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Essential Bicycle Dynamics for Microscopic Traffic Simulation: An Example Using the Social Force Model

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Abstract:

Microscopic traffic simulation is a popular tool in traffic research and planning. It enables the evaluation of interventions in a traffic system based on the movement of individual simulated agents. These can be for example infrastructural changes or the introduction of new road users like automated vehicles. Historically, this focused exclusively on car traffic. For heterogeneous settings with different kinds of road users, the original simulation concepts have to be adapted. Car-focused simulations often model vehicle dynamics as a combination of longitudinal movement along a prescribed lane and discrete lane change. However, road users like cyclists and pedestrians can operate more freely around the road infrastructure and hence their behavior is difficult to capture with current lane-based models (Twaddle et al., 2014). We propose a microscopic model describing bicycle interaction using the social force paradigm (Helbing and Molnár, 1995). Here we take into account bicycle kinematics, to create realistic bicycle paths. Qualitative evaluation shows simulated interactions with plausible cyclist trajectories. Inspired by particle physics, Helbing and Molnár (1995) introduced the social force model to simulate pedestrian movement. They assume that the movement of a single pedestrian in a crowd is governed by attractive and repulsive effects exerted on the individual by their intentions, other people, and infrastructure. The social force $\boldsymbol{F}(t) := \frac{\mathrm{d}\boldsymbol{v}(t)}{dt}$ describes this relationship. The overall social force is the sum of the effects on a person a in their environment defined as follows.

$$\boldsymbol{F}_a = \boldsymbol{F}_a^0 + \sum_b \boldsymbol{F}_{a,b} + \sum_B \boldsymbol{F}_{a,B} + \sum_i \boldsymbol{F}_{a,i} \tag{1}$$

$\boldsymbol{F}_a^0$ is a social force towards the destination based on the difference between the current and desired speed in the direction of the destination. $\boldsymbol{F}_{a,b}$ is a repulsive social force between persons a and b which prevents approaching closely. $\boldsymbol{F}_{a,B}$ are repulsive forces of delimiting infrastructure and $\boldsymbol{F}_{a,i}$ are attractive forces between persons that lead to group formation. Each of these forces can be calculated as the negative gradient of a potential $W(\boldsymbol{x}, \boldsymbol{y})$. The acceleration $\frac{\mathrm{d}\boldsymbol{v}}{dt}$ caused by the resulting force then leads to a simulation of 2D movement. To use social forces with cars and bicycles, researchers separate the lateral and longitudinal components of the resulting force and control the respective movements of the pedestrian model (Kaths, 2017) or the steer and acceleration of a two-wheeled kinematic vehicle model considering wheel slip (Huang et al., 2011; Schönauer et al., 2012). Schönauer et al. (2012) conclude that dedicated bicycle kinematics are needed to generate accurate cyclist path simulations.

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} x \\ y \\ \varphi \\ v \\ \delta \end{bmatrix} = \begin{bmatrix} v\cos\varphi \\ v\sin\varphi \\ \frac{v}{l}\tan\delta \\ a \\ \omega_\delta \end{bmatrix} \tag{2}$$

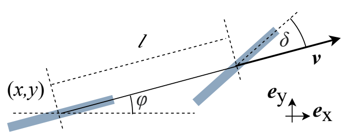

Figure 1: Geometry of the kinematic bicycle model.

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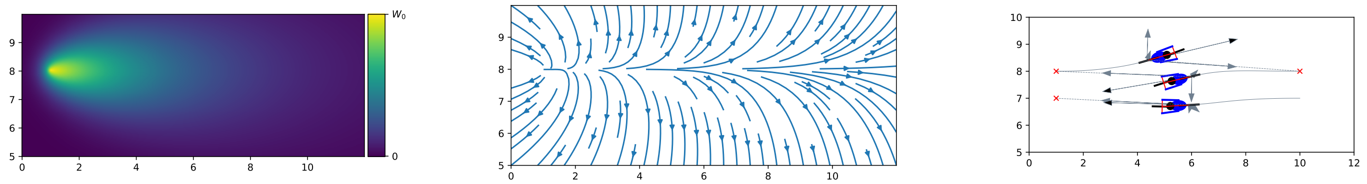
This work pairs an adapted social force paradigm with the kinematic bicycle model. Centering on the rear wheel axis (Figure 1), Equation 2 describes the kinematic bicycle model (Corke, 2017, p. 101). x, y are the bicycle position in cartesian coordinates, θ is its orientation, v and a are its longitudinal velocity and acceleration, and δ and ω_δ are the steering angle and steering rate respectively. l is the distance between the rear and front wheels. Other than the pedestrian model (Helbing and Molnár, 1995), the bicycle model constrains lateral movement. Hence, the original definition of the social force, which causes instantaneous motion in the direction of the force, can't be applied directly. Rather, the resulting social force should cause the cyclist to apply a control input to the dynamic system. Hence, we redefine the social force as $\boldsymbol{F} := \boldsymbol{v}$. This cyclist social force becomes a vector field of preferred velocities under social and environmental influences. Through the steer rate ω_δ and acceleration a, a cyclist tries to align the movement of the bicycle with the direction and magnitude of the social force vectors. We use two proportional controllers with the gains $K_{\mathrm{p},1}$ and $K_{\mathrm{p},2}$ to emulate this control effort.

$$a = K_{\mathrm{p},1}(\|\boldsymbol{F}\| - v) \quad (3) \qquad \omega_\delta = K_{\mathrm{p},2}\left(\arctan\frac{F_{\mathrm{y}}}{F_{\mathrm{x}}} - \varphi - \delta\right) \quad (4)$$

Following Helbing and Molnár (1995) and Huang et al. (2011), we use elliptic potentials with exponential decay and speed-dependent excentricity to calculate repulsive forces. Figure 2 exemplarily shows an elliptic potential (Figure 2a) and the corresponding force field derived from its gradient (Figure 2b) of the left cyclists at the beginning of the simulated evasive maneuver of Figure 2c. In this scenario, three originally opposing cyclists take appropriate and realistic action to evade each other, controlled solely by the social force model. Grey arrows show the individual forces and black arrows show the resulting force.



(a) Potential of the left cyclist (b) Repulsive force field of the left cyclist (c) Evasive maneuver

Figure 2: Simulation of a conflict scenario with the bicycle social force model

Continuing with our project, we aim to gradually integrate more complex bicycle models with the social force concept to introduce other effects that constrain bicycle movement into microscopic traffic simulation. For example, the inverted pendulum model includes the bicycle lean angle and the stabilization task (Karnopp, 2013, p. 146). This requires to countersteer and hence influences simulated cyclist trajectories and their capability to realistically react to their environment. We hypothesize, that these effects will lead to a more accurate simulation of road user conflicts which is vital for robust estimation of traffic safety and efficiency within traffic simulation. Going forward, we will use real-world data to develop and validate this model.

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