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Optimization of traffic flow at freeway sags by controlling the acceleration of vehicles equipped with in-car systems

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A B S T R A C T

Sags are bottlenecks in freeway networks. According to previous research, the main cause is that most drivers do not accelerate enough at sags. Consequently, they keep longer headways than expected given their speed, which leads to congestion in high demand conditions. Nowadays, there is growing interest in the development of traffic control measures for sags based on the use of in-car systems. This paper aims to determine the optimal acceleration behavior of vehicles equipped with in-car systems at sags and the related effects on traffic flow, thereby laying the theoretical foundation for developing effective traffic management applications. We formulate an optimal control problem in which a centralized controller regulates the acceleration of some vehicles of a traffic stream moving along a single-lane freeway stretch with a sag. The control objective is to minimize total travel time. The problem is solved for scenarios with different numbers of controlled vehicles and positions in the stream, assuming low penetration rates. The results indicate that the optimal behavior involves performing a deceleration-acceleration-deceleration-acceleration (DADA) maneuver in the sag area. This maneuver induces the first vehicles located behind the controlled vehicle to accelerate fast along the vertical curve. As a result, traffic speed and flow at the end of the sag (bottleneck) increase for a time. The maneuver also triggers a stop-and-go wave that temporarily limits the inflow into the sag, slowing down the formation of congestion at the bottleneck. Moreover, in some cases controlled vehicles perform one or more deceleration-acceleration maneuvers upstream of the sag. This additional strategy is used to manage congestion so that inflow is regulated more effectively. Although we cannot guarantee global optimality, our findings reveal a potentially highly effective and innovative way to reduce congestion at sags, which could possibly be implemented using cooperative adaptive cruise control systems.

1. Introduction

Sags (or sag vertical curves) are freeway sections along which the gradient increases gradually in the direction of traffic (see Fig. 1). The capacity of sags is generally lower than that of freeway sections with other vertical profiles (Xing et al., 2010). Therefore, sags constitute bottlenecks in freeway networks. Indeed, traffic often becomes congested at sags in high

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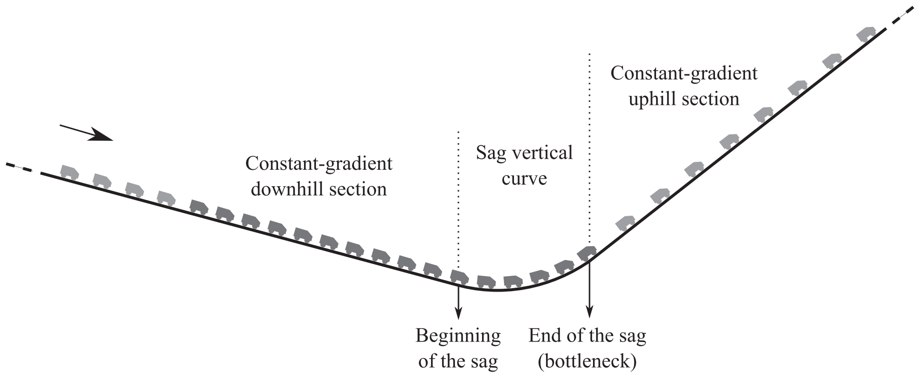

Fig. 1. Freeway stretch with a sag: vertical profile and typical traffic conditions with high demand (light-gray vehicles are driving in free flow; dark-gray vehicles are driving in congested flow).

demand conditions (Koshi et al., 1992; Brilon and Bressler, 2004; Patire and Cassidy, 2011). In some countries, such as Japan, sags are one of the most common types of freeway bottleneck (Xing et al., 2014; Hatakenaka et al., 2006). The scientific literature suggests that the main cause of traffic congestion at sags is that most drivers do not accelerate enough as they move along the vertical curve. Generally, drivers do not compensate instantaneously for the increase in resistance force resulting from the increase in gradient, which limits the acceleration of their vehicles (Yoshizawa et al., 2012). As a consequence, most drivers keep significantly longer distance headways than expected given their speed (Koshi, 2003; Goñi-Ros et al., 2013). This leads to periodic formation of stop-and-go waves when traffic demand is sufficiently high (Koshi et al., 1992; Patire and Cassidy, 2011; Goñi-Ros et al., 2014). The bottleneck is generally the end of the vertical curve (Brilon and Bressler, 2004; Patire and Cassidy, 2011).

During the last two decades, various traffic management measures have been proposed for mitigating congestion at sags. In general, the goals of those measures are: (a) to increase the free-flow capacity of sags; (b) to prevent the formation of congestion at sags in nearly-saturated conditions; and/or (c) to increase the queue discharge capacity of sags. The proposed measures use very diverse strategies to achieve those goals, such as improving the ability of drivers to compensate for the increased grade resistance force at sags (Ozaki, 2003), limiting the inflow into the vertical curve (Goñi-Ros et al., 2014), and encouraging drivers to accelerate fast after leaving congestion at sags (Sato et al., 2009). Most proposed measures, particularly those which are in more advanced development stages, use variable message signs (VMS) as actuators (Xing et al., 2014; Goñi-Ros et al., 2014; Sato et al., 2009). However, in recent years there has been growing interest in the development of traffic management measures that use in-car systems as actuators. The systems used for that purpose are mainly advisory systems (Hatakenaka et al., 2006) or basic/advanced adaptive cruise control (ACC) systems (Ozaki, 2003; Kesting et al., 2006; Papacharalampous et al., 2015). Although traffic management measures based on the use of in-vehicle systems have great potential, they are mostly in early phases of development. We argue that, at this stage, it is important to determine how vehicles equipped with this type of systems should behave at sags under various circumstances in order to generate the greatest possible reduction in congestion. This would clarify what are the most effective strategies to mitigate congestion at sags via in-car systems and what are the mechanisms by which these strategies reduce congestion, thereby laying the theoretical foundation for developing effective traffic management applications. The present study constitutes a first step in this direction.

The main goal of the study is to identify the way in which vehicles equipped with in-car systems need to move at sags in the longitudinal direction in order to reduce congestion as much as possible, assuming penetration rates that are realistic for the coming years (i.e., limited numbers of equipped vehicles). To this end, we formulate an optimal control problem in which a centralized controller regulates the acceleration of some vehicles belonging to a traffic stream that moves along a single-lane freeway stretch with a sag. The objective of the controller is to minimize the total travel time of all vehicles. The problem is solved for various scenarios defined by the number of controlled vehicles and their positions in the stream. By analyzing the results, we identify the main strategies that vehicles equipped with in-car systems should use at sags to reduce congestion to the greatest possible degree. Therefore, the main contribution of this paper is twofold. First, we present a new optimization-based method for identifying the best way to manage traffic by means of in-vehicle systems. Second, we determine the most effective strategies to manage traffic via in-car systems at sags, providing a detailed description of the principles of these strategies. In this respect, we are mostly interested in identifying the optimal trajectories of individual vehicles (which are assumed to be equipped with some kind of in-car systems), and their effects on traffic flow. The development of specific traffic management measures to make individual vehicles move in the identified optimal way is out of the scope of this paper and is left for future work. For this reason, the control problem formulation does not specify the type of in-car system that vehicles are equipped with, nor does it specify any technical aspects of this system: the formulation is based on the assumption that the acceleration of some vehicles can be regulated or influenced via some type of in-car system.