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Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments

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ABSTRACT

Traffic waves are phenomena that emerge when the vehicular density exceeds a critical threshold. Considering the presence of increasingly automated vehicles in the traffic stream, a number of research activities have focused on the influence of automated vehicles on the bulk traffic flow. In the present article, we demonstrate experimentally that intelligent control of an autonomous vehicle is able to dampen stop-and-go waves that can arise even in the absence of geometric or lane changing triggers. Precisely, our experiments on a circular track with more than 20 vehicles show that traffic waves emerge consistently, and that they can be dampened by controlling the velocity of a single vehicle in the flow. We compare metrics for velocity, braking events, and fuel economy across experiments. These experimental findings suggest a paradigm shift in traffic management: flow control will be possible via a few mobile actuators (less than 5%) long before a majority of vehicles have autonomous capabilities.

1. Introduction

1.1. Motivation

The dynamics of traffic flow include instabilities as density increases, where small perturbations amplify and grow into stop-and-go waves that travel backwards along the road (Treiterer and Myers, 1974; Sugiyama et al., 2008; Flynn et al., 2009; Kerner, 2012). These so-called *phantom* traffic jams are an experimentally reproducible phenomenon, as demonstrated in different experiments

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(Sugiyama et al., 2008; Tadaki et al., 2013; Jiang et al., 2014; Jiang et al., 2017). Common wave triggers include lane changing (Laval and Daganzo, 2006; Laval, 2006; Zheng et al., 2011), but they can even be generated in the absence of any lane changes, bottlenecks, merges, or changes in grade (Sugiyama et al., 2008; Tadaki et al., 2013). Moreover, these waves can be captured in microscopic models of individual vehicle motion (Bando et al., 1995; Nagel and Schreckenberg, 1992; Garavello et al., 2016) (see also the reviews (Brackstone and McDonald, 1999; Chowdhury et al., 2000; Helbing, 2001)) and macroscopic models described via solutions to continuum problems (Flynn et al., 2009; Payne, 1971; Whitham, 1974; Aw and Rascle, 2000; Zhang, 2002; Greenberg, 2004). Since these waves emerge from the collective dynamics of the drivers on the road, they are in principle avoidable if one could affect the way people drive. Recognizing the rapid technological innovations in traffic state estimation and control, this work provides experimental evidence that these waves can be reduced by controlling a small number of vehicles in the traffic stream.

A necessary precursor to dissipating traffic waves is to detect them in real-time. Advancements in traffic state estimation (Gazis and Knapp, 1971; Wang and Papageorgiou, 2005; Blandin et al., 2012) have facilitated high resolution traffic monitoring, through the advent of GPS smartphone sensors (Herrera et al., 2010; Work et al., 2010; Fabritiis et al., 2008; Hofleitner et al., 2012) that are part of the flow—termed *Lagrangian* or *mobile* sensors. Now commercialized by several major navigation services, the use of a small number of GPS equipped vehicles in the traffic stream has dramatically changed how traffic is monitored for consumer-facing mobility services, which previously relied on predominantly fixed sensing infrastructure.

Currently, traffic control is dominated by control strategies that rely on actuators at fixed locations or are centralized. Such systems include *variable speed advisory* (VSA) or *variable speed limits* (VSL) (Nissan and Koutsopoulos, 2011; Hegyi et al., 2005b; Smulders, 1990; Hegyi et al., 2008; Popov et al., 2008), which are commonly implemented through signs on overhead gantries, and ramp metering (Papageorgiou and Kotsialos, 2002; Gomes and Horowitz, 2006; Papageorgiou et al., 1991), which relies on traffic signals on freeway entrance ramps. More recently, coordinated systems to integrate both ramp metering and variable speed limits have been proposed (Hegyi et al., 2005a; Papamichail et al., 2008; Lu et al., 2010; Han et al., 2017b). A common challenge of VSL and ramp metering systems is the small flexibility of the systems due to the high cost of installation of the fixed infrastructure, which consequently limits the spatial resolution of the control input. Additionally, compliance with the speed advisory is not guaranteed, which can limit the effectiveness of the control strategy.

Recent advancements in vehicular automation and communication technologies have the potential to substantially change surface transportation (Wadud et al., 2016; Harper et al., 2016; Milakis et al., 2017; Wan et al., 2016; Wang et al., 2017). In particular, these advancements provide new possibilities and opportunities for traffic control in which these smart vehicles act as Lagrangian actuators of the bulk traffic steam. When a series of adjacent vehicles on a roadway are connected and automated, it is possible to form dense platoons of vehicles which leave very small gaps. A key challenge for vehicle platoons is to design control laws in which the vehicle platoon remains stable, for which significant theoretical and practical progress has been made (Levine and Athans, 1966; Swaroop and Hedrick, 1996; Shladover, 1995; Fenton and Mayhan, 1991; Darbha and Rajagopal, 1999; Besselink and Johansson, 2017; Ioannou et al., 1993; Buehler et al., 2009; Rajamani et al., 1998). Recent work has shown that commercially-implemented, string-stable *adaptive cruise control* (ACC) systems may result in an unstable traffic state when implemented on a platoon of ACC-enabled vehicles, motivating the need for vehicle connectivity in such systems (Milanés and Shladover, 2014; Milanés et al., 2014). In contrast to the vehicle platoon setting, in which all vehicles are controlled, or the variable speed limit and ramp metering strategies which actuate the flow at fixed locations, this research aims to dissipate congestion-based stop-and-go traffic waves using only a sparse number of autonomous vehicles already in the flow, without changing how the other, human-driven, vehicles operate.

The notion to dissipate stop-and-go waves via controlling vehicles in the stream represents a shift from stationary to Lagrangian control, mirroring the transition to Lagrangian sensing that has already occurred. The key advantage in mobile sensing projects (Herrera et al., 2010; Fabritiis et al., 2008; Hofleitner et al., 2012) is that a very small number of vehicles being measured (3–5%) suffices to estimate the traffic state on large road networks (Work et al., 2010). In the same spirit, our research experimentally demonstrates that a small number of Lagrangian controllers suffices to dampen traffic waves.

The ability of connected and automated vehicles to change the properties of the bulk traffic flow is already recognized in the transportation engineering community. For example, the works (Davis, 2004; Talebpour and Mahmassani, 2016; Guériau et al., 2016; Wang et al., 2016b; Knorr et al., 2012) directly address the setting where a subset of the vehicles are equipped with automated and/or connected technologies, and then assess via a stability analysis or simulation the extent to which the total vehicular flow can be smoothed. Recently, several works have explored extensions to the variable speed limit control strategies in which connected or automated vehicles are used to actuate the traffic flow (Wang et al., 2016a). For example, the work by Han et al. (2017a) develops a VSL strategy that is implemented in simulation with connected vehicles where the traffic evolves according to the kinematic wave theory. It follows a similar strategy proposed by van de Weg et al. (2014), where a coordinated VSL and ramp metering strategy is implemented via actuation of the entire vehicle fleet (i.e., 100% penetration rate). Although not explicitly designed as a variable speed limit controller, Nishi et al. (2013) advocates a “slow-in, fast-out” driving strategy to eliminate traffic jams, using a microscopic model also in line with kinematic wave theory. The work by He et al. (2016) proposes a similar jam absorbing strategy as Nishi et al. (2013) based on Newell’s car following theory, and its effectiveness is assessed in simulation.

Interestingly, an experimental test of the “slow-in, fast-out” strategy (Nishi et al., 2013) is provided by Taniguchi et al. (2015), in which five vehicles are driven on a closed course. The lead vehicle in the platoon of five vehicles drives initially at a constant speed, then decelerates as if driving through a congestion wave, and then accelerates back to the cruising speed. The third vehicle in the platoon initially leaves a large gap, and due to the extra gap it is able to maintain the cruising speed and effectively absorb the jam. In contrast to the experiment by Taniguchi et al. (2015), the present work fully replicates the setup of Sugiyama et al. (2008) and Tadaki et al. (2013), in which the stop-and-go wave is generated naturally from the human drivers in the experiment, without an external cause. Moreover, the controllers proposed in the present work are distinct.