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Real-time route diversion control in a model predictive control framework with multiple objectives: Traffic efficiency, emission reduction and fuel economy

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ABSTRACT

In this paper, the route recommendation provided by the traffic management authority, rather than the uncontrollable bifurcation splitting rate, is directly considered as the control variable in the route guidance system; a real-time en-route diversion control strategy with multiple objectives is designed in a Model Predictive Control (MPC) framework with regard to system uncertainties and disturbances. The objectives include not only traffic efficiency, but also emission reduction and fuel economy, which respectively correspond to minimizing the total time spent (TTS), total amount of emissions and fuel consumption for all vehicles moving through a network. In the MPC framework, the routing control problem is transformed to be a constrained combinational optimization, which is solved by the parallel Tabu Search algorithm. Two representative traffic scenarios are tested, and the simulation results show: (1) The room for improvement in each objective by means of route diversion control is not consistent with each other and varies with the utilized traffic scenario. In the peak hour, the routing control can lead to significant improvements in TTS and fuel economy, while a relatively small improvement in emission reduction is achieved; in the off-peak hour, however, it is opposite, which indicates that routing is possibly dispensable from the aspect of improving traffic efficiency, but is required from the aspect of emission reduction. (2) The conflict among the multiple objectives varies with the utilized traffic scenario in route diversion control. Improving traffic efficiency often conflicts with emission reduction in both scenarios. For the objectives of traffic efficiency and fuel economy, they are not conflicting in peak hour, while in the off-peak hour, the two objectives are likely conflicting, and the improvement in one objective can lead to the degradation in the other objective. (3) Regardless of the scenarios of peak hour or off-peak hour, the proposed control strategy can result in a proper trade-off among the three chosen objectives.

1. Introduction

Due to the increasing travel demand, traffic congestion has emerged to be a severe problem in urban areas around the world, which leads to longer trip time, higher accident risk, underutilized network infrastructure, and increased energy.

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In the advanced traffic management system, route guidance control through in-vehicle devices, radio, or variable message sign (VMS) are designed to provide information (i.e., road blocked or route recommendations) to travelers and influence their route-choice behavior (Kotsialos and Papageorgiou, 2004; Papamichail et al., 2007; Erke et al., 2007; Zhong et al., 2014). Nowadays, the route guidance control is widely implemented on motorways to mitigate traffic congestion, and improve the utilization of network infrastructure by redistributing the traffic flow, i.e., diverting the flow from the overloaded routes to the routes with more spare capacity (Messmer et al., 1998; Basu and Maitra, 2010; Spiliopoulou et al., 2013, 2014).

In the real-time route guidance control, the route suggestions or recommendations are offered to influence the flow distribution on routes, and this effect can be described by the splitting rates at the bifurcations where the route guidance is provided. Therefore, the splitting rates at the bifurcations (decision points) are often considered as the control variables or decision variables in the routing controller design (Kotsialos et al., 2002; Xu et al., 2011; Cong et al., 2013; Majid et al., 2013). However, the bifurcation splitting rates are not directly controllable, since it is not realistic to disseminate the message that a certain portion of traffic should follow one route. In the VMS-based route guidance system, what can be controlled are when or what route recommendation is provided on the VMS board. Although we can obtain the desired splitting rates at the controlled bifurcation nodes based on the current network condition, and then convert them to the route recommendations using some methods (i.e., pulse width modulation), the results from conversion may be suboptimal, and it will cause frequent switching of the route guidance signal that may confuse travelers (Messmer and Papageorgiou, 1995). Therefore, the controllable variable, which refers to the route recommendation on the VMS board here, is directly considered as the control variable. In some research (Messmer and Papageorgiou, 1995; Wang et al., 2006; Spiliopoulou et al., 2013), the VMS control variable is defined to be 1 if the main route (typically the geometrically shortest one) is recommended, and 0 if the alternative route is recommended, then the route diversion control is transformed to a bang-bang controller. However, the case that the traffic management authority does not provide any route recommendation (i.e., VMS board is blank or only provides safe driving admonition) is not covered. It can be reasonably imagined that, when the travel demand is low, there is a little room for improvement in the network efficiency by means of route diversion control, which means no need for providing route recommendation. Therefore, providing no route recommendation is also an option for the control in the problem under discussion.

In most of the literature on this topic, the control objective for the routing control is to reach either system-optimum (SO) or user-equilibrium (UE) (Kotsialos et al., 2002; Boyce, 2004; Jahn et al., 2005; Wang et al., 2006; Xu et al., 2011; Majid et al., 2013). The system-optimum objective is to minimize the total time spent of all the travelers in a network of interest, and the routing may sacrifice some travelers and lead them to the longer-time routes. The user-equilibrium objective leads to the situation that all used routes between the same origin-destination pair have identical travel time, so the routing strategy will divert drivers to the shortest-time routes. In either of the system-optimum and user-equilibrium routing, only the travel time (traffic efficiency) is considered, while the environmental effect is rarely considered. With the increasing greenhouse gas (GHG) emissions and the climate change, reducing traffic emissions has become the focus of traffic management authority all over the world. In the US, transportation represents 28% of the total GHG emissions (EPA, 2013). To change this situation, policies such as the Clean Air Act Amendments of 1990, and the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) have been passed, and the US government is required to reduce the emissions for the improvement in air quality. In addition, transportation consumes over 20% of the energy, of which more than 70% comes from oil use (Davis et al., 2015). Oil is a non-renewable resource, and hence the reduction in fuel consumption saves the money for car owners and increases energy sustainability. Exploring techniques and methodologies for the reduction of emissions and fuel consumption has been a research hotspot in traffic control (Csikós et al., 2011; Zegeye et al., 2013; Pasquale et al., 2014; Han et al., 2015). In the route-choice decision-making process, it is reported that the fastest route is not always the best from the perspective of environment and energy economy (Ahn and Rakha, 2008). Ericsson et al. (2006) established the fuel consumption factor for 22 street classes, and proposed the fuel-saving routing based on historical data. Aziz and Ukkusur (2014) explored the route-choice behavior with the consideration of both travel time and emissions. Nie and Li (2013) proposed eco-routing to find a route that minimizes the travel time and fuel cost for a single vehicle, and meanwhile meets the given emission standard. However, these efforts are for pre-trip routing. In this paper we focus on the real-time en-route diversion control, and multiple objectives are considered, which include traffic efficiency, emission reduction and fuel economy.

In order to optimize the emission and fuel consumption in the route diversion control, traffic emission and fuel consumption models are required. Microscopic traffic emission and fuel consumption models characterize the individual vehicles based on the instantaneous data of single vehicle velocity and acceleration, such as VT-micro model (Ahn et al., 1999), Comprehensive Modal Emissions Model (CMEM) (Barth et al., 2000). The microscopic models are accurate, but the data of individual vehicles are hard to obtain, and the computation is time-consuming. For the traffic management authority, macroscopic traffic flow measurements are available. Macroscopic traffic emission and fuel consumption models calculate the emission and fuel consumption of traffic flow based on the macroscopic traffic data, for instance, the average-speed-based emission models (Ntziachristos and Kouridis, 2007; Liu et al., 2014). The macroscopic emission and fuel consumption models need less computing time, but they are less accurate. In order to get a balance between the computation time and the accuracy, Zegeye et al. (2013) integrated the microscopic emission and fuel consumption model, VT-micro, with the macroscopic traffic flow model, and then established a new macroscopic emission and fuel consumption model, VT-macro model. The VT-macro model was validated analytically and empirically, and it was shown that the model is suitable for the