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Overcoming challenges in road pricing design with an agent-based transport simulation

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1 Abstract

Vast majority of economists and transportation planners today agree on congestion pricing being an efficient instrument for regulation of growing transport demand and addressing the urgent issue of road congestion in urban areas. However, many are still concerned with challenges associated with the transferability of the marginal cost pricing approach to simplified, real-world tolling solutions, the computation of optimal toll as well as the feasibility of large-scale implementations. The goal of this paper is to demonstrate the potential and the benefits resulting from the use of agent-based simulation models in order to address these concerns and provide powerful tools for detailed evaluation of road pricing scenarios. Thereby, advantages of toll scenario implementation and analysis within an agent-based model are discussed based on the multi-agent transportation simulation toolkit - MATSim and associated challenges and drawbacks are considered. Furthermore, potential applications of an agent-based simulation for large-scale scenario analysis with different road pricing schemes are presented and outlook of future work using a simulation-based optimization approach for the design of road pricing schemes is given.

2 Introduction

Road pricing as an economic concept refers to the direct charging of travelers for the use of roads. The imposed tax on road usage can have various motivation and the optimal level and scheme of taxation are strongly dependent on the goal of the particular road pricing concept. Hereby, different criteria, strongly dependent on the policy decisions, can be applied for the design of road pricing schemes. Maximizing the social welfare by optimizing the overall network performance in terms of total travel time is among the economists the most accepted approach. Another optimization goals can be profit- and revenue maximization or the maintaining of the traffic flow on certain minimal speed. Dependent on chosen design criteria and pricing scheme implementation, outcomes of pricing policies can strongly differ and under certain conditions even lead to welfare loses as compared to the no toll policy (Small and Yan, 2001).

According to the standard economic perspective, congestion is a result of market distortions arising from public roads under heavy usage conditions becoming a congested public good with rival nature of private goods (Hau, 2005). With speed dropping under the free flow speed of the road, the actual travel costs perceived and borne by the individual road user don't fully reflect the total travel cost imposed on the society. These additional costs are called external cost or externalities and result from the delay and associated additional time cost that the motorist imposes on other users of the same road. The difference between perceived cost and total social cost of travel for each individual is called the marginal external congestion cost. Setting the road toll equal to the marginal external congestion cost for each user individually leads to an economically efficient, competitive equilibrium. The imposed toll corrects the market distortion by creating the right (dis)incentives for road users and leads to the elimination or temporal shift of less beneficial trips. Thereby road charging concept allows decentralized decision-making and evaluation of the trip value by the individual economic agent for each single trip and is therefore superior to other tax policies as for instance the fuel tax. As under imposition of optimal toll, the total travel time in the network is minimized, the system converges to the state equivalent to the system optimum as defined by Wardrop (1952).

It must be noted, that besides of the delay costs, there are another externalities caused by traveling as pollution, noise or traffic accidents (Mayeres *et al.,* 1996, Parry *et al.,* 2007). These externalities are often strongly correlated with congestion and are highly relevant for the social wellbeing. Though, as these externalities don't directly affect the optimal system state defined by minimized total travel time, they are usually not considered within classic road pricing theory. In line with this, marginal external congestion cost are assumed to be equal to the marginal social cost and to dependent only on the delay imposed on others.

The theoretical concept of marginal external congestion costs is widely known as "first-best" pricing, providing the maximization of social surplus and welfare. It serves a useful theoretical benchmark for optimal network performance, but due to number of simplifying assumptions, faces practical limitations and constrains in the real-world implementation. Road pricing schemes designed under these constrains are referred to as "second-best" solutions. Computation of tolls for a second-best pricing scheme with goal of best approximation of first-best conditions turns out to be a non-trivial task, requiring significant amount of information (Verhoef and Small, 2004). At the same time the second-best solutions have to be easy understandable, predictable and transparent for road users in order to allow rational response to (dis)incentives set by road tolls and corresponding adjustment of travel behaviour. Furthermore, with transportation being a backbone of modern economy, effects of road pricing on economic activity and its interaction with other economic and behavioural processes within urban areas must be considered. Traditional, analytical models are stretched to their limits trying to account for all effects and processes involved and interweaved with road pricing design and implementation. New solution concepts for this problem can be provided by combination of microscopic network simulation models with highly disaggregated information on travel demand, travel behaviour, activity locations and land-use.

Modelling of travel demand based on activity patterns and activity locations represents a fundamental approach to transport planning and involves processing of substantial amounts of highly disaggregated data. With advances in information technology, integration of the activity based demand and the dynamic traffic assignment within large-scale agent-based transport simulation framework became feasible. Models developed within such an agent-based simulation incorporate large parts of behavioural information required for analysis and optimization of road pricing scenarios. In following we present one of such frameworks and discus, how it can be used to overcome major challenges in road pricing design and optimization.

In this work, we use the **M**ulti-**A**gent **T**ransport **Sim**ulation Toolkit (MATSim) (Matsim.org) in order to demonstrate the potential of such simulation tools in context of analysis and optimization of road pricing strategies. MATSim integrates human behavioural models with queue-based traffic flow simulation and provides capability for the implementation of large-scale scenarios with several million agents. Therefore, this simulation-based approach allows to account for dynamic interaction of interdependent processes, incorporated within a comprehensive transport model and allows to address number of problems associated with modelling and optimization of congestion pricing, which arise when using conventional analytical methods.

The goal of this paper is to highlight the opportunities provided by an agent-based model for overcoming some of the important challenges in design and optimization of congestion pricing scenarios. First, in section 2, we summarize the economic fundamentals of road pricing and give a brief overview of associated implementation complications concerning equity and public acceptance. Section 3 briefly addresses state-of-the-art approaches for modelling of congestion pricing as well as central complications arising with design of second-best pricing schemes. In section 4 we present how agent-based simulations can be used to overcome major challenges existing in modelling of second-best pricing schemes and what are the limitations and the technological difficulties associated with such implementation. Following, in section 5, application examples of agent-based simulation for design and evaluation of different real-world congestion pricing scenarios and policies are discussed and an outlook on use of simulation based optimization concept in context of road pricing is given.

3 Economic theory of road pricing

Traffic congestion is a common phenomena in many urban areas all other the world and is a result of travel demand exceeding the supply of road capacity. In modern economies the cost of congestion adds up to significant amounts and is estimated reach up to 1.5% of GDP in certain countries (Nash *et al.*, 2003, Schrank *et al.*, 2010, de Palma and Lindsey, 2011). The idea of using congestion pricing as a tool for regulating demand and alleviating congestion was indroduced by Pigou (1920) and Knight (1924) and later developed by Vickrey (1963). More recently various economists addressed the question of economic fundametals of road pricing (e.g. Hau (2005), Lindsey (2006)). In general, there is a strong consensus about the use of congestion pricing as a tool for regulating congestion and reducing cost to economy resulting from it (Lindsey, 2006). However, despite of this consensus, the number of implemented road pricing schemes is very limited. Next to dynamic pricing schemes limited to a single facility (e.g. I-15 in California, Sydney Harbour Bridge) or nearly fixed zone-based pricing (Stockholm, Norway), so far only Singapore adopted some form of a comprehensive congestion related prcing scheme covering the city centre as well as major expressways (see Small and Verhoef (2007), Tsekeris and Voß (2009), de Palma and Lindsey (2011) for overview). This lack of translation from the theory into the practical realization is mainly due to two reasons: first is the complications and concerns associated with practical implementation of second-best congestion pricing schemes and the second is the negative public opinion towards road pricing.

In practice, major complications are associated with modeling and implementation issues are heterogeneity of travelers, different influence of congestion pricing on individual travel decisions (Small and Yan, 2001), optimal design of second-best pricing scheme and its effect within a large-scale urban road networks as well as technical realization and administration costs. The reason for public rejection is comprehensively shown by Hau (2005) and is a consequence of disadvantages, which the majority of travelers faces after introduction of congestion pricing. In general, at the fist sight vast majority is left worse off as in comparison to a toll-free scenario. For motorists, who are still using the road, the cost of toll generally exceeds the advantages through time-saving and others, for whom the marginal cost exceeds their willingness to pay for the road usage, are tolled off the road completely. The achieved social welfare gain is directed towards the government in form of toll revenues, making it the main profiteer of congestion pricing. The only exception from this, is the case of hypercongestion, where everyone in the society benefits from the imposed congestion tolls (Hau, 2005). The failure to divert the newly collected road toll revenues back to road users and pass on the social welfare gain can be considered as the major factor which prevents congestion pricing to gain broad public support. There are different economic opinions existing on the question, how to recycle these revenues. Some argue, that revenues from road tolls should be invested in public transportation, service and infrastructure, others that they should be returned to the taxpayer by reducing other vehicle related charges and keeping the revenue neutrality. There are also voices advocating complete flexible use of revenues (for more detailed discussion see (Lindsey, 2006)). No matter which policy prevails, it's in governments responsibility to communicate and show the social benefit of congestion pricing to public in order to achieve its acceptance. It should also be noted, that at the social optimum congestion is not fully eliminated and the traffic speed on the road can still be significantly below the free flow speed. This factor may play an another important role in the perception of congestion pricing efficiency by the road users.

Another important issue associated with the second-best implementation of road pricing and strongly related to the usage of revenues from it, is the question of equity. In contrast, to the general consensus among economists over the basic principle and the benefits of marginal congestion pricing, views on equity issues associated with imposing congestion charges are mixed. As described above, imposing congestion charges results in welfare gain for the society due to the increases of the social surplus. The economically efficient state though does not comprise any statement on the equity or the fairness of resource distribution. As equity is defined in relative terms, there are many divergent notions of it, associated with different levels. Detailed overview on notion of equity in context of congestion pricing is given by Ecola and Light (2009). As authors note, it is common to distinguish between vertical equity, which refers to the distribution of costs and benefits between groups and horizontal equity, which relates to the distribution of costs and benefits within a certain group. Thereby vertical equity is usually defined in terms of personal or household income, and horizontal equity is often associated with spatial effects and is defined in terms of mobility or accessibility (Anas and Lindsey, 2011). As was shown by Arnott *et al.* (1994) and Hau (2005), low income groups suffer often disproportionately from road pricing, making it often a regressive measure prior to recycling (Basso and Jara-Diaz, 2012). An overview of studies on equity and revenue recycling from road pricing is also given by Levinson (2010). More recently Anas and Lindsey (2011) discussed the equity issue and distributional impact of road pricing from more general perspective of urban transportation externalities. In another recent work, based on cordon toll scenarios of Chicago central area, Anas and Hiramatsu (2011) point out the strong dependency of the welfare distribution on the size of the cordon toll area, the spatial income distribution as well as the need of considering the effects of road tolls on real estate market.

As pointed out earlier, recycling of revenues plays a crucial role for acceptance of road pricing and from the government perspective, understanding both, horizontal and vertical equality changes due to road tolls is crucial for effective toll revenue distribution. Such distribution policy, as it could be the commitment of toll revenues for improvement of public transport as in case of Stockholm for example, can lead to overall progressive effect of road pricing (Eliasson and Mattsson, 2006). Furthermore, a better understanding of disaggregated effects on different consumer groups and the detailed assessment of winners and losers based on socio-economic characteristics as well as spatial home, work and activity locations of individuals, can assure fair and most effective revenue distribution. Such disaggregated analysis of road pricing effects would allow correction of inequalities and establishment of a Pareto improving policy. Furthermore, in case of deviation from optimal pricing concepts by granting discounts and exemptions, consequences of such policies require a detailed assessment, as they can compromise the efficiency of the whole system.

Additional, often neglected aspect of road pricing, is its long-term effects on urban development, residential and commercial location choice and vibrancy of urban areas. Some of previous works tried to address this issue (Anas and Hiramatsu, 2011), but a comprehensive model relating short-term changes in travel costs and time to urban development is still to be developed.

4 Complications in modelling and implementation

In practice the concept of first-best marginal congestion pricing is of limited relevance. The two main reasons for that are the high cost and technological challenges associated with the implementation of the time- and link-specific charges in the whole road network as well the lack of user acceptability due to obscurity of the pricing scheme and low predictability of actual charges for a particular trip in advance. Therefore, first-best pricing can rather be considered as a benchmark for the evaluation of alternative, more affordable and transparent second-best congestion pricing schemes. The design and the optimization of second-best pricing schemes is a complex task, as number of indirect effects must be considered and the rules of first-best pricing design can't be applied straightforward. Among others Lindsey and Verhoef (2000), Small and Verhoef (2007) and Fosgerau and van Dender (2010) discuss some of the issues of second-best pricing including network aspects as untolled route alternatives, limitations in continuous toll variation over time, undifferentiated tolls among all types of users, interactions with other distorted markets, effects of stochastic congestion as well as lack of information on the individual level. Another important aspect is the drivers response to the complexity of the pricing scheme and the uncertainty of the road toll for a certain route before the travel. As the optimal congestion charging implies that the toll depends not only on the severity of congestion but also on its duration, charges raised for a certain travel might appear elusive to the driver. Paying for the delay of travelers, who arrived to the congested link after the payee already left it might appear counterintuitive to many road users. This unpredictability of road charges and the elusive perception might lead to irrational choices and failure of the congestion pricing to achieve optimal performance. Aversion to complexity as well as mistrust and privacy concerns associated with technological implementation, involving an electronic metering device in each vehicle, were major reasons for opposition of congestion metering scheme discussed and tested in Cambridge, London (Ison, 1998, Ison and Rye, 2005).

As a consequence, design of second-best congestion pricing schemes requires integrated evaluation, accounting for interactions of congestion and traffic network dynamics with heterogeneous behavioral as well as socio- and spatio-economic factors. Challenges arising from second-best congestion pricing solutions and methodologies for addressing them have been discussed in various recent papers and books (Fosgerau and van Dender, 2010, Small and Verhoef, 2007, de Palma and Lindsey, 2011, Tsekeris and Voß, 2009). Though, only few explicitly consider agent-based models and simulation tools in order to overcome these problems. de Palma *et al.* (2005) are one of the first to apply a dynamic equilibrium simulator with endogenous departure-time decisions as well as mode and tour choice on individual level for analysis of road pricing schemes for a small-scale laboratory network. Main drawback of the METROPOLIS model though are the lack of trip chaining and the lack of model for secondary location choice. Therefore change in destinations, as for example shopping location, due to different road toll policies can not be modelled. In another paper, Zhang *et al.* (2008) used agent-based techniques to explore the welfare consequences of product differentiation on congested networks and demonstrated the crucial role of user heterogeneity. In the overview of state-of-the-art road pricing design and evaluation, Tsekeris and Voß (2009) highlight the potential of agent-based models, due to its bottom-up approach with significant degree of disaggregation, intelligence, autonomy and ability to capture interactions among individuals. They endorse an integrated framework, combining models of macro- and micro-level effects. Nagel *et al.* (2008) use MATSim to show, how multi-agent simulations approach with full daily plan for each ageant can be applied for economic policy evaluation on a large-scale scenarios using Zurich metrpolitan are as a case study. Thereby though, no mode choice or location choice models are included. Kickhöfer *et al.* (2011) expand this approach and evaluates income dependent effects of road pricing on welfare distribution using MATSim. In most recent work Zheng *et al.* (2012) combine a macroscopic modeling of traffic congestion in urban networks with MATSim in order to study and optimize cordon pricing schemes. They show how dynamic cordon tolls can be efficiently controlled using macroscopic fundamental diagram and investigate its effect on behavioral changes, as in particular time shift of certain activities. Though, as their model does not incorporate detailed public transport simulation, effects of mode choice dynamics are not addressed in detail as well as questions on equity are not considers on this stage.

Based on conclusions and findings of researchers mentioned above, it can be argued, that despite the fact, that MATSim does not incorporate any macro-economic models at the current stage, its representation of the interaction between individual economic agents and network and congestion dynamics on micro-economic level, offers significant advantages over the majority of other approaches and allows detailed investigation of short-term effects of road pricing for large scale scenarios. These advantages and the potential benefit of agent-based simulation for road pricing studies will be discussed in detail in the following two sections.

5 Addressing complications of road pricing design on agent-level

5.1 Characteristics of multi-agent transport simulation

MATSim is an agent-based transport simulation, integrating travel demand based on activity-schedules for each single agent with dynamic traffic assignment based on a queuing model (MATSim-T, 2012). Major features of MATSim are the integration of route choice, mode choice, activity start time and departure time allocation as well as secondary-activity location choice into fully dynamic model and transport simulation of one full day with the time-step of 1 second. Furthermore, its capability of simulating several million agents on large-scale, high-resolution transportation network, allows implementation of real-world scenarios for large urban areas.

The key characteristic of an agent based simulation model, is the representation of each single person within the study area by a software agent within the simulation. Each agent has certain socio-demographic characteristics, residential locations, and if applicable, work or education location attached to it. Derived from these characteristics, each agent has an initial daily schedule, also called daily plan, assigned to it. The evaluation of these plans is based on a scoring function, which assigns a score to each plan dependent on the success of plans execution during the simulation. Disutilities from traveling and utilities from performing activities are summed for the day, allowing to capture a full-day dynamics of activity schedules. Long travel times and late arrivals get punished, timely performance of all activities as scheduled in the plan is rewarded. In case of being late for work in the morning, the requirement of staying at work for a fixed time period leads to negative effects on after-work activities and the schedule-delay during the rest of the day. This scoring-concept allows easy integration of additional cost terms as road tolls and public transport fares into the scoring function. In the course of the simulation, each agent is trying to improve its plan score by changing routes, modes, departure times, second-activity locations etc. This is an iterative process, where certain number of agents change their plans after each iteration. With progression of the simulation, each agent keeps several daily plans in its memory, which it can choose from. It requires a repeated simulation of the same day for about 100-200 iterations, till an equilibrium is reached and no agent can significantly improve its score.

5.2 Common complications and possible solutions

Heterogeneity of Value of Travel Time: One of the major common challenges in designing any economic instrument for influencing and changing people's behaviour, is the heterogeneity among economic agents and therefore different reactions to provided incentives accordingly to one or several heterogeneous attributes. One of major factors of heterogeneity among road users is the value of travel time. As pointed out by Small and Yan (2001), Fosgerau and van Dender (2010) and Verhoef and Small (2004), the heterogeneity of value of travel time and its distribution among the road users can have substantial influence on road toll level and the corresponding welfare gain. Values of time is usually considered to be strongly correlated with income, but can also depend on trip duration or traffic conditions (Axhausen *et al.,* 2008). Within common aggregated travel demand models it is very difficult to account for differences on the individual level. Agent-based demand models however, usually already contain the income information for every agent, which makes it possible to define individual values of time for every agent as a function of income. This increases the capability of simulation to reflect travel behaviour and choices among different groups more accurately, allows evaluation of income dependent road pricing effects (Kickhöfer *et al.,* 2011) and enables simulation of differentiated toll policies. Furthermore, as for every agent and every trip, its duration as well as prevailing traffic conditions and traffic density can be obtained, the adjustment of value of travel time based on a single trip according to the severity of congestion is feasible.

Trip chaining and within-day schedule dynamics: Another important aspect of congestion pricing are trip-timing dynamics and the evolution of travel demand and traffic flow over time and space. Trip-timing plays a crucial role in the emergence of congestion, as it can be clearly seen during the peak hours. Preferences for certain departure and arrival times are one of the most important behavioral factors, which can be in influenced by time-dynamic congestion tolls and so contribute to more efficiency in the network. In order to account for these dynamics, time-dependent bottleneck model and concept of schedule-delay cost were first introduced by Vickrey (1969), followed by other time-dependent modelling approaches (see Hall (1999), Lindsey and Verhoef (2000)). Despite of modelling advances in this area, all these models fail to account for trip chaining and trip timing dynamics through the course of the day. Taking characteristic of a full daily schedule into account and allowing delay propagation through out the day with influence on timing of later activities, is an important property of MATSim due to its agent-based demand model. Furthermore, the presence of daily schedule allows integration of realistic activity rescheduling model, where each agent tries to optimize its activity timings during the day with respect to other constrains as activity type, minimal activity duration and opening hours of corresponding facilities. These properties of MATSim are highly beneficial for modelling and evaluation of trip timing dynamics in connection with road pricing policies.

Mode choice dynamics: Considering alternative transport modes during design, implementation and evaluation of road pricing is inevitable and cannot be neglected within an accurate transport and economic model. The importance of integration of all modes in process of modelling and price optimization, due to the interdependency between optimal, welfare maximizing congestion pricing and public transport fares as well as service frequency has been recently discussed by Basso and Jara-Diaz (2012). Furthermore, response to policy changes directly affecting one transport mode, strongly depends on accessibility, reliability, quality and price of alternative modes of transport, as has been pointed out, among others, by Anas and Lindsey (2011). Certain policy for one mode, can influence some or even all of these characteristics of other modes. As in case of road pricing, the service level of reliable and high quality public transport systems can deteriorate under additional demand caused by mode switching. This loss of quality service level can lead to loss of trust in the public transport and trigger an opposite reaction, substantially reducing effects of road pricing. Consequently, a detailed mode choice model is vital for accurate design and evaluation of pricing schemes as well as associated policies, such as expansion of capacities of public transport, in areas significantly affected by the introduction of road pricing. Such comprehensive assessment of road pricing effects on public transport for each service line and time of day, can best be done with an agent-based simulation model.

Due to its iterative structure, MATSim incorporates a mode-choice modelling approach, which is fundamentally different from the classical four-step model. With each iteration, a certain percentage of agents changes their plans in order to find a better alternative to the existing ones. One of the changeable parameters, next to route, departure time, activity start time or location of a secondary activity, is the travel mode. In case the plan with the chosen alternative mode turns out be a bad choice, the executed daily plan gets a low score and won't be used in the future. If though the score can be improved, agent will keep the new plan in its memory and preferably execute it during future iterations. Due to iterative design and utility-based plan evaluation, this rather simple best response mode choice model has been shown to perform well (Rieser, 2010). Furthermore, agent-based simulation allows to account for is the impact of quality and comfort of travel, which in case of public transport often depends on crowdedness and seat availability. As has been shown by Chakirov and Erath (2011), based on smart-card data in Singapore, seat availability can play a crucial role in route choice and for some public transport users be worth up to 15 min of the additional travel time. Within MATSim the disutility of crowdedness and the utility of seat-availability can be included into the scoring/utility function of each agent, as the number of agents traveling on certain bus or train as well as number of seats of particular vehicle can be obtained during the simulation.

Travel time uncertainty: Traffic flow on congested roads is highly sensitive to small disruptions, which increases the variations of travel speed. Hence, increased traffic density on the road is not only reducing the average travel time but also adding uncertainty and variability to it. Travelers facing greater uncertainty in their travel time, make different trip scheduling decisions and depart earlier as travelers, who can rely on the expected travel time. Despite of the extra added buffer time, travelers with greater travel time variability may often arrive too early, or too late to their destination. Thus, as argued by Fosgerau and van Dender (2010), travel time variability adds to the total travel costs and should be taking into account for computation of optimal toll level. This though turns out to be not trivial. As studies (Small *et al.,* 2005) indicate, the value of travel time variability is dependent on the shape of travel time distribution, which remains unknown within standard models and can only be to limit extend captured by a single number as e.g. standard deviation or the variance of travel time.

MATSim offers convenient way for implementation of travel time variability measures for each trip individually based on mean travel time, traffic density or travel speed during the journey. Though, considering the travel time distribution as a measure of travel time variability, as suggested by Fosgerau and van Dender (2010), turns out to be not a trivial task, as the concept of travel time distribution refers to an extended period of time with a typical length of several months. MATSim however simulates only one day of traffic. Alternative measures for travel time variability as, for instance the sensitivity of travel time to small shifts in departure time or travel time variability between travelers with similar origin and destination location within a certain period of time, e.g. 15 minutes, can be considered and evaluated. Further research is necessary in order to develop, implement and evaluate such method within an agent-based simulation framework.

5.3 Challenges of drawbacks of congestion toll implementation for agent-based simulation

As described in Sections 2 and 3, first-best optimal road toll is based on the concept of marginal social cost and should be set equal to the cost imposed on others by traveling on the same route, with identical origin and destination locations. Marginal congestion cost can be computed on a link-by-link basis through the network without accounting for effects of toll on the one link on other links in the network (Yang and Huang, 1998, Small and Verhoef, 2007, Safirova *et al.,* 2007). Hence it can be easily implemented in form of individual link tolls for the whole network within the large-scale agent-based simulation framework and would lead to an optimal system (Quinet and Vickerman, 2004). Lämmel and Flötteröd (2009) presented the derivation of marginal social cost based on travel time for an agent-based queuing model and provided a simplified approximation for the the marginal social cost based on the assumption of stationary flow through the time of the existence of the queue. Though this assumption seems to be reasonable,which is supported by presented simulation results, and also leads to a computationally inexpensive continuous evaluation of social cost for each agent on every link in the network, the implications of this approximation on the result and its derivation for the social optimum still have to be studied.

Another technological challenge results from the iterative nature of MATSim, as any change within the system disturbs the equilibrium. It can take between 60 and 150 iterations for agents to adjust their travel behavior according the new conditions and for the system to reach the new equilibrium (Balmer *et al.,* 2010*,* 2009). After changing the toll scheme and so the travel cost with every iteration, by adding congestion dependent marginal cost to it, the system does not have time to reach the state of relaxation. One the one hand it reflects the real-world conditions, as economic agents needs transparent information on pricing and certain time in order to adjust their behaviour rationally, which both is not exactly given in case of optimal toll. On the other hand, the influence of dynamics of simultaneous adjustment of toll and travel behaviour through the simulation, on degree of optimality for reached equilibrium remains unclear. Possibility of the system being caught in a local minimum must be considered and evaluated.

A conceptual drawback of MATSim framework at this point, is the absence of a budgeting concept. Specifying a certain travel and activity budget for each agent and accounting for respective expenditures for traveling and performing activities would allow to model trade-offs between the two. As, for instance, in case of road toll introduction, cost of transport might exceed benefits from performing a certain activity, which hence would be dropped. Implementation of budgeting though would require significant changes within the simulation framework and create the need for additional information such as expenditures for parking or performing of leisure activities.

6 Use of agent-based simulations for road pricing policy and design

6.1 Design of different pricing schemes

With route choice, mode choice, secondary location choice and variable trip timing models on individual level, integrated agent-based simulation framework like MATSim is well suited for the evaluation of policies, which influence travel behaviour in all these dimensions. As the precise impact of a specific policy can be obtained for each single agent, equity issues can be extensively studied. Especially the impact on the vertical equity, which is related to income, can be analyzed and benefits and drawbacks of social equalizing policies such as discounts for low-income travelers can be shown. In the following examples, benefits of using agent-based simulation for the design and evaluation of second-best road pricing scenarios, are presented based on more specific, common pricing schemes:

Area tolls For evaluation of area based tolls, where a road user needs to pay the entrance charge to the particular area only once a day, an agent-based simulation offers the advantage of travel decision making on individual level and based on full day time horizon. This allows to perform route planning and mode choice for each agent based on distribution of toll costs to all trips to the charged area during the day. This may lead to different choices as compared to cost evaluation for each trip separately, without considering other trips of the day. Same logic applies to the secondary location choice. Furthermore, the agent-based approach conveniently allows modeling of exemptions and discounts from the area charge, as for example in case of residents. As such exemptions are inconsistent with marginal external congestion cost theory, evaluation of effects from such policies is an important issue in process of designing an optimal area toll scheme.

Cordon-tolls In case of cordon-toll scenarios one of the main advantages of large-scale agent-based simulation is the consideration of network dynamics within the whole simulated urban area. This is particularly important as charging only certain links can have unexpected effects on other links, which were initially not affected by congestion. Accounting for such effects on untolled alternatives represents a major problem of cordon toll design. Furthermore, equity implications of cordon tolls strongly dependent on spatial distribution of income, resident and work locations as well as secondary-activity locations of the studied area (Santos and Rojey, 2004, Ecola and Light, 2009). This emphasizes once more the need of cordon toll evaluation with the whole picture of affected urban region in mind.

In terms of optimization of cordon tolls, implementation of macroscopic fundamental diagram approach presented by Geroliminis and Daganzo (2008), Daganzo and Geroliminis (2008) into agent-based simulation represents an interesting strategy. In their work Geroliminis and Daganzo demonstrate, that the concept of fundamental traffic flow diagram can be applied on aggregated scale within large urban areas and suggest control strategies based on it. Agent-based simulation allows the calculation of aggregated flow and density relationship within any predefined areas of the network. Dynamic adjustment of cordon toll along the perimeter of controlled area according to the optimal mid-range traffic density within this area represents a promising control strategy, which can be evaluated based on large scale real-world scenario implemented in MATSim, as shown by Zheng *et al.* (2012). Furthermore, study of transferability of this approach to optimization of area- or distance-based tolls represents another highly relevant research direction.

Distance-based tolls Distance-based tolls allow pricing the used road dependent on the distance driven on the particular road. The direct linkage between usage of the road and the road charge allows the use of the tax not only as a congestion regulation tool, but also as a substitute for fuel or emission taxes. Depending in the technology used, distance-based toll can be varied over time, distance, vehicle type and road type. With these four variables, design of an optimal charging scheme is again a challenging problem, which can be addressed in full scale with an agent-based simulation framework. Thereby, effects of different pricing functions, such as linear or logarithmic can be evaluated. Moreover, the impact of differentiated road pricing and social equalizing subsidies on toll efficiency can be evaluated by setting daily road charge ceilings dependent on the income.

6.2 Optimization within agent-based simulation framework

An optimization of certain control parameters based on an agent-based simulation is a complex and computationally expensive task. Number of detailed and disaggregated models embedded within an agent-based simulation lead to the nonlinear, stochastic nature of the overall system. The complexity arises from the objective function, which expresses the parameter to be optimized as for instance total travel time in the system, being depend on variables accounting for total demand, network topology, road capacities as well as traffic interactions. Such objective function does not have a close form solution and can only be estimated. The computation of these estimates though involves running numerous replications, which for large-scale scenarios bursts the limits of computational and time budgets. Osorio and Bierlaire (2010) recently addressed this problem by presenting a simulation-based optimization framework for urban traffic control. The main idea hereby it to use a metamodel that combines the information from the simulation and a network model that analytically captures the characteristic structure of the traffic simulation. This metamodel is computationally cheaper to evaluate and is integrated within a derivative-free trust region optimization framework. This framework was applied in order to optimize signal control timing in the city of Lausanne using a microscopic traffic simulation model implemented within the AIMSUN simulator.

In order to address the problem of second-best road pricing design, the same simulation-based optimization concept can be implemented within MATSim. Defining the objective function as total travel time in the system and the decision vector as time dependent charging scheme constrained to a certain area or links in the network, the optimization of the charging scheme can be performed and the result evaluated against the system optimum. Alternatively in case of distance based toll the decision vector can consist out of a time-dependent conversion-factor from distance to money for a certain set of links. Central challenges for both cases thereby, is how to relate the toll charge considered in decision vector to the analytical network model, which forms part of the metamodel, and how well it will reflect the underlying structure of the problem.

7 Conclusion and Outlook

As shown in this paper using the example of MATSim, agent based simulation approach opens new prospects for road pricing design and evaluation. Especially its ability to account for travel demand patterns of economic agents on individual scale including their socio-demographic attributes makes it a highly suitable and attractive tool for evaluation of transportation policies including road pricing. The setup of a large scale agent based model is a laborious task with extensive data requirements on transportation infrastructure, building stock, population statistics, travel behaviour as well as residential-, business-, work- and education locations within the whole urban area of the simulation (Erath *et al.,* 2012). Though once such model is established, it provides a variety of benefits for scenario-based analysis and due to large amount of disaggregated data incorporated in it, allows a wide range of applications. The next logical steps are to implement methods described in this paper into the MATSim framework and evaluate their effects first based on the well known Sioux Falls network and after on large-scale scenario of Singapore with 5 million agents. Thereby, in case of Sioux Falls scenario, implementation of a simple public transport network is required in order to account for the mode choice dimension. Once the marginal congestion pricing can be implemented and verified, alternative second-best pricing scenarios can be evaluated and optimized with social optimum scenario as a benchmark.

8 References

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