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The structure of user equilibria: Dynamic coevolutionary simulations vs. cyclically expanded networks

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Abstract

A variety of approaches exist that model traffic time-dependently. While all approaches have their advantages and disadvantages but have to find a balance between modeling traffic as realistic as possible and being still manageable in combinational terms. While transport simulations are efficient in evaluating user equilibria in large scale scenarios, their potential to be used for optimization is limited. On the other hand, analytical formulations like models based on cyclically time-expanded networks can be used to optimize traffic flow, but are not suitable for large scale scenarios. By optimizing the network structure in a mathematical model and evaluating its effect in a more realistic transport simulation, two models can benefit from each other. Detailed knowledge about model properties and differences in traffic flow behavior help to understand results and potential difficulties of such a model combination. In this paper, properties of two such models are compared regarding traffic flow modeling. It is shown that the set of user equilibria in both models and, therefore, the resulting route distributions can be structurally different.

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Keywords: transport modeling, transport simulation, cyclically time expanded networks, user behavior, user equilibria, system optimum

1. Introduction

In times were congestion levels are growing in many urban areas, there is a need to improve and refine transportation networks. Traffic models provide assistance with predicting traffic patterns and designing and evaluating traffic policies. A variety of modeling approaches exist. All of them have to make compromises between capturing the reality as good as possible and keeping the model complexity at a manageable level. Because of their simplicity, static flow models are widely used to optimize traffic management schemes like tolls, traffic signal plans, or other network adaptions. These models' theory is well established, e.g. in terms of the effect of selfish users on the system welfare.[1] Despite their time independence, static flow models can be used to model traffic of specific, fixed points in time where traffic flow can be assumed to be constant for a while, e.g. during rush hours.

In reality, however, traffic is *not* time-independent and travel times and demand change over time. There are approaches to translate static flow models into more realistic ones, capture time dependency but keep some of the

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properties to benefit from its simplicity. One idea is to expand the network over time by creating copies of every node and link per time step[2] (see section 2.1 for a detailed explanation of time-expansion). With this, flow travels over time in a static network. Time-expansion only works for constant, i.e. flow-independent link travel times. Otherwise, the properties of links in the time-expanded network would depend on route decisions of travelers. Constant link travel times seem to give realistic results in urban areas, where links are short, speed limits exist, and platoons of vehicles drive with a similar speed as single vehicles. Congestion occurs while waiting at signals or crossings and is modeled by waiting links at nodes. Route travel times then arise as the sum of constant link travel times and waiting times, which renders them non-constant again.[3] Hence, time-expanded models can capture dynamic flows with constant link travel times in a static network and at least some results on static flows are transferable.[4] A major disadvantage of time expansion is that the size of the network increases immensely compared to the size of the original network. Thus, applying optimization algorithms from static flow theory directly to time-expanded networks is no suitable approach in general. Still, it is possible to construct other algorithms using properties of time-expanded networks.[4]

An approach to handle the size of time-expanded networks is to expand the network only for a fixed, short time interval and cyclically combine the interval boundaries. This results in a manageable network size, but limited time dependency. Like in static flow models only stationary demand patterns are representable. At least, demand repeats in each cycle and does not have to be constant all the time.

In contrast to time-expanded networks where link travel times have to be constant, there are also approaches for flows over time with flow-dependent transit times. These lead to more realistic results, but also to mathematical difficulties.[5] Due to the lack of well-defined analytical models for this kind of flows, few results are known for them.

Another approach omits the analytical part and instead uses simulation tools. Transport simulation may capture a lot of the complex, realistic behavior of traffic flows like time-dependent demand and travel times, spill back to upstream parts of the network, and a more detailed user behavior that includes not only route, but also time and mode choice. This is done by an iterative approach that simulates agents traveling through the network and performing their daily activities. The daily plans of agents are then evaluated and some agents are allowed to re-plan their day until the iterations reach a stable state, i.e. no agent wants to change their plan anymore. Hence, transport simulation tools find user equilibria for complex systems where not all relations are known in terms of closed mathematical formulations. They result as fixed points of the iterative routing and assignment process.[6,7,8] On the other hand, simulation tools miss the optimization potential because of the complex system they capture.

Knowing the properties of the different models, one can try to find a combination of the different approaches which benefits from the advantages of the models while overcoming their specific weaknesses: While transport simulations are efficient in evaluating user equilibria in large scale scenarios, their potential to be used for optimization is limited. On the other hand, analytical formulations like models based on cyclically time-expanded networks can be used to optimize traffic flow, but are not suitable for large scale and highly time-dependent scenarios. By optimizing the network structure in the mathematical model and evaluating its effect in the more realistic transport simulation, both models can benefit from each other. Detailed knowledge about model properties and differences in traffic flow behavior helps to understand results and potential difficulties of such a model combination.

This paper compares two of the discussed approaches to model traffic in a time-dependent way: A cyclically time-expanded network model and a dynamic coevolutionary transport simulation. For the time-expanded model an approach by Köhler and Strehler at BTU Cottbus, which was developed for fixed-time traffic signal optimization, is considered.[3] On the other side, the transport simulation MATSim is used.[9] Both models have already been coupled to optimize fixed-time traffic signal plans in a real world scenario. For this, the scenario is provided by the transport simulation and converted into a cyclically time-expanded network. The static model then approximates optimal fixed-time signal plans for all signalized intersections by solving a mixed integer program (MIP) with the high performance solver CPLEX. These optimized signal plans are returned to the transport simulation to evaluate travel time effects in a more realistic model. Initial results have been presented by Grether[10].

The structure of this paper is the following: The two models are introduced in the next section and compared in section 2.3 regarding their model properties. Resulting flow patterns, i.e. user behavior of both models are compared in section 3. Conclusions are drawn in Section 4.