or more specific plausible future worlds. Such policies are termed 'robust'. The future worlds are called scenarios. Examples of the use of scenarios in trying to understand the development of AVs and ATs, and planning for their implementation, include the following: (Townsend, 2014; Fagnant and Kockelman, 2014, 2015a,b; Milakis et al., in press; Gucwa, 2014; Childress et al., 2015; International Transport Forum, 2015; Zmud et al., 2015; Correia et al., 2016; Bischoff and Maciejewski, 2016). However, traditional scenario-based approaches are insufficient to deal with 'deep uncertainties'.

AT development and implementation is characterized by many Level 4 uncertainties (see, for example International Transport Forum, 2015). First, the possible influence of external forces, including technology developments in automated vehicles, is highly uncertain. At the same time, technological progress alone is unlikely to drive the implementation process. Automated vehicles (and their use as ATs) are disruptive technologies. Their introduction might require some structural changes in the urban transport system. It is far from certain what changes would be made, how they might be made, and how they would be responded to by the public. Second, the outcomes from the introduction of ATs are highly uncertain. The way implementation might affect transport system performance is currently unknown, since the key-relationships determining transport system performance from the implementation of ATs are very uncertain; some of the expected benefits might fail to be achieved, and there could be negative outcomes as well. Finally, the valuation of the outcomes from implementation is highly uncertain. Stakeholders are likely to have different opinions about the costs and benefits of implementing an AT system in their city. As such, the willingness of stakeholders to accept (or reject) outcomes of the implementation ATs is uncertain. The main contribution of this paper is to suggest a way that implementation of ATs can proceed in spite of these deep uncertainties.

Dynamic adaptive policymaking

Summarizing what we found in Section "A framework for policy analysis", there are Level 4 uncertainties about external developments, the outcomes of policy decisions with respect to ATs, and the valuation of the outcomes by stakeholders involved in or affected by these decisions. The Level 3 (scenario) approach to dealing with these uncertainties has many problems dealing with Level 4 uncertainties, including the implicit assumption that bounds can be placed on future developments.

One way forward for policymaking in the face of these 'deep uncertainties' is to use an approach that implements an initial 'provisional' policy, is prepared to adapt it to future events, and fully exploits knowledge that becomes available as time

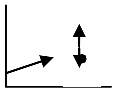
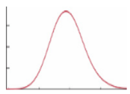
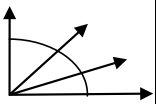
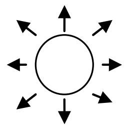
Complete Certainty		Level 1	Level 2	Level 3	Level 4	Total ignorance
	Context (X)	A clear enough future (with sensitivity) 	Alternate futures (with probabilities) 	A multiplicity of plausible futures (unranked) 	Unknown future 	
	System Model (X)	A single (deterministic) system model	A single (stochastic) system model	Several plausible system models, with different structures	Unknown system model; know we don't know	
	System Outcomes (O)	A point estimate for each outcome (with sensitivity)	A confidence interval for each outcome	A known range of outcomes	Unknown outcomes; know we don't know	
	Weights on outcomes (W)	A single set of weights	Several sets of weights, with a probability attached to each set	A known range of weights	Unknown weights; know we don't know	

Fig. 2. The progressive transition of levels of uncertainty from complete certainty to total ignorance (based on Walker et al., 2013).

proceeds. Walker et al. (2001) developed an approach to policymaking called dynamic adaptive policymaking (DAP) that does not rely on unreliable forecasts and uncertain models, but allows policymakers to cope with the uncertainties that confront them by creating policies that respond to changes over time and that make explicit provision for learning. DAP has been explored in various applications, including flood risk management in the Netherlands in light of climate change (Rahman et al., 2008), transportation infrastructure planning in light of climate change (Wall et al., 2015), and policies with respect to the implementation of innovative urban transport infrastructures (Marchau et al., 2008), congestion road pricing (Marchau et al., 2010), intelligent speed adaptation (Agusdinata et al., 2007), and 'magnetically levitated' (Maglev) rail transport (Marchau et al., 2010). Central to DAP is the acknowledgment of uncertainty: that "in rapidly changing world, fixed static policies are likely to fail" (Kwakkel et al., 2010). As new information becomes known over the life of a policy or plan, it should incorporate the ability to adapt dynamically through learning mechanisms (Walker, 2011).

DAP makes adaptation explicit at the outset of policy formulation. Thus, the inevitable policy changes become part of a larger, recognized process and are not forced to be made repeatedly on an *ad-hoc* basis. Adaptive policies are devised not to be optimal for a best estimate future, but to be robust across a range of plausible futures. Such policies combine actions that are time urgent with those that make important commitments to shape the future and those that preserve needed flexibility for the future. Under this approach, significant changes in the urban transportation system would be based on a policy analytic effort that first identifies system goals, and then identifies policies designed to achieve those goals and ways of modifying those policies as conditions change. Within the adaptive policy framework, individual actors would carry out their activities as they would under normal policy conditions. But policymakers, through monitoring and mid-course corrections, would try to keep the system headed toward the original goals.

DAP occurs in two phases: (1) a design phase, in which the dynamic adaptive policy, monitoring program, and various pre- and post-implementation actions are designed, and (2) an implementation phase, in which the policy and the monitoring program are implemented and adaptive actions are taken, if necessary. The five steps of the design phase are shown in Fig. 3. Once the basic dynamic adaptive policy is established through the five design steps shown, the policy is implemented, and monitoring commences. In particular, the following steps summarize the process for creating and implementing an adaptive policy.

Step I is the *stage-setting* step. It involves the specification of objectives, constraints, and available policy options. This specification should lead to a definition of success, i.e. the specification of desirable outcomes.

In Step II, a *basic policy* is assembled, consisting of the selected policy options and additional policy actions, together with an implementation plan. It involves (a) the specification of a promising policy and (b) the identification of the conditions

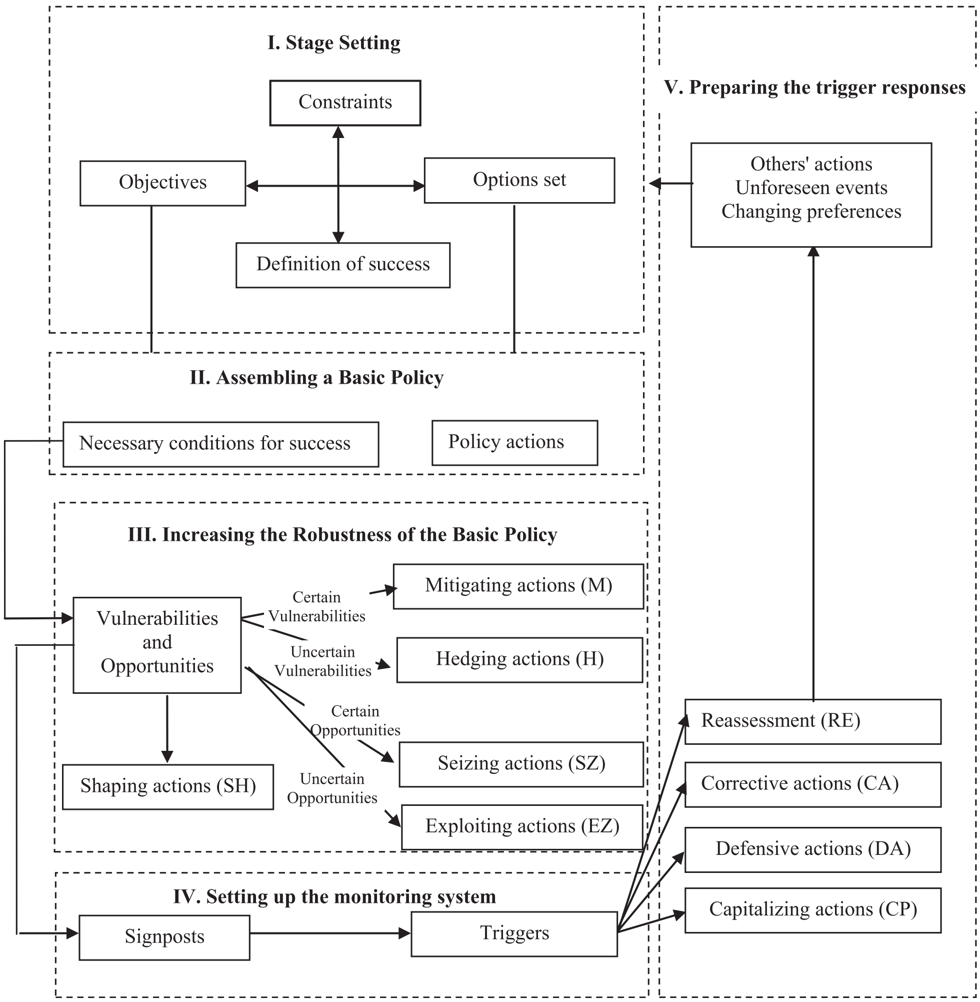


Fig. 3. The DAP process (adapted from Walker et al. (2013)).

needed for the basic policy to succeed. Note that both the first and the second step are basically the same steps as are currently used in traditional policy formulation.

In the remaining three steps of the DAP process, the *rest of the policy* is specified. These are the pieces that make the policy adaptive. This step is based on identifying, in advance, the basic policy vulnerabilities and opportunities – the conditions or events that could make the policy fail or succeed better – and specifying actions to be taken in anticipation (Steps III and IV) or in response to them (Step V). Step III involves (a) the identification of the vulnerabilities and opportunities of the basic policy, and (b) defining actions to be taken immediately. *Vulnerabilities* can reduce the impact of a policy to a point where the policy is no longer successful, but *opportunities* are new developments that can make the policy more successful, or succeed sooner. In Step IV, signposts are defined that should be monitored in order to be sure that the underlying assumptions remain valid, that implementation is proceeding well, and that any needed policy adaptation is taken in a timely and effective manner. In Step V the actions are specified that will be taken in the future if trigger events occur after the actions in Steps II and III have been implemented.

Actions are defined related to the type of vulnerability and opportunity, and when the action should be taken. Both certain and uncertain vulnerabilities and opportunities can be distinguished. 'Certain vulnerabilities' can be anticipated by *mitigating actions* – actions taken in advance to reduce the certain adverse effects of a basic policy, and 'certain opportunities' can be anticipated by *seizing actions*. Uncertain vulnerabilities are associated with '*hedging actions*' – actions taken in advance to reduce or spread the risk of possible adverse effects of a basic policy; and uncertain opportunities are associated with '*exploiting* actions'. For possible future actions to deal with uncertain vulnerabilities and opportunities, *signposts* are defined to monitor when actions are needed to guarantee the progress and success of the policy. In particular, critical values of signpost variables (*triggers*) are specified, beyond which actions should be implemented to ensure the policy progresses in the right direction and at proper speed.

Once the above policy design is agreed upon, the basic policy is implemented together with the actions to be taken immediately, and a signpost monitoring system is established. After implementation of the initial actions, the adaptive policymaking process is suspended until a trigger event is reached. As long as the original policy objectives and constraints remain in place, the responses to a trigger event have a defensive or corrective character – that is, they are adjustments to the basic policy that preserve its benefits, meet outside challenges, or capitalize on opportunities. Under some circumstances, neither defensive nor corrective actions might be sufficient. In that case, the entire policy might have to be reassessed and substantially changed or even abandoned. If so, however, the next policy deliberations would benefit from the previous experiences. The knowledge gathered in the initial policymaking process on such things as outcomes, objectives, measures, and the preferences of stakeholders, would be available and would accelerate the new policymaking process.

The DAP approach seems promising for urban transportation system development in terms of how, in the face of deep uncertainty, policymaking can and should occur. In the following section the concept of adaptive policymaking described above will be illustrated for developing a policy regarding the implementation of an AT policy in a (generic) urban environment. The case is a simplified example of how DAP could be applied to the AT situation, and is not meant to include all relevant details that need to be considered.

DAP for the implementation of urban automated taxis

As discussed in the introduction, there are many problems associated with the urban transport system, and with individual ownership of cars. Automated driving promises many benefits: improved safety, reduced congestion, and lower stress for car occupants, among others (International Transport Forum, 2015). Also, most privately owned cars spend a great deal of time sitting idle (less than 11% of vehicles are 'in use' throughout the day (Fagnant and Kockelman, 2015a). Thus, there has already been a movement toward car sharing, which allows individuals to share vehicles rather than each household owning its own car. Even so, a common assumption is that cars, buses, and taxis will remain the dominant local passenger transport modes in the future. However, these traditional modes are slowly beginning to lose market share to intermediate modes, such as shared taxis, ride-sharing schemes, demand-responsive transport services, and car clubs (Enoch, 2015). These trends could end in the emergence of an entirely new dominant passenger mode called automated taxis (ATs).

As described in the introduction, this new mode could offer society and individual users significant benefits. But, its implementation faces major hurdles, and is surrounded by deep uncertainties. What we discuss here is an approach to implementation that is based on dynamic adaptive policymaking (DAP), which begins with a basic policy based on current conditions, and adapts the policy as experience and knowledge is gained. For illustrative purposes, we assume that our 'problem owner' is the government of a (generic) large city, and that the problem that needs to be addressed involves issues of limited parking space, congestion, safety, and pollution. There is some expectation that ATs can help address these issues. But, the technology is untested, the public is skeptical, taxi drivers are opposed, and there is no legal framework in place for its implementation. There are four major categories of actors/stakeholders to be considered, each of which has its own set of objectives (and related outcomes of interest) to be taken into account: the city government, the residents of the city (including the travelers), the taxi operators (including their drivers), and the automobile manufacturers (including the technology developers).

The Society of Automotive Engineers International (SAE) On-Road Automated Driving Committee (ORAD) has defined six levels of driving automation to help industry and consumers understand how vehicle automation can progress safely, ranging from Level 0 (no driving automation) to Level 5 (full driving automation) (Society of Automotive Engineers, 2016). In the following, we will go through the five DAP steps to design an adaptive policy for achieving the city's objectives, including the implement an AT system. We will show how the city might begin with a system involving 'conditional automation' – the system takes over all aspects of the dynamic driving tasks with the expectation that the human driver responds appropriately to a request to intervene. And how it might then use DAP to design a policy for implementing an AT system involving 'full automation' – the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver. In other words we consider a transition from a manned, automated, but human-supervised taxi, to an unmanned automated taxi.

Step I (Setting the Stage)

The problem faced by the city government is fairly clear. It would like to make better use of its space (e.g., reduce the space currently needed for street parking and parking garages), reduce congestion on the streets, improve traffic safety, and improve the environment (e.g., reduce air pollution). The set of options for addressing the problem is quite large. It includes improving public transport, implementing new traffic management procedures within the city, introducing road pricing (as has been done in London), and introducing automated taxis (ATs). ATs are seen as a promising way to achieve some of these objectives in an innovative way. However, there are many constraints and many uncertainties. Most important are the concerns about safety. Automated vehicles have the potential to dramatically reduce accidents. Human error is the cause of over 90% of all vehicle crashes in the United States (National Highway Traffic Safety Administration, 2015). Similar figures have been reported for European countries. This percentage should be able to be substantially reduced. But, it is not known how safe automated vehicles will be. Hayes (2011) suggests that vehicle fatality rates (per person-mile traveled) could eventually approach those seen in aviation and rail – about 1% of current rates. But, Kalra and Paddock (2016) have estimated that automated vehicles would have to be driven hundreds of millions of miles, or even hundreds of billions of miles, to demonstrate their reliability in terms of fatalities and injuries. Therefore, adaptive implementation makes sense. Other constraints and uncertainties include infrastructure costs and public acceptance.

The taxi operators (e.g., Uber) are very interested in implementing ATs. It is expected that they would be able to make better use of their fleet (fewer 'empty miles'), at considerably lower cost (no expenses for taxi drivers). One of the biggest barriers to this policy is likely to be opposition from those who are currently taxi drivers. Implementing such a system in a large city is likely to be extremely disruptive. For example, New York City has over 50,000 taxi drivers and over 13,000 taxicabs. The average wait time for a passenger hailing a cab is 5 min (you cannot call a cab to come and pick you up). According to Burns et al. (2013), a fleet of only 9,000 automated vehicles could replace these cabs, with an average passenger wait time of 36 s and an average cost of about $1.00 per trip (vs. about $7.80 per trip with the current system).

The public (the customers) will be most interested in the level of service (wait times and transport times), cost, and safety. The results from Burns et al. (2013) suggest significant reductions in wait times, transport times, and costs. But, convincing the customers about improved safety might be quite hard, and will likely require some demonstrations, pilot projects, experience, and/or education campaigns. In general, acceptance for new driving support systems might increase as customers experience their benefits. The automobile manufacturers are most interested in gaining acceptance of automated vehicles with few legal restrictions or hurdles to jump through, and liability issues settled to their satisfaction. According to the manufacturers, technology is not the problem. The technology for automated vehicles already exists, or will exist fairly soon.

The city (the problem owner) will judge the policy to be a success based on the number of people who use it, the amount of opposition (e.g. by travelers, operators, drivers, operators, travelers, and other levels of government), and the contribution to the general urban transport goals (including congestion, safety, pollution, and parking spaces). Other critical success factors are that the technology works properly and can be upgraded easily, that liability for any system failures is clearly assigned, and that all actors are satisfied with the privacy of the information being collected within the system.

To summarize the results of Step I, any new urban transport policy (including ATs) should meet certain conditions for it to be judged a success. In particular, the success of a policy for ATs will be judged by the following criteria (shown in Column 1 of Table 1):

1. Support by regional/national government and other stakeholders
2. Travel demand for taxis develops as originally forecast
3. Acceptance by taxi drivers, operators, and travelers
4. AT technology performance
5. Travel supply by other modes develops as originally forecast
6. AT performance in relation to general urban transport goals

Step II (Assembling a basic policy)

Based on the objectives, the constraints, the definition of success, and the initial set of options, we assume that the basic policy, to be implemented first, without adaptation or increased robustness, would be to implement an Uber-like system in the city (similar to systems already functioning in cities throughout the world; the service is currently available in over 66 countries and 449 cities worldwide), with conditional automated vehicles. The vehicles would have a human driver, but, would have all aspects of the driving task automated, with the expectation that the human (taxi-)driver would respond if requested to resume control (within a sufficient time margin).

Step III (Increasing the robustness of the basic policy)

In this step, actions are added to the basic policy to protect it from failing or to seize opportunities to enhance its success. The vulnerabilities and opportunities are either certain (in which case the actions should be taken at the time the policy is implemented), or uncertain (in which case a monitoring system should be set up to see how the uncertainties are developing before taking action; but the actions in response to the developments being monitored should be prepared in advance). Columns 2–5 of Table 1 list the vulnerabilities (V) and opportunities (O) of the basic policy developed in Step II; whether the vulnerability/opportunity is certain or uncertain; and the action to be taken at time = 0 to increase the robustness of the basic policy – mitigating (M), hedging (H), seizing (SZ), or shaping (SH).

In the following text, we will go through all of the rows of Table 1, but we will not go through all of the elements in Columns 2–5. We will highlight a few to communicate the essence of the resulting dynamic adaptive policy. Consider Row 1. There is definitely uncertainty about the acceptance of the basic policy by governments and stakeholders. To promote acceptance, anticipatory measures can be undertaken, such as lobbying and negotiating with these stakeholders in order to clearly communicate the benefits of ATs.

A second uncertainty (Row 2, Table 1) concerns the future development of the demand for taxis. In anticipation of both higher demand (opportunity) and lower demand (vulnerability) than originally predicted, adaptive actions can be planned. For higher demand, plans for the expansion of the AT-fleet can be made (a seizing action); for lower demand, plans can be

Table 1
Vulnerabilities and opportunities in the basic policy, and related actions.

Conditions for Success	Vulnerability (V)/Opportunity (O)		Certain/ Uncertain	Actions taken at Time = 0 (Increase Basic Policy Robustness)	Signpost Monitoring (begins at Time = 0) and Trigger Events	Actions taken at Time > 0 (Adaptive Actions)
1. Support by regional/national government and other stakeholders	V	Insufficient support	Uncertain	**(SH)** Negotiate and lobby, e.g. implement public relations campaign to increase benefits of ATs **(SH)** Partner with transport research institutions to better communicate the benefits associated with ATs	**Monitor** stakeholder feedback on the basic policy. **Trigger**: If approval drops below predetermined approval threshold, take CR action	**(CR)** Adjust basic policy in response to specific feedback (e.g. adjust AT services in line with stakeholder preferences).
2. Travel demand for taxis develops as originally forecast	O	Future travel demand increases faster than predicted	Uncertain	**(SZ)** Develop plans for expanding the AT-fleet above those planned for in the basic policy	**Monitor** travel demand. **Trigger**: If demand exceeds upper threshold, take CP action	**(CP)** Implement additional AT plans in case those developed as part of the basic policy become insufficient
	V	Future travel demand decreases	Uncertain	**(H)** Develop plans to expand the AT services to e.g. underserved specific groups/travelers within the urban region	**Monitor** travel demand. **Trigger 1**: If demand drops below lower threshold, take CR actions. **Trigger 2**: If demand remains below threshold for e.g., some years, take RE- action	**(CR-1)** Implement plan to serve underserved, specific groups by AT. **(CR-2)** Implement plan to expand the AT-serving region. **(RE)** Reassess the policy
3. Acceptance by taxi-operators, taxi-drivers, and travelers	V	Opposition by operators, drivers, and travelers	Certain	**(M1)** Educate operators, drivers, and travelers on the benefits of automated driving, e.g.: • Operators on improved fleet performance. • Drivers on less stressful and safer driving tasks. Travelers on costs of vehicle ownership versus AT use.**(M2)** Assure travelers on the privacy of their information	**Monitor** opposition per group. If opposition keeps going on, implement DA, CR, or RE action	**(DA)** Intensify educational campaigns on the benefits of ATs **(CR)** Improve privacy protection **(RE)** Delay AT implementation until society is ready for acceptance
4. AT technology performance	V	Technology failure	Uncertain	**(H1)** Provide insurance in case of large failure. **(H2)** Establish an AT Safety Board	**Monitor** technology failures. **Trigger** In case of failure implement CR-action or even RE-action (large failure)	**(CR)** Conduct a study (AT Safety Board) on causes of malfunctioning and fix it. **(RE)** In case of large system failure, reassess the entire policy
	O or V	Technological breakthrough on automated vehicles	Uncertain	**(E)** Develop plans to upgrade the ATs from 'conditional automation' to 'full automation'. **(E)** Prepare the legislation and regulations to implement fully automated taxis. **(H)** Begin negotiations with the taxi-drivers how to compensate for job losses (e.g. severance pay)	**Monitor** AT 'full automation' technology development and performance. **Trigger** In case of 'full automation' feasibility, implement CP- and CR-actions	**(CP)** Upgrade AT fleet to 'full automation'. **(CR)** Implement severance pay scheme

5. Travel supply by other modes develops as originally forecast	V	Other modes become more attractive (e.g., Mobility as a Service (MaaS))	Uncertain	**(H)** Work together with MaaS developers to include ATs in their future supply	**Monitor** development of MaaS infrastructure. **Trigger**: In case other modes reach a predefined attractiveness level, implement CP-action	**(CP)** Make AT mode part of MaaS supply
	O	ATs become the dominant mode	Uncertain	**(E)** Plan for city-wide upscaling of ATs.	**Monitor** development of AT use in relation to use of other modes. **Trigger**: In case AT mode reaches a predefined attractiveness level, implement CP- and DA-actions	**(DA)** Educate the public on the benefits of cycling and walking. **(CP)** Implement AT fleet on city-scale.
6. AT performance in relation to general urban transport goals	V	AT performs poorer than some of the targets set by the municipality on congestion, safety, pollution, parking spaces	Uncertain	**(H)** Integrate the AT basic policy with other traffic and transport policies in order to improve acceptance	**Monitor** impacts of basic policy. Depending on which type of target is not met, implement DA, CR, or RE action	**(DA)** Educate the public on the costs of car ownership and what they can gain from AT-use. **(CR)** Encourage AT-use through travel subsidies. **(RE)** Reassess the entire policy

(H) = Hedging Action; **(M) =** Mitigating Action; (**E**) **=** Exploiting Action; **(SH) =** Shaping Action; **(SZ) =** Seizing Action; **(CR) =** Corrective Action; **(DA) =** Defensive Action; **(CP) =** Capitalizing Action; **(RE**) **=** Reassessment.

made to expand the AT-services for specific groups of travelers and/or surrounding regions that are not currently served by the basic policy (a hedging action).

Looking at Row 3 of Table 1, one of the biggest certain vulnerabilities of the basic policy is the active opposition of the taxi operators, the currently employed taxi drivers, and the travelers. In anticipation of these problems, various mitigation measures can be taken. For example, taxi companies can be educated on the operating cost-reductions that AT implementation will bring. Some accommodation would have to be reached with the taxi drivers – perhaps an agreement on severance pay. Also, the public need to be educated on the current cost of traffic accidents in the city, and how much that might be reduced when automated vehicles replace the regular vehicles. There might also be some free public demonstrations of the service, in order to encourage public acceptance. Also, privacy concerns have to be addressed. Fagnant and Kockelman (2015a) suggest five data-related questions that need to be addressed prior to implementation of ATs: Who should own or control the vehicle's data? What types of data will be collected? With whom will these data be shared? In what ways will the data be made available? For what ends will the data be used?

A major uncertain vulnerability is the current lack of a legal framework for liability in case of technical failure of an automated vehicle (see Row 4 of Table 1). Anticipatory risk-reduction measures for this are offering insurance against technological failures, and establishing an AT Safety Board to investigate any incidents and identify their causes. Assuming that the technology develops in such a way that fully automated ATs can be implemented, the government should begin the process of establishing the legal framework for transitioning from conditional to full automation, perhaps in cooperation with other jurisdictions and the automobile manufacturers. It should also begin negotiating with the taxi drivers on how they are to be compensated if they are no longer needed. Also, liability could be shifted from drivers to manufacturers. The allocation of liability among the parties needs to be established, and adjudication methods need to be developed. To avoid early 'lock-in', some regulatory flexibility would be desirable – for example, allowing circumscribed uses, such as low speed operation within certain areas in order to gain experience with ATs, before implementing a blanket set of rules (International Transport Forum, 2015).

The basic policy is clearly disrupting the current taxi system. But, the policy implementers should remain aware of other external developments that might affect the demand for ATs. For example, other modes might change their operations to become more attractive, or another disruptive mode might appear (see Row 5 of Table 1). One such mode (which could make ATs vulnerable, or might actually increase their attractiveness) is implementation of seamless transportation across modes, such as Mobility as a Service (MaaS) Hietanen, 2014. MaaS is a mobility distribution model in which a customer's transport needs are met over a single interface. It is enabled by combining individual public and private transport services through a unified gateway that creates and manages the trip, and which users pay for with a single account. It is also well possible that ATs become the dominant mode in the future. In fact, Enoch (2015) foresees modal convergence into a "universal automated taxi service". In order to anticipate such a future, plans for further city-wide implementation of ATs should be prepared.

A final uncertain vulnerability is that the implementation of ATs may not contribute as much as expected to the goals, in terms of congestion, safety, space, and the environment (Row 6, Table 1). For example, the use of ATs could lead to more dispersed development, which could lead to more travel overall Enoch (2015). In anticipation of this, in addition to the previously mentioned proactive measures of Step III, plans should be made to integrate the AT policy with other mobility measures (e.g., traffic management measures) designed to help meet the goals.

Step IV (Setting up the Monitoring System) and Step V (Preparing the Trigger Responses)

The conditional AT system would be set up as a pilot operation – on a small scale (one city) with a great deal of monitoring (and interaction with the car manufacturers and technical development specialists). There are several things to monitor and actions to be prepared (see Columns 5 and 6 of Table 1). Future AT use could remain too low (see Row 3), given policy objectives in Step I. Therefore, an education campaign should be prepared or even a travel subsidy policy implemented. The speed of technological development on automated vehicles should be monitored to allow an upgrade from conditional automation to full automation (see Row 4). The plans for such an upgrade have been prepared at $t = 0$, together with an agreement with taxi drivers on how to compensate for job losses. A final example involves the monitoring of the ongoing development of other transport modes, e.g. MaaS (see Row 5). A corrective action could be that the previous collaboration with the MaaS developers (started at $t = 0$) be generalized to enable future integration of the AT-mode within the services offered by MaaS. A defensive action (if there is too big a shift to ATs) could be to educate the public on the benefits of cycling and walking.

Conclusion

This paper has illustrated a way to handle the deep uncertainties surrounding the implementation of an innovative urban transport solution from the perspective of public policymaking. The combination of automated vehicles and technology-enabled taxi operations (i.e., Automated Taxis (ATs)) has great potential to contribute to urban transport policy goals. On the other hand, public policy and decision making is confronted with the existence of large uncertainties related to the implementation of these ATs, which pose barriers to implementation. The challenge for enlightened policymaking is to develop innovative approaches for handling these uncertainties.

The paper has proposed an approach involving a flexible or adaptive policy that allows for adaptations over time as experience and knowledge about the real-world functioning of ATs proceeds. In particular, policymakers are encouraged to first develop a normative view, and then guide the policy development, implementation, and adaptation process based on gathering information that allows for the resolution of the uncertainties over time. The adaptive policy approach was illustrated for a simplified, hypothetical case. We showed how policymakers can cope with uncertainties concerning AT by implementing an adaptive policy, and how such a policy can be adjusted as new information becomes available on its real-world performance. The illustration shows that, compared to traditional policymaking, the adaptive approach is highly promising in terms of handling the range of uncertainties related to AT implementation.

In particular, a basic policy, to be implemented first, would be to implement an Uber-like taxi-system in the city with 'conditional automated' vehicles. These taxis would have all aspects of the driving task automated, with the expectation that the human (taxi-)driver would respond if requested to resume control (within a sufficient time margin). Actions are added to the basic policy to protect it from failing or to seize opportunities to enhance its success. These actions include education of taxi drivers, a subsidy for AT-fleet development, AT-campaigns for the larger public, providing insurance in case of technology failures, as well as preparing for (uncertain) future developments, such as future acceptance of AT, technological breakthroughs on automated driving technology, and progress on alternative modes. These developments are monitored, and plans are prepared to respond to predefined trigger events.

Developing and implementing such an adaptive policy will not be easy. There are significant legal, political, and analytic barriers to be overcome. However, compared with traditional policymaking, the adaptive approach is highly promising in terms of handling the range of uncertainties related to AT implementation.

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