Simulating Taffic Dynamics Subject To Perceptional Errors

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Keywords: Microscopic Traffic Models, Perception Errors, Accidents, Traffic Flow.

1 Introduction

Automotive technology is advancing rapidly. Through additional driver assistance systems, vehicles partially take over control, eventually becoming fully autonomous. In an ideal world, autonomous vehicles are assumed to be accident-free. However, there will always be a (small) probability for a collision. Additionally, novel technology gives rise to new threats: It was recently shown how sensors of an autonomous vehicle can be deceived, forcing the vehicle to enter the oncoming traffic lane (cf. Tencent Keen Security Lab (2019)).

Statistical data are not yet available for future traffic systems. To overcome this lack of information, we develop a simulation model that can create artificial data. This enables us to analyze various designs of vehicles and traffic systems. We explicitly allow for the possibility of perceptional errors. Their size can be freely adjusted in our model to capture different levels of reliability of future systems.

We model traffic using a (stochastic) car-following model. Such models describe the movement of each vehicle individually. We incorporate errors using stochastic processes and generate case studies by means of Monte Carlo simulations. We obtain traffic and collision data and compute performance measures such as number of accidents, number of collided vehicles, and traffic flow.

2 Method

2.1 The Traffic Model

Let $[0, L]$ be a one-lane road and let $\mathcal{M} = \{1, 2, \dots\}$ denote a set of vehicles driving on this road. For each vehicle $i \in \mathcal{M}$, we assume $(\varepsilon_t^{i,1})_{t\geq 0}$, $(\varepsilon_t^{i,2})_{t\geq 0}$, and $(\varepsilon_t^{i,3})_{t\geq 0}$ to be three stochastic processes fluctuating around 1. We denote i's current position by $x^i(t)$ and its velocity by $v^i(t)$.

A car-following model asserts the acceleration of each vehicle depending on certain input values such as current velocity $v^i(t)$, distance to the preceding vehicle $\Delta x^i(t)$ and approaching rate $\Delta v^i(t)$. We include perceptional errors by distorting the true values with the stochastic processes. Each vehicle chooses its acceleration according to a suitable function $f^i \colon \mathbb{R}^3 \to \mathbb{R}$. The traffic model (with perceptional errors) is given by:

$$\begin{cases} \frac{\mathrm{d}x^i(t)}{\mathrm{d}t} &= v^i(t), \\ \frac{\mathrm{d}v^i(t)}{\mathrm{d}t} &= f^i(\varepsilon_t^{i,1} v^i(t), \varepsilon_t^{i,2} \Delta x^i(t), \varepsilon_t^{i,3} \Delta v^i(t)), \\ x^i(t_0^i) = 0,\ v^i(t_0^i) = v_0^i,\ t \geq t_0^i,\ i \in \mathcal{M}. \end{cases} \tag{2.1}$$

Particular car-following models correspond to specific choices of f^i. Without errors, these models are typically accident-free. A well-known model is the *Intelligent Driver Model* proposed by Treiber, Hennecke, and Helbing (2000). Our research group developed an extension with perceptional errors in the sense of (2.1) (cf. Berkhahn et al. (2018)).

More complex traffic systems consisting of t-junctions and intersections can be modeled by intersecting multiple one-lane roads. For this, additional conflict detection and reaction mechanisms need to be incorporated which is explained in Berkhahn et al. (2019).

2.2 Simulation Method

The model (2.1) determines the movement of vehicles by a system of coupled ordinary differential equations which additionally depend on stochastic processes. Such equations are known as random ordinary differential equation (RODE) and deterministic calculus can be applied pathwise to obtain solutions. However, as stochastic processes often do not satisfy regularity assumptions such as differentiability, classical higher order schemes are not applicable. With few adjustments, we utilize the RODE-Taylor scheme suggested by Jentzen and Kloeden (2009) which is specifically designed for RODEs.

3 Results

The simulations confirm that errors accumulate over time and lead to accidents. The general formulation of the model allows to describe the formation of collisions in different traffic systems. In case studies, we study the impact of accidents on traffic dynamics by means of Monte Carlo simulations; in particular, we evaluate efficiency and safety in terms of traffic flow and number of accidents.

More precisely, we study different traffic scenarios such as one-lane roads, t-junctions, and intersections. As a stochastic process for the errors, we use Ornstein-Uhlenbeck processes. In our stylized examples, we assume the vehicles to be homogeneous and analyze the effects of parameters controlling safety distances. For that, we independently simulate traffic for a fixed period of time and compute averages of different performance measures.

The simulations show that there is a tradeoff between safety and efficiency; more careful driving (increasing safety distances) leads to fewer accidents but is less efficient. Conversely, a lower headway results in higher traffic flow but increases the probability of collisions – which result in a breakdown of flow. In the results, this tradeoff is reflected by a unique maximum in the traffic flow for varying safety distances, i.e., the approach allows to determine optimal driving parameters.

Qualitatively, this tradeoff is expected from real-world experience. However, by means of our modeling approach, we can characterize this behavior quantitatively; in numerical case studies, all performance measures and other quantities of interest are explicitly computable. The simulations produce detailed data on traffic and accident behavior which can be used for further analyses.

4 Conclusion

To overcome the lack of accident data for future traffic systems, we build a microscopic traffic model which accounts for perceptional errors. Perceptional errors lead to accidents. The model generates data which can be used for risk management and design of future traffic systems. In the simulations, we explicitly calculate number of accidents, traffic flow and other performance measures. We can determine optimal driving parameters. Our results reflect the tradeoff between safety and efficiency of traffic systems.

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