Towards optimal pricing in a multi-modal context with dynamic demand: An agent-based simulation approach

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January 2015

1 Introduction

Traffic congestion is a prevailing phenomenon in many cities and metropolitan regions worldwide, leading to social welfare losses, pollution and negatively affecting the quality of life. Use of road pricing as a traffic management instrument to enable more efficient use of road infrastructure has been widely studied and evaluated in numerous publications (see Small and Verhoef (2007) and Tsekeris and Voß (2009) for detailed overviews). Introduced by Pigou (1920) and Knight (1924) and later developed by Vickrey (1963), today the benefits of first-best pricing are widely recognized (see Hau (2005), Lindsey (2006)). However, in most cases the question of optimal road pricing is addressed under consideration of the car mode only. In reality, in most of the cities buses share the road space with cars and are affected by congestion. More recently Gonzales and Daganzo (2012) and Daganzo (2013) examined system optimum solutions for mixed mode operations with distributed demand. Solving system optimum for the bottleneck model and extending the results to urban networks, the authors state the existence of SO solution which can be achieved with given time-dependent tolls and fares.

This work addresses the optimal pricing question for roads shared among private and public transport vehicles. Applying the idea of marginal social pricing within an agent-based simulation framework, 3 scenarios are compared: the base case without tolls, vehicle based first-best pricing and the passenger flow based pricing. The passenger flow based case implies internalization of delay cost caused not only to other car drivers and car passengers but also to public transport passengers.

Thereby three degrees of freedom: route choice, mode choice and departure time choice are considered and contributions from each of these choice dimensions to the welfare gains resulting from shift towards the system optimal state are analysed.

Analysing the components of disaggregated utility function, the outcomes of simulation experiments are discussed with regard to classical, analytical economic models of congestion pricing, as presented by Small and Verhoef (2007) . In particular the analysis of components within the travel cost function as there are travel time, travel distance and monetary toll or fare allow to better understanding implications of congestion pricing policies on travel behaviour.

The major research contributions of this work can be summarized as following:

1. Investigation of optimal first-best toll in a fully integrated, multi-modal networks based on vehicle and passenger flows and evaluation of outcomes against no toll policy.

2. Analysis of influence of different degrees of freedom as route, mode and time choice.

3. Comparison of outcomes to analytical solutions presented in the literature.

2 Methodology

In order to compare the vehicles flow –based vs. people flow based approaches to first-best pricing, as well as to investigate implications of heterogeneous, income-dependent values of time within the population, the Multi-Agent Transport Simulation framework (MATSim) is used. By integrating travel demand based on daily activity-schedules with dynamic traffic assignment using a queue-based traffic flow simulation and employing a multi-modal transportation network, MATSim provides capabilities of accounting for interaction of travel behaviour and traffic dynamics. Fully integrated simulation of private and public transport enables to capture the dynamics of bus and car interaction and account for delays experienced by bus passengers in the process of toll calculation. Based on a co-evolutionary algorithm, agents alter their behaviour from iteration to iteration, trying to find optimal routes, modes and departure times and therefore maximize the total utility of their daily activity schedule. The selection of travel alternatives from the choice set of each agent is performed based on a random utility model which, after a number of iterations, leads to a convergence of individual and total utilities and therefore to an agent-based Stochastic User Equilibrium (SUE) (Nagel and Flötteröd, 2009).

This study is conducted using two scenarios: a simple corridor scenario and an enriched, agent-based small scale scenario with dynamic demand and an integrated public transport system based on the commonly used Sioux Falls road network. The development and properties of the second scenario are presented in Chakirov, Fourie (2014).

The first – best pricing in agent – based simulation is implemented using the marginal social coast approach, initially presented by Lämmel, G. and Flötteröd, G. (2009) and later adjusted by Lämmel, G. (2010). For the calculation of people flow based toll, the approach is adjusted in order to account for buses carrying multiple passengers.

For the analysis of simulation experiments aggregated realized utility of travellers together with monetary amounts paid for toll and public transport fare is used as a welfare indicator. Furthermore, in order to access the overall state of the system, the concept of "Macroscopic Fundamental Diagram" (MFD), where the number of vehicles in the network is related to the space-mean flow of the network, is employed. Initially proposed Godfrey (1969), Geroliminis and Daganzo (2007, 2008) demonstrated that MFD is a property of the network itself. Recently Geroliminis, Zheng and Aboudolas (2014) expanded the MFD concept to the passenger flows in bi-model networks. Therefore it can be used to study performance of the network and use it for system optimization, as have been shown in various publications (e.g. Geroliminis et al. (2012), Zheng et al. (2012), Gonzales and Daganzo (2012)).

3 Results

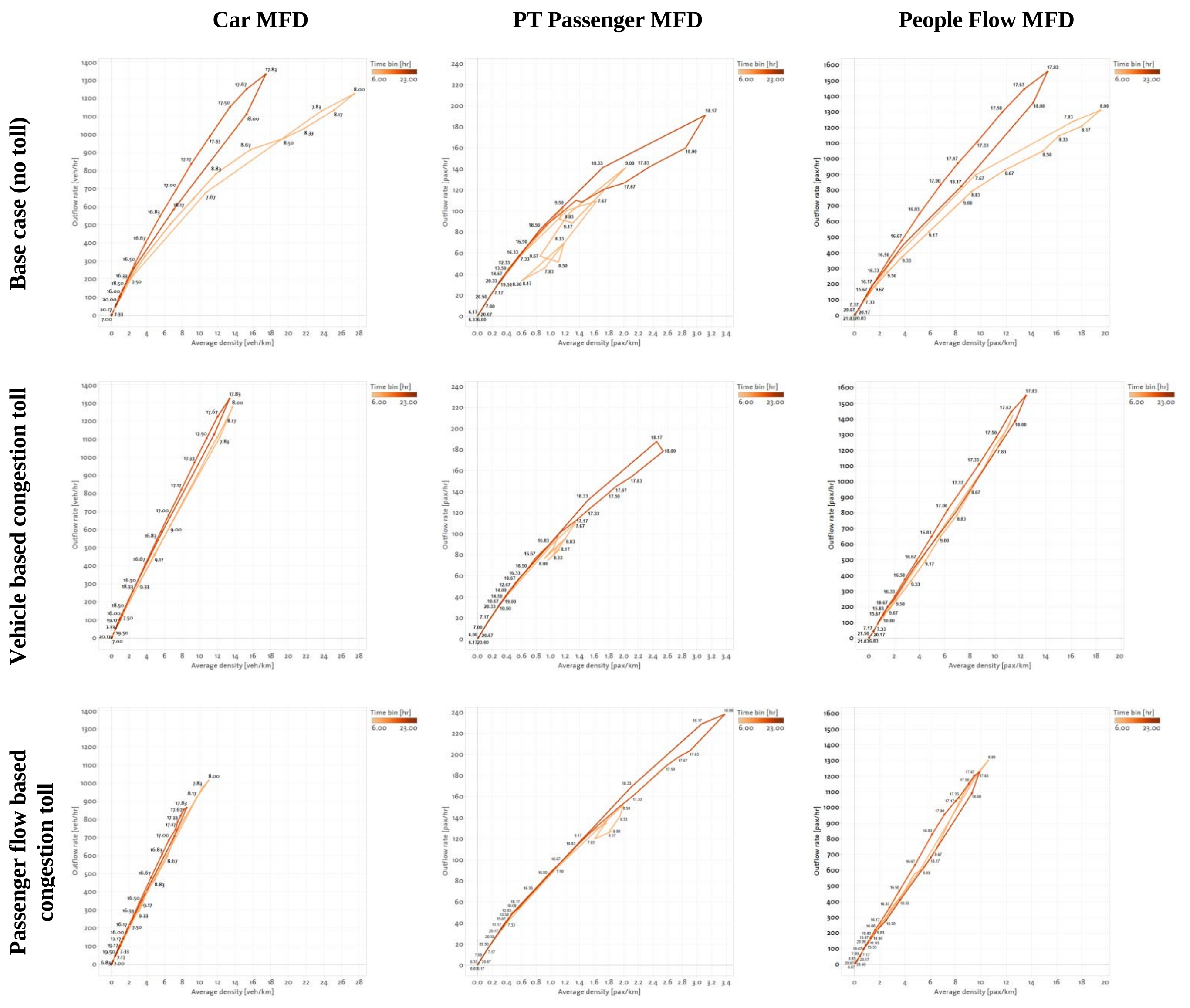
Comparing the simulation-based approach to the classical economic theory of first-best pricing with dynamic congestion as presented by Small and Verhoef (2007), two major differences should be emphasized. First, in the optimal state of analytical model, no travel delay exist, which is not true for the simulation, which is based on the queuing model. Second, the travel delay cost in simulation-based approach are implicitly determined by the activity utility functions, which are commonly non-linear.

The preliminary results suggest that in case of allowing for three degrees of freedom: route mode and departure time choice, both congestion toll policies lead to the increase in total welfare based on the predefined welfare indicator and drive the system towards the system optimal state. Comparing the both congestion toll policies against each other, the vehicle based congestion toll yields to higher total welfare than the congestion toll based on passenger flows.

In case of passenger flow based congestion toll the higher tolls more car drivers switch to the bus mode, increasing the number of bus passengers and pushing car drivers to use alternative routes minimizing interference with buses. Though minimizing delay for bus passengers, the road capacity on shared roads is not utilized optimally, leading to welfare loses compared to the case of vehicle based congestion tolling. Other effects as access cost to public transport (e.g. walking distance to a stop) and at this stage fixed public transport capacity and fares has additional negative effects and require further study. Allowing for the dynamic public transport fares and different bus headways, may lead to higher welfare in case of passenger based tolling.

Alternative way to analyse the state of the system, is to look at the macroscopic fundamental diagram for vehicle flow, public transport passenger flow and the total passenger flow in the network. Figure 1 exhibits this 3 MFD types for the each of the 3 simulation experiments. Thereby 2 effects can be observed. For both toll policies, MFD is shifted towards the maximal flow-density border line and does not reach a saturated state, as in case of the no toll scenario. Another effect is the reduction of hysteresis phenomena, which is associated with capacity drop due to inhomogeneous distribution of vehicles in the network, instability of the network during reloading or inability of the network to sustain throughput at the peak value. This phenomena have been previously addressed and discussed by e.g. Saberi, Mahmassani (2013), Gayah, Daganzo (2011), Geroliminis, Sun (2011).

Figure 1 Comparison of Macroscopic Fundamental Diagrams for vehicle flow, public transport passenger flow and total traveller flow for the 3 scenarios (no toll, vehicle based congestion toll, traveller flow based congestion toll)



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