Assessment of the necessary width of a bicycle lane by means of multibody simulations on a bicycle-rider system.

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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. 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 method. We hypothesize that the dynamic properties of the bicycle together with the rider control determine the necessary width of a 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 act of countersteering to change heading direction.

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 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: roll angle, steer angle and forward velocity. Unfortunately, no such generally accepted model for a rider as a controller is yet 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 feedback 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 f.i. 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.

Results and Conclusion In the simulations we start the bicycle at a given forward speed and with a roll rate perturbation of 0.1 rad/s. After three seconds the bicycle should be on track again, straight up, with zero heading and zero steering. This defines the boundary value problem. To determine the optimal steering control we use a cost function that minimise the steering effort, as in $J_{min} = \int_0^3 T_{steer}^2 \mathrm{d}t$, with the steer torque T_{steer}. The resulting maximum lateral displacement of the bicycle with respect to the centreline of the bicycle lane, y_{max}, at various forward speeds, together with the relative value of the cost function, are depicted in Figure 1. At low forward speed, $v < 4$ m/s, the bicycle needs about 23 cm width from the centre line to recover from a lateral perturbation of 0.1 rad/s. Above 4 m/s the necessary width decreases with forward speed, which is exactly the opposite of what happens in multitrack vehicles like cars. There the necessary width increases with forward speed.

A useful method has been developed on the basis of multibody dynamics 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.

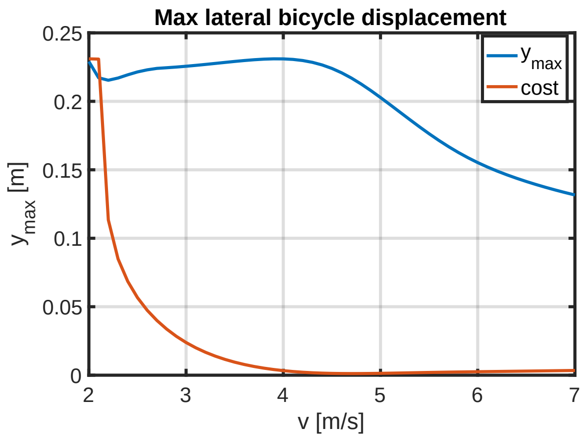

Fig. 1: Maximum lateral displacement of the bicycle from the centre line of the bicycle lane, y_{max}at various forward speeds v. The initial perturbation is a roll rate of 0.1 rad/s and the steering manoeuvre is finished with the bicycle back on track after three seconds.The red line is the relative value of the optimal control cost function $J_{min} = \int_0^3 T_{steer}^2 \mathrm{d}t$, with the steer torque T_{steer}. Notice the very low values of this cost function starting around $v = 4$ m/s, there the bicycle becomes selfstable.

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