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A fast simulation algorithm for multiple moving bottlenecks and applications in urban freight traffic management

Michele D. Simoni*, Christian G. Claudel

Dept. of Civil, Architectural, and Environmental Engineering, University of Texas at Austin, 301E Dean Keeton, St., Austin, TX 78712, USA

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ABSTRACT

Moving bottlenecks are moving capacity restrictions that affect traffic flows, and they can be used to describe the effects of buses and trucks in transportation networks. The computation of solutions associated with the presence of moving bottlenecks is complex, since they both influence and are influenced by surrounding traffic. In this study, we propose a fast numerical scheme that can efficiently compute the solutions to an arbitrary number of moving (and fixed) bottlenecks, for a stretch of road modeled by the Lighthill–Whitham–Richards (LWR) model. Several different moving bottlenecks can be simulated endogenously all together by means of an algorithm based on a semi-analytic Lax–Hopf formula. Since the numerical scheme is semi-analytic and requires a very low number of operations, it can be employed for traffic estimation problems where fast and accurate solutions are required. We demonstrate the capabilities of the method by implementing two alternative traffic management strategies designed to minimize the negative impacts of trucks and buses in urban environments.

1. Introduction

In traffic flow theory, different typologies of “slow” vehicles (or platoons) can be modeled as “moving bottlenecks” . These obstructions in traffic streams are usually associated with the presence of buses in urban traffic, and trucks or slower vehicles on highways. All these situations are characterized by a partial blockage of the road that causes a capacity reduction (typically the right lane in right hand driving countries). The concept of moving bottleneck can be extended to fixed bottlenecks, which represent static (spatially) and time varying capacity restrictions that can result, for example, from traffic lights or traffic incidents.

Some main challenges of modeling moving bottlenecks concern identifying and modeling features regarding their speed (depending on the traffic conditions and on the maximum speed of the vehicle), their discharge flow (maximum rate at which vehicles overtake), and the extent of the queue held back. Several studies have highlighted the importance of the effects of moving bottlenecks on traffic (Munoz and Daganzo, 2002; Daganzo and Laval, 2005) and have developed methodologies to include them into existing traffic models. Gazis and Herman (1992) developed a model based on the conservation of flow, unconditional existence of the flow-density relation, and independence of capacity state from the bottleneck state. Newell (1993, 1998) subsequently proposed the first complete formulation based on the Lighthill–Whitham–Richards (LWR) model in which the moving bottleneck is assumed to behave as a scaled-down version of the freeway’s fundamental diagram

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* Corresponding author.
E-mail addresses: m.simoni@utexas.edu (M.D. Simoni), christian.claudel@utexas.edu (C.G. Claudel).

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not influenced by the bottleneck speed. In recent years, Munoz and Daganzo (2002), Leclercq et al. (2004), and Daganzo and Laval (2005) have proposed more comprehensive formulations of the moving bottleneck problem. Other studies have focused on numerical methods to solve the fixed and moving bottleneck problems within the LWR model (Lebacque et al., 1998; Giorgi et al., 2002; Leclercq, 2007; Laval and Leclerq, 2008). Referring to the "Three-phase traffic theory," Kerner and Klenov (2010) thoroughly explored features of moving bottlenecks, such as the critical speed at which traffic breaks down. Moving bottlenecks have also been studied in the field of applied mathematics by Lattanzio et al. (2011), Gasser et al. (2013), and Delle Monache and Goatin (2014a,b, 2016), where coupled PDE-ODE models are used to reproduce the dynamics between car traffic flows and slow vehicles.

To date, not many studies have developed methods to simulate an arbitrary number of moving bottlenecks. Daganzo and Laval (2005), and Laval and Leclercq (2008) modeled multiple moving bottlenecks (with exogenous passing rates) by means of a numerical method based on the Kinematic Waves (KW) theory. Other studies (Leclerc and Becarie, 2012; Laval and Leclercq, 2013; Joueiai et al., 2015) have shown how solving the LWR model with different coordinate systems (mesoscopic approach) would allow addressing multiple internal boundary conditions. However, in these models bottleneck trajectories are assumed to be known in advance. In this article, we offer a more general approach that endogenously accounts for the impact of moving bottlenecks on surrounding traffic and the converse. Additionally, we provide an efficient algorithm that allows the simulation of an arbitrary number of moving bottlenecks associated with different maximum speeds. The effects of moving bottlenecks' stops along the curbside can also be incorporated without significant changes in the algorithm.

To achieve this, we propose a new formulation that computes the parameters associated with moving and fixed bottlenecks (trajectories and passing flows) without having to compute the complete solution. This method improves computational times by orders of magnitude over classical numerical schemes, and does not affect the computational accuracy.

As previously mentioned, the problem of computing the trajectories and parameters (passing flows) associated with moving bottlenecks is not straightforward because bottlenecks both influence and are influenced by surrounding traffic. Thus, in order to compute the density map associated with a general problem (involving initial conditions, boundary conditions and bottlenecks), it is necessary to simultaneously compute the solution to the LWR model and the corresponding trajectories of the bottlenecks (that are initially unknown). Since the solution itself affects the trajectories of the moving bottlenecks, this computationally intensive process requires us to map the solution on the entire computational domain.

The algorithm we propose allows, instead, determining the parameters and trajectories of the moving bottlenecks without requiring us to compute the solution on the entire computational domain. The approach is based on an extension of the semi-analytical solutions to arbitrary Hamilton-Jacobi equations introduced in Mazaré et al. (2011). Using semi-explicit solutions, we show that the trajectories of an arbitrary number of fixed and moving bottlenecks can be simultaneously marched forward in time for a very low computational cost. Indeed, when considering piecewise affine initial conditions containing n_i "blocks" (intervals over which the function is linear), the piecewise affine upstream and downstream boundary conditions containing n_u and n_d blocks respectively, and n_b bottlenecks, the future evolution of each bottleneck can be computed by at most $(n_i + n_b + 2)$ calculations of explicit functions. Once this set of calculations is done, the future evolution of the moving bottleneck is completely determined, in function of the difference between the current value of the solution to the Hamilton Jacobi equation along the trajectory, and its future value along the predicted trajectory. When this process is marched forward in time, it allows one to simultaneously compute the parameters associated with all moving and fixed bottlenecks of the problem, and to not have to compute the solution everywhere (solutions are only required along the trajectories of the bottleneck, thus greatly reducing the computational time required to solve the problem).

Once identified the parameters and trajectories of all moving and fixed bottlenecks, it is possible to use this information to efficiently compute the solution of the problem everywhere using the Lax–Hopf algorithm whose computational benefits have been described in Claudel and Bayen (2010a). Since the Lax–Hopf algorithm can compute the solution at any point of the space time domain using only initial, boundary, and bottleneck data, this approach is well adapted to optimization problems in which we are only interested in knowing the solutions at a limited number of points (on which the objective function of the problem depends).

This algorithm's very favorable computational error characteristics also render it advantageous. The only errors induced by the proposed scheme are errors related to the discretization in time of the moving bottleneck trajectories when they enter a different traffic regime, and an approximation of the behavior of the bottlenecks around intersections of bottleneck trajectories (if moving bottlenecks overtake each other). Non-event-based numerical methods for moving bottleneck problems (for example, based on LWR (Leclercq, 2007) or on the Variational Method (Daganzo and Laval, 2005)) require discretized moving and fixed bottleneck trajectories, but also use approximate solution methods to solve the LWR equation. Event-based methods (such as the wave-front tracking method) can be exact, but require the computation of the solution on the entire computational domain (therefore reducing the computational performance in specific applications where the solution is only needed at a low number of points). Furthermore, to date, algorithms based on wave-front tracking are capable of handling multiple moving bottlenecks only in certain scenarios (closed road) and under certain conditions (same features) (Delle Monache and Goatin, 2016).

Thanks to these favorable properties, the proposed algorithm could be used to efficiently tackle complex traffic estimation and control problems characterized by the presence of several trucks or buses. As a main practical contribution of this research, we present the application of the algorithm to evaluate two alternative traffic management strategies for trucks in urban settings by using a macroscopic traffic flow model. The first consists in the joint coordination of traffic lights and trucks departures on an arterial corridor in order to maximize its throughput. The second consists in a parking-loading