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Improving traffic flow at a 2-to-1 lane reduction with wirelessly connected, adaptive cruise control vehicles

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HIGHLIGHTS

- Wirelessly connected vehicles randomly mixed with manual vehicles reduce congestion.
- A prototype bottleneck, the 2-to-1 lane reduction, is analyzed.
- Control algorithm based on connected-vehicle-reported velocities is evaluated.
- Decelerating connected vehicles influence manual vehicles to make beneficial early lane changes.

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ABSTRACT

Wirelessly connected vehicles that exchange information about traffic conditions can reduce delays caused by congestion. At a 2-to-1 lane reduction, the improvement in flow past a bottleneck due to traffic with a random mixture of 40% connected vehicles is found to be 52%. Control is based on connected-vehicle-reported velocities near the bottleneck. In response to indications of congestion the connected vehicles, which are also adaptive cruise control vehicles, reduce their speed in slowdown regions. Early lane changes of manually driven vehicles from the terminated lane to the continuous lane are induced by the slowing connected vehicles. Self-organized congestion at the bottleneck is thus delayed or eliminated, depending upon the incoming flow magnitude. For the large majority of vehicles, travel times past the bottleneck are substantially reduced. Control is responsible for delaying the onset of congestion as the incoming flow increases. Adaptive cruise control increases the flow out of the congested state at the bottleneck. The nature of the congested state, when it occurs, appears to be similar under a variety of conditions. Typically 80–100 vehicles are approximately equally distributed between the lanes in the 500 m region prior to the end of the terminated lane. Without the adaptive cruise control capability, connected vehicles can delay the onset of congestion but do not increase the asymptotic flow past the bottleneck. Calculations are done using the Kerner–Klenov three-phase theory, stochastic discrete-time model for manual vehicles. The dynamics of the connected vehicles is given by a conventional adaptive cruise control algorithm plus commanded deceleration. Because time in the model for manual vehicles is discrete (one-second intervals), it is assumed that the acceleration of any vehicle immediately in front of a connected vehicle is constant during the time interval, thereby preserving the computational simplicity and speed of a discrete-time model.

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1. Introduction

The dynamics of vehicular traffic flow has been investigated extensively [1–3], in part due to its relationship to self-organization and non-equilibrium phase transitions. From a societal perspective, the economic cost of congestion motivates research to improve traffic efficiency. With the advent of autonomous vehicles that eliminate reaction times of human drivers and other behavioral characteristics, prospects for increased flow and reduced delays appear good. Furthermore, the widespread adoption of wireless communication between vehicles (and infrastructure) potentially offers substantial improvements. However, ways to use these new capabilities, the so-called connected vehicle systems, remain incompletely explored.

Representative papers relevant to connected vehicles include the following. Schönhof et al. [4,5] studied information flow and detection of traffic jam fronts with wireless communication. Thiemann et al. [6] modeled the longitudinal hopping of information for various vehicle trajectories. Kerner et al. [7] described potential enhancements in traffic efficiency using wireless communication. Orosz and collaborators [8,9] analyzed the effects of communication delays on the stability of connected vehicle systems. Technical advances have expanded the capabilities of vehicles so that wirelessly connected autonomous cars could be commonplace in the near future [10–14].

The purpose of this paper is to demonstrate how wireless communication and control without any sensors embedded in the roadway can improve flow at a bottleneck caused by a 2-to-1 lane reduction, which is discussed in Section 2 and related simulations are presented in Section 3. The nature of the congested state near the bottleneck is examined in Section 4; while Section 5 pertains to connected, but manually driven vehicles. My conclusions are in Section 6.

2. Model for bottleneck at a 2-to-1 lane reduction

A prototypical traffic bottleneck is the 2-to-1 lane reduction of a highway [15–17]. Vehicles in the terminated lane must change to the continuous lane prior to reaching the end of the lane. When traffic flow is light, no congestion happens. However, when the incoming flow increases, congestion can be self-organized even when the total flow is substantially less than the capacity of a single lane. Congestion occurs because drivers do not change lanes in a system-optimal manner. Yamauchi et al. [18,19] have described this situation as having a prisoner's dilemma game structure.

I consider the use of wirelessly connected vehicles (WCV) for improving flow at a 2-to-1 lane reduction of a highway. The idea is to mix in randomly a fraction f of WCV to mitigate self-organized congestion. I assume that the WCV are also adaptive cruise control vehicles [20,21].

The lane configuration is depicted in Fig. 1. One lane ends at x_B while the other continues. Prior to the bottleneck is a section of each lane denoted as the "slowdown region" [22]. In these sections, the WCV are instructed to decelerate if preceding vehicles detect congestion building up and communicate this information to others. The current value of the minimum speed of the WCV (self-measured) is reported and a time-dependent function is calculated (possibly by the infrastructure):

$$v_{slow}(t) = \max\left\{v_{slow}^{min}, \min\left\{v_i(t)\right\}\right\}, \tag{1}$$

where i is the index of any WCV. When $x_B - L < x_i \leq x_B$ and $v_i > v_{slow}$ the vehicle i moves according to

$$\frac{dv_i}{dt} = \min\left\{a_{decel}, a_i^d\right\}, \tag{2a}$$

$$a_{decel} = -0.1\ \mathrm{m/s^2}, \tag{2b}$$

$$a_i^d = \alpha\left[\frac{x_{lead} - x_i - D}{h_d} - v_i\right] + k_d\left(v_{lead} - v_i\right). \tag{2c}$$

Vehicle velocities are bounded by the speed limit $v_{lim} = 32$ m/s. Here $v_{slow}^{min} = 20$ m/s, $L = 5000$ m (terminated lane) or 2000 m (continuous lane). No exhaustive search to optimize these parameters was attempted because the values used seemed to work well. The other parameters are $D = 7.5$ m, $\alpha = 2\ \mathrm{s^{-1}}$, $h_d = 1$ s, $k_d = 1\ \mathrm{s^{-1}}$. Manual vehicles are assumed to move according to the Kerner–Klenov (KK) stochastic discrete time model [23–25] (see Appendix); and the rules for lane changes of all vehicles are given by this model with the exception that the WCV do not change from the continuous to the terminated lane. Because the KK model uses discrete times (one-second update time), it is assumed that for any of the WCV the vehicle immediately in front (labeled "*lead*") moves during a time interval t_n to t_{n+1} with constant acceleration that is given by $\frac{v_{lead}(t_{n+1}) - v_{lead}(t_n)}{t_{n+1} - t_n}$.

3. Simulations of flow

For simulations reported in this paper, the incoming flow is shown in Fig. 2. After the maximum flow is reached, the flow remains constant at this value. Each lane has the same incoming flow, the maximum of which is slightly less than half of the