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1 INTRODUCTION

It can be observed that there is a wide variety in the width of bicycle lanes. It can range from wide to very narrow, see figure 1. Several guidelines disagree on the desired width of a bicycle lane [1, 2]. These guidelines are mainly based on observations and best practices. Instead of such an evolutionary approach we propose to determine the necessary width by means of a scientific approach. We hypothesize that the dynamic properties of the bicycle together with the rider control determine the needed width of the bicycle lane. The inherent lateral instability of the bicycle with fixed steer input results in unavoidable lateral contact point displacements to keep the bicycle upright. Additionally, think of the necessary act of counter-steering to change heading direction.

Figure 1. Example of a very narrow bicycle lane, photo by Legreve.

2 METHODS

To investigate the dynamics of the bicycle–rider system we use multibody dynamics models. For the bicycle model we use the so-called Carvallo/Whipple model, which has recently been benchmarked [3] and experimentally been validated by Kooijman *et al.* [4]. This model consists of a rear frame, front fork assembly and two wheels. The wheel–ground contact is non-holonomic, which results in a low-dimensional model with only three degrees of freedom: lean, steer and forward velocity. However, no such generally accepted model for a rider as a controller is available. Some initial work on an optimal preview controller has been done by Land [5], Savkoor [6], and for bicycles by Sharp [7], whereas Doyle [8] approaches the bicycle rider control from a psychological point of view. Experimental results on bicycle control together with an optimal control model are presented by Moore *et al.* [9]. An overview on rider control bicycles is presented by Schwab and Meijaard [10].

Instead of an often applied continuous controller we propose to use a bell-shaped controller as presented by Benderius [11]. To mimic a non-continuous observation of the state we introduce a zero-order hold filter [12]. Realistic perturbations are needed and we choose to perturb the bicycle roll rate, which can be caused by gusts of wind. Simulations at various forward speeds, sizes of perturbations and settings of the human controller give the lateral displacement of the contact point of the front wheel with respect to the centre line of the bicycle lane.

In a second approach we determine the necessary width by solving an optimal control boundary value problem. The boundaries are an initial upright configuration with a lateral perturbation on the roll rate and/or steer rate and after some fixed time or distance an upright configuration with zero lateral displacement from the centre line, straight heading, and zero roll and steer rate. We assume a constant forward speed. The control input is a steer torque. Under the assumption that the rider is an optimiser, we define the cost function as the control effort, where control torques are assumed to stay within human bounds. Optimisations at various forward speeds, sizes of perturbations and settings of the human control bounds, give the lateral displacement of the contact point of the front wheel with respect to the centre line of the bicycle lane.

3 CONCLUSIONS

Some useful methods have been developed on the basis of simulation models to determine the lateral displacements of a perturbed bicycle–rider system. These displacements can be used as a guideline for the necessary width of a bicycle lane.

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