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Co-design of traffic network topology and control measures

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ABSTRACT

The two main directions to improve traffic flows in networks involve changing the network topology and introducing new traffic control measures. In this paper, we consider a co-design approach to apply these two methods jointly to improve the interaction between different methods and to get a better overall performance. We aim at finding the optimal network topology and the optimal parameters of traffic control laws at the same time by solving a co-optimization problem. However, such an optimization problem is usually highly non-linear and non-convex, and it possibly involves a mixed-integer form. Therefore, we discuss four different solution frameworks that can be used for solving the co-optimization problem, according to different requirements on the computational complexity and speed. A simulation-based study is implemented on the Singapore freeway network to illustrate the co-design approach and to compare the four different solution frameworks.

1. Introduction

In order to improve the performance of a traffic network, the traffic authorities and policy makers usually pose this problem in one of the following two forms: changing the network topology or introducing traffic control measures. Network topology design involves construction work such as building new links or expanding existing links in the network. The advantage of this approach is that it can directly and effectively solve the capacity limitation problem, while the disadvantage is that the implementation may be very expensive and time-consuming, and sometimes the required free space may be not available. On the other hand, traffic control measures aim at a more efficient use of the existing infrastructure, without changing the network topology. However, this approach may be not able to improve traffic flows in some cases, e.g., when the total demand exceeds the capacity of the network. Therefore, we introduce a co-design method that applies the network topology design and the traffic control measures jointly in the traffic network. Intuitively, a better performance of traffic networks is expected by doing co-design of network topology and control measures compared to doing each of them separately. In fact, we will show in this paper that the co-design approach can indeed yield better results in terms of overall costs. Moreover, the co-design approach can be used to assist in the design of the network, as it allows to compare different network topologies including variations in types and locations of traffic control measures.

In this paper, we focus on freeway networks, but the co-design approach can also be easily adopted to urban traffic networks. In a freeway network, topology design refers to adding or removing links, or changing the numbers of lanes of links. It seems counterintuitive to remove links or lanes in order to improve the performance of the network, but the fact is that additional road capacity can sometimes induce extra traffic demand, and if not accurately predicted and planned, this extra traffic

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may lead to the road becoming congested sooner (a well-known example is the Braess paradox (Braess et al., 2005)). Moreover, from an environmental point of view, when freeway networks are built near or through existing communities, the quality of life in the neighborhoods is decreasing due to noise and pollution. In this case, it could be considered beneficial for social reasons to remove or reduce links in the network. In summary, network topology design is a multifaceted problem, where different questions such as environmental impact, budgeting, safety, and public inconvenience, have to be considered together. Moreover, some post-design issues such as network maintenance after construction should be also taken into account.

Sometimes, it is not necessary to change the network topology in order to improve the performance of the network, because it is possible that the available infrastructure in the network is not effectively used. Traffic congestion can be caused by the fact that drivers choose routes selfishly or drive in an inappropriate manner. In this case, traffic authorities can introduce traffic control measures to influence driving behavior so that traffic congestion can be eliminated or at least reduced. Papageorgiou et al. (1998) illustrate with a simple example that in a congested area, the total time spent (TTS) in the controlled case is 14% less than in the uncontrolled case, if the traffic outflow is improved by 5% thanks to appropriate traffic control measures. However, this consequence also implies that any disturbance that reduces the traffic outflow with a few percents may significantly increase the TTS, and hence decrease the performance of the network.

While the network topology is not changed once determined for the given design period, the traffic control measures do need to be adapted to the time-varying traffic situations. Due to this different time scale, one usually chooses a standard "optimal" setting of the control strategy, which is static, for the topology design. However, this method is not accurate enough to capture the dynamic nature of the traffic flows in the network. Therefore, we introduce a so-called *parameterized traffic control* approach (Zegeye et al., 2012), where the parameters of the control laws are optimized according to a pre-defined objective function. The reason for using the parameterized control is that for some other control approaches such as optimal control or model predictive control (see Section 2.2.2), the traffic control inputs usually consist of dynamic signals that vary on a minute to minute basis according to the time-varying traffic situations; however, in the parameterized control approach, the parameters of the control laws are considered fixed over the design period, and the control laws generate dynamic traffic signals based on the state of the traffic network. Moreover, we can even consider a more comprehensive quasi-dynamic setting (see Section 4.2), where the design period is divided into different sub-periods, and where each sub-period has a separate group of control law parameters. By using the predicted long-term future evolution of traffic demand, both the topology and the control law parameters can be optimized jointly. It is however important to note that although we use the co-design approach to determine the parameters of control laws for the traffic control measures, this does not mean that these parameters should be fixed for the entire design period. Instead, we can still use online control measures, and regularly retune or optimize the parameters of the control law based on the real traffic situation, via e.g. standard traffic control strategies, optimal control, or model predictive control.

The main aim of solving the co-design problem is to find the optimal topology design decisions and the optimal parameters of the control laws. In order to obtain those optimal solutions, both topology design decisions and traffic control measures are applied to a traffic model, and a cost is calculated based on the resulting traffic states (typically traffic density, flow, and speed), and used to evaluate the performance of the traffic system under the impact of topology changes and traffic control measures (see Fig. 1). From the traffic management point of view, the objectives of the co-design problem can vary from avoiding traffic congestion to increasing network safety and reliability, and to decreasing fuel consumption and pollution, etc. In this paper, we consider a total monetary cost that includes the budget of construction and maintenance for the network, and a valuation of travel time and travel distance. Note that the construction cost is only spent once, but the maintenance cost is spent every year. Moreover, the price level of the maintenance is not constant but rising every year because of inflation effects. The value of travel time is often used for appraisal of road and public transport projects. It should be included in the monetary cost because it is closely related to the economical factors, e.g., drivers' wages, and interest or depreciation of the freight, etc. A full discussion of value of travel time is out of the scope of this paper, but we refer the interested reader to DeSerpa (1971) and Wardman (1998) for more information on this topic. Moreover, travel distance is taken into account in this paper as well because it is also related to the economic factors such as fuel consumption and wear of vehicles.

The main contributions of this paper are:

1. We define a unified problem formulation for co-design of network topology and traffic control measures. We formulate the co-design problem in a model-based optimization framework, where the network topology design and traffic control measures are jointly applied to a traffic model, and a monetary cost is used to evaluate the performance of the traffic network.
2. We discuss four different solution frameworks for solving the proposed co-design problem, namely separate optimization, iterative optimization, bi-level optimization, and joint optimization, according to different requirements regarding performance and computational speed.

The rest of this paper is structured as follows. Section 2 briefly summarizes the state-of-the-art on network topology design and traffic control measures. Section 3 presents the problem statement. We formulate the co-design problem in a mathematical way in Section 4, and propose four different solution frameworks in Section 5. A simulation-based case study