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Kinematic wave models of sag and tunnel bottlenecks

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ABSTRACT

Sags and tunnels are critical traffic bottlenecks, as they can cause capacity reduction, capacity drop, and extreme low acceleration rates when vehicles accelerate away from the upstream queue. In this paper, we present a behavioral kinematic wave model to explain the three bottleneck effects of sags and tunnels. Assuming increasing time gaps, we derive location-dependent triangular fundamental diagrams to explain the capacity reduction effect; with a bounded acceleration constraint on the stationary states inside the capacity reduction zone, we demonstrate the occurrence of capacity drop and derive a formula to calculate the dropped capacity from the fundamental diagram, road geometry, and acceleration process; from the structure of continuous standing waves we verify the low acceleration rate out of the upstream queue. We also present a simplified phenomenological model of capacity drop at sag/tunnel bottlenecks and two Cell Transmission Models for numerical simulations. With four stationary trajectories at the Kobotoke tunnel in Japan, we calibrate and validate the behavioral model and find that the theoretical predictions match the observations very well. This study can help to develop better design and control strategies to improve the performance of a sag or tunnel bottleneck.

1. Introduction

Sags (downgrades or upgrades) and tunnels, as illustrated in Fig. 1, are critical traffic bottlenecks, where the road capacity can be substantially reduced, compared with a normal road. In Koshi (1984) and Koshi et al. (1992), it was found that they have the following three types of bottleneck effects, which all lead to substantial travel delays: (i) a regular road's capacity is about 2000 vphpl, but sags and tunnels reduces the "capacity before congestion" to about 1500 vphpl; (ii) when an upstream queue forms, the "capacity during congestion" further drops to about 1300 vphpl; and (iii) when vehicles accelerate away from the upstream queue, the acceleration rate is extremely low. The first effect is related to capacity reduction, which was observed for the Holland and Lincoln tunnels in1950's (Edie and Foote, 1958), and the second effect is related to the capacity drop or two-capacity phenomenon, which was reported for two upgrades in Banks (1991). Many recent studies also confirm these effects (Brilon and Bressler, 2004); in Patire and Cassidy (2011), the positive and negative impacts of lane changes at such bottlenecks were studied.

The severe bottleneck effects of sags and tunnels have motivated the development of variable speed limits and ramp metering strategies, which later become standard traffic control measures (Newell, 2002). Even though a number of car-following models have been proposed to simulate traffic dynamics at such bottlenecks (Koshi et al., 1992;

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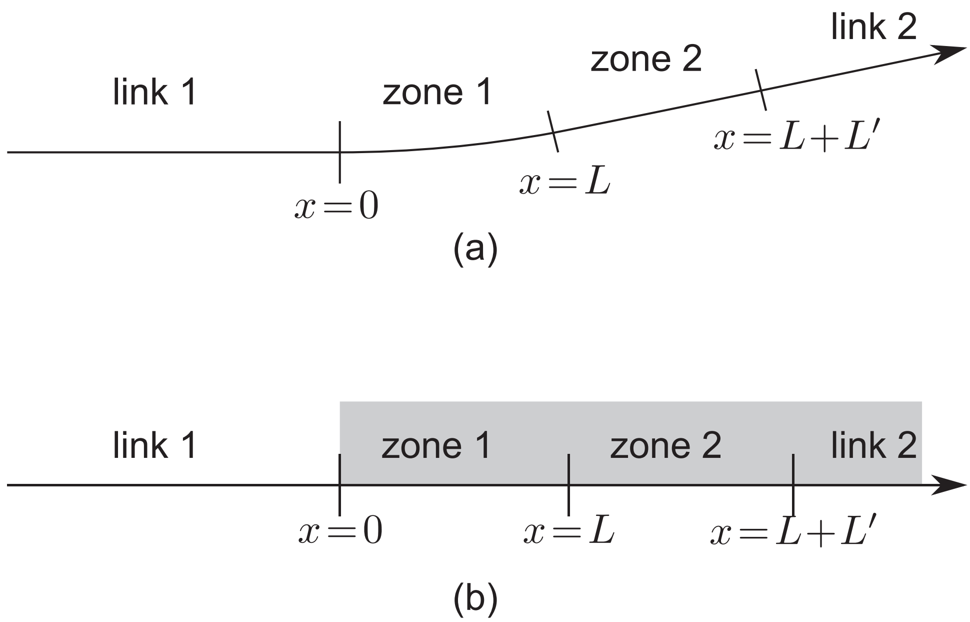

Fig. 1. Illustration of a sag bottleneck (a) and a tunnel bottleneck (b).

Xing and Koshi, 1995; Oguchi and Konuma, 2009), there has been no simple explanation of the mechanisms for capacity reduction, capacity drop, and the peculiar accelerating behavior.

In the literature, several kinematic wave models of capacity drop have been developed for lane-drop bottlenecks. In Jin et al. (2015), a phenomenological model was proposed to capture capacity drop by a discontinuous boundary flux function at a discontinuous (point) lane-drop bottleneck, such that the boundary flux is bounded by the dropped capacity when the upstream demand is higher than the downstream supply. It was shown that this model describes three macroscopic features of capacity drop: the maximum throughput equals the downstream capacity without an upstream queue, capacity drop occurs with an upstream queue, and the observed steady states are incomplete. In Jin (2017b), three kinematic wave models were studied for lane-drop bottlenecks: the first model for a discontinuous lane-drop bottleneck uses an optimization formulation of the entropy condition introduced in Jin et al. (2009) and leads to instantaneous discontinuous standing waves inside the lane-drop zone; the second model for a continuous lane-drop bottleneck was an inhomogeneous model (Lighthill and Whitham, 1955; Richards, 1956) and admits asymptotic continuous standing waves; and the third model is based on the first and second models with instantaneous continuous standing waves. Further in Jin (2017a), the third model in Jin (2017b) was extended by introducing an additional bounded acceleration constraint on the stationary states[1] inside a continuous lane-drop zone, and the new model leads to capacity drop, which endogenously depends on road and driving characteristics. The two studies clearly show that bounded acceleration is the necessary and sufficient condition for capacity drop at lane-drop bottlenecks. In addition, the behavioral model of capacity drop at a lane-drop bottleneck in Jin (2017a) was shown to be consistent with the phenomenological model in Jin et al. (2015), if we ignore the instantaneous continuous standing wave at the bottleneck.

In this study, we extend the modeling framework in Jin (2017a) to develop a first-order behavioral model of capacity drop at sag/tunnel bottlenecks and also derive a phenomenological model as in Jin et al. (2015). We use the models to explain the aforementioned three bottleneck effects of such bottlenecks. First, we propose location-dependent triangular fundamental diagrams inside a sag/tunnel bottleneck between $x=0$ and $x=L$ in Fig. 1, where the capacity gradually decreases. Inside a continuous lane-drop bottleneck, capacity reduction is caused by the reduction in the number of lanes. In contrast, at a sag/tunnel bottleneck, the number of lanes is constant, and arguably both the free-flow speed and jam density are also location-independent; thus we propose that the time gap increases inside the bottleneck, based on the observation that more work is needed on the throttle when accelerating on an upgrade or more careful driving under different light conditions inside the tunnel. At $x=L$, the time gap is the largest; i.e., the grade is the largest, or vehicles' driving behavior is the most careful. For $x>L$, the time gap can become smaller with smaller grades or better light conditions. But since the bottleneck is between $x=0$ and $x=L$, the downstream part has no additional bottleneck effect. Thus we simply assume that the road characteristics is the same for $x>L$. Second, we extend the first-order behavioral model of capacity drop in Jin (2017a) to explain the occurrence of capacity drop at sag/tunnel bottlenecks. In the model, the upstream and downstream roads are connected by an instantaneous continuous standing wave, comprising of the LWR stationary states inside zone

[1] Note that in this study stationary states are (only) time-independent; in contrast, steady states are both time- and location-independent.