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Including bicycling in a multimodal urban street intersection: a model-based predictive control approach

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1 Introduction

The benefits of using bicycles are numerous (Gatersleben and Haddad, 2010). Regular bicycling is an important form of exercise, which is relevant to reduce risk of coronary heart disease, stroke, diabetes, health cost, and to improve quality of life for people of all ages. In addition, the use of bicycles instead of motorized forms of transport for short journeys can help to reduce the overall level of fuel consumption, while also decreasing emissions from cold starts caused by short car trips. Bicyclists can often bypass congestion and grid-locked traffic, and in some instances may even arrive at their destinations faster than if they had driven a car. In many countries, the cost of owning and operating a car can account for almost 18 percent of a typical household's income, so bicycling can provide options also for those who would like to save money. The use of a bicycle on a regular basis can play an important role as a mode of transportation, while also in addressing climate change problems, and obtaining energy, health, economic, and quality of life benefits. In this work, we aim to improve the efficiency of bicycling in multimodal urban street intersections. For doing that, a Model Predictive Control (MPC) approach is proposed to obtain the appropriate re-timing which incorporates the dynamics of bicycling explicitly in the decision making process. The approach is compared with a fixed-time, and a traffic responsive strategy using a two-intersections arterial as benchmark arterial.

2 Multimodal traffic intersection

The level of service in controlled vehicular traffic intersections for motorized vehicles is usually based on controlling delays or queue lengths of automobiles. However, at urban street intersections automobiles, buses, pedestrians, and bicycles interact with each other such that improvements in quality of service to one mode may improve or lower the quality of service for another mode. For example, what travelers in motorized vehicles may consider quite acceptable could be considered as a quite bad service for non-motorized vehicle travelers. Therefore, in this paper we propose the use of the MPC approach to consider a balanced trade-off between bicycles and vehicles.

To add prediction models in the decision making process is a crucial step to explicitly consider the dynamic behavior of a transportation system (Núñez et al., 2012). For the modeling of vehicles in the urban traffic intersection we will use the S model (Lin et al., 2011). Regarding the dynamic for bicycling, many characteristics make cycle traffic unique and an interesting topic of research. These characteristics include the speeds and acceleration characteristics of cyclists, the impact of bicycles on the behavior of motor vehicles, the phenomenon that drivers provide greater passing distances to some kind of cyclists (Parkin and Meyers, 2010), the short episodes of high exposure to air pollution that occur while commuting, etc. In this paper we use a model for bicycle traffic that is similar to the S model, considering as state variables the number of bicycles $\eta^{\mathrm{b}}_{u,d}(k_d)$ in link (u,d) at time step k_d, and the number of bicycles $q^{\mathrm{b}}_{u,d,o}(k_d)$ waiting in the queue to direction o. The model is quite simple and is very practical for MPC purposes. However, in a further research we will investigate how to include other characteristics of bicycling, roads where cycling is more complicated due to the weather, potential mode switching, route choices, and the health benefits, etc.

3 Model Predictive Control for a Multimodal Traffic Intersection

The MPC optimization problem at the time step k is as follows:

$$\begin{aligned}
&\min_{U_k} J\left(U_k, x_{\mathrm{v}}(k), x_{\mathrm{b}}(k)\right) \qquad\qquad (1)\\
\text{s.t.}\quad & x_{\mathrm{v}}(k+t+1) = f_{\mathrm{v}}\left(x_{\mathrm{v}}(k+t), u(k+t), \nu_{\mathrm{v}}(k+t)\right), \quad x_{\mathrm{v}}(k) = x^{\mathrm{v}}_{k},\\
& 0 \leqslant \eta^{\mathrm{v}}_{u,d}(k_d+t) \leqslant C^{\mathrm{v}}_{u,d}, \quad 0 \leqslant q^{\mathrm{v}}_{u,d,o}(k_d+t), \quad \text{(vehicles)}\\
& x_{\mathrm{b}}(k+t+1) = f_{\mathrm{b}}\left(x_{\mathrm{b}}(k+t), u(k+t), \nu_{\mathrm{b}}(k+t)\right), \quad x_{\mathrm{b}}(k) = x^{\mathrm{b}}_{k},\\
& 0 \leqslant \eta^{\mathrm{b}}_{u,d}(k_d+t) \leqslant C^{\mathrm{b}}_{u,d}, \quad 0 \leqslant q^{\mathrm{b}}_{u,d,o}(k_d+t), \quad \text{(bicycles)}\\
& 0 \leqslant g_{u,d,o}(k_d+t-1) \leqslant c_d, \quad \text{for} \quad t = 0,\dots,N_{\mathrm{p}}-1, \quad (u,d) \in L, \quad o \in O
\end{aligned}$$

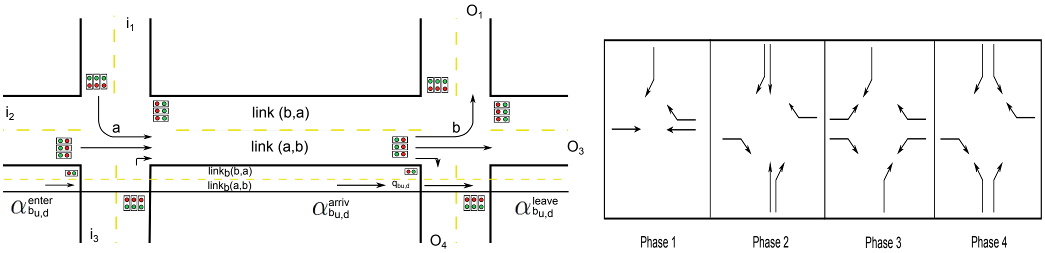
where J is the objective function, $x_{\mathrm{v}}(k)$ and $x_{\mathrm{b}}(k)$ the state vector of the vehicles and the bicycles respectively at time step k, $U_k = [u(k)^T, ..., u(k+N_{\mathrm{p}}-1)^T]^T$ is the control sequence for the traffic signal at the intersections in L, $\nu_{\mathrm{v}}(k+t)$ and $\nu_{\mathrm{b}}(k+t)$ the predicted demands in the origins O. There are also maximum capacities for vehicles $C^{\mathrm{v}}_{u,d}$ and bicycles $C^{\mathrm{b}}_{u,d}$ in the links, and the inputs $u(k)$ are the green times $g_{u,d,o}(k_d)$ for each phase of the traffic signal, and c_d is the sampling time for intersection d. The functions $f_{\mathrm{v}}(\cdot)$ and $f_{\mathrm{b}}(\cdot)$ are given by the S model including bicycling. Note that the coupling of the vehicle and bicycle states is due to the control actions (this is reasonable in cases where bicycles do not share the same road that vehicles, and the only interaction between them occurs at the traffic lights), L and O are the set of links and origins relevant for the intersections. Once (1) is solved, from the control sequence only the first control action $u(k)$ is applied at each intersection, and the same procedure is repeated in the next instant step $k+1$ considering the new measurements (rolling horizon procedure).

4 Simulation results

The benchmark system consists of two connected intersections, as shown in Figure 1(a). The simulation model and the prediction model are the same. The sampling time for intersection d is $c_d = 30$ s for all intersections, and to run the simulation the initial states are 20 vehicles in each link, 5 vehicles at each input queue, 10 bicycles in each link and 0 bicycles at each input queue. Each link has a length of 448 m, average length of each vehicle is 7 m, average length of each bicycle is 1.7 m, all links are designed with 3 lanes for vehicles and 1 lane for bicycles, and the free-flow velocity for vehicles is 50 km/h and for bicycles 15 km/h. The capacity of each link is 192 for vehicles and 264 for bicycles. The maximum flow is 300 bikes/h and 1800 veh/h/lane. At each intersection traffic signals are located with the phases shown in Figure 1(b), designed so that bikes can cross in the phase 1, and in the rest of the phases they can just turn right or left. The inflow rates at origins are 300 veh/h each, and the inflow rates of bicycles were 80 bikes/h. The input flow rates for each of the 3 admissions link $(2, a)$ have a time variant characteristic. Table 1 presents results of total time spent (TTS) using the different control strategies. The MPC-based controller improves the TTS with respect to the other methods.

Table 1: Comparison of total time spent (TTS)

Configuration	TTS vehicles (vehicles ·h)	TTS bicycles (bike·h)	TTS vehicles and bicycles
Fixed Time	1583.1	645.3	2228.4
Centralized MPC	1222.8	288.1	1510.8
State Feedback	1229.7	290.4	1520.1



(a) (b)

Figure 1: a) Benchmark, b) Traffic signal phases

5 Conclusion and further research

In this paper, we have incorporated explicitly the dynamic effect of bicycling in a systematic methodology to control multimodal traffic lights based on a model predictive control approach. Further research will include the effect of buses and pedestrians. Other control measures can be considered like dedicated bicycle lanes, bike-sharing, and dynamic route guidance to assist cyclists to find the routes that fit personal preferences about travel distance, safety, areas featuring trees, while also considering delays due to controlled traffic crossings, traffic jam locations, pollution level, etc.

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References

B. Gatersleben and H. Haddad. Who is the typical bicyclist?. *Transportation Research Part F*, 13(1):41–48, 2010.

S. Lin, B. De Schutter, Y. Xi, and J. Hellendoorn. Fast Model Predictive Control for Urban Road Networks via MILP. *IEEE Transactions on Intelligent Transport Systems*, 12(4):846–856, 2011.

A. Núñez, D. Sáez and C.E. Cortés. *Hybrid predictive control for dynamic transport problems.* Springer-Verlag London, Series Advances in Industrial Control, England. Edition: 2013.

J. Parkin and C. Meyers. The effect of cycle lanes on the proximity between motor traffic and cycle traffic. *Accident Analysis and Prevention*, 42(1):159–165, 2010.