Dampening traffic waves with autonomous vehicles

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Introduction. In congested traffic, minor disturbances or fluctuations in the velocity of a single vehicle may induce dynamically evolving traffic instabilities such as stop-and-go waves [1]. This work demonstrates in simulation that through intelligent control of a small number (e.g., 1-5%) of *autonomous vehicles* (AVs) soon to be present in the traffic flow, it is possible to dampen and in some cases completely remove these traffic waves in the entire traffic stream.

The main result of this work is the design of a velocity controller for an autonomous vehicle which stabilizes a microscopic model of traffic flow. The model is calibrated with field data collected from a series of ring road experiments conducted in July 2016 in Urbana, Illinois. The experiments replicate the ring road tests of Sugiyama et al. [2, 3] that demonstrated that traffic waves can arise in traffic in the absence of external bottlenecks. The collected datasets allow a *Optimal-Velocity Follow-The-Leader* (OV-FTL) [4] model to be calibrated to reproduce the traffic waves observed in the experiments. Under the calibrated model parameters the model is shown to be unstable. Consequently a velocity controller is designed and applied to a subset of vehicles, which stabilizes the traffic conditions and is shown to eliminate traffic waves. The presented work is part of a larger project to demonstrate the control potential of a few AVs in the traffic stream on the majority of human controlled vehicles.

The concept of traffic stability with respect to stop-and-go waves dates back to as early as the 1950s and the early car-following models [5, 6]. Previously, control of vehicular traffic through intelligent vehicles has focused mostly on either platoon control or mixed human-automated traffic when a high fraction of autonomous vehicles are present in the traffic stream. In platooned traffic, the entire vehicle fleet is equipped with the same technology and communication hardware, and vehicles cooperate to achieve traffic stability [7–10]. More

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realistic in the near future are systems with a mix of human-driven and autonomous vehicles. When a mix of AVs and human-controlled vehicles are considered, stability analysis is more challenging and simulation is commonly used to demonstrate stability [11, 12]. This work extends previous work in that it considers the local stability introduced by control of a single AV instead of a large number of AVs working together.

Modeling human driving behavior. A series of field experiments is conducted using between 12 and 22 vehicles at the University of Illinois in Urbana, Illinois to re-create the traffic waves observed in the Sugiyama experiment, and gain a more complete understanding of what range of vehicle densities and speeds cause traffic waves to arise. Vehicle trajectories are collected using a 360-degree panoramic camera placed at the center of the circular track and extracted using video processing techniques. Additionally, all vehicles used in the experiments are equipped with *onboard diagnostics* (OBD-II) scanners to record the velocity, engine speed, fuel rate, and fuel consumption of each vehicle throughout each experiment. This provides additional data that allows us to compare fuel consumption in traffic with stop-and-go waves to uniformly-flowing traffic.

In this work, human traffic flow is modeled using the combined OV-FTL model [4]. This human-driver model is calibrated using vehicle trajectories collected in the experiments at the University of Illinois such that the macroscopic quantities of the model output (average velocity, wave growth time, wave propagation speed) match the experimentally-observed quantities. Using a stability analysis on the linearized traffic model around equilibrium, the model is shown to be unstable under calibrated parameters at the densities considered.

Traffic control. Control is applied to a ring road with 22 vehicles with the same initial vehicle density as in the experiments conducted. Control is introduced by replacing the human-driver dynamics of one vehicle with the AV dynamics. The modified system is linearized about an equilibrium traffic flow and a feedback controller and pole placement are used to stabilize the system. If a sufficient controller gain is selected, the resulting system is stable. Simulation results show that when all vehicles use the human driver dynamics, the system is unstable, while replacing a single vehicle's dynamics with the AV dynamics is able to stabilize the flow and prevent stop-and-go waves from emerging in the simulated 22-vehicle system.

Conclusions and societal impacts. The societal implications of this work are broad since most drivers experience delays and increased fuel consumption due to unstable and non-uniformly flowing traffic. While complete automation of the entire vehicle fleet may be many years away, in the short term, it is likely that some vehicles will be capable of driving autonomously in the near future. This research demonstrates that a single autonomous vehicle can locally stabilize traffic in dense traffic flow, and prevent stop-and-go waves from arising. This results in smoother traffic for all drivers. These findings are preliminary results for a larger research project that aims to demonstrate the benefit that a small number of autonomous vehicles can bring to the traffic flow in terms of traffic stability and fuel consumption if controlled correctly.

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