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Stochastic bottleneck capacity, merging traffic and morning commute

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A B S T R A C T

This paper investigates the impact of stochastic capacity at the downstream bottleneck after a merge and the impact of merging behavior on the morning commuters' departure-time patterns. The classic bottleneck theory is extended to include a uniformly distributed capacity and the commuters' equilibrium departure patterns are derived for two different merging rules. The results show that uncertainty in the bottleneck capacity increases the commuters' mean trip cost and lengthens the peak period, and that the system total cost is lower under give-way merging than under a fixed-rate merging. Capacity paradoxes with dynamic user responses are found under both merging rules.

1. Introduction

The economic analysis of morning commute in congested traffic networks has followed the seminal work of Vickrey (1969) who formulated the morning commute problem to a mono-centric city center as a bottleneck model where commuters choose their departure times to avoid periods of high congestion at the bottleneck. This model represents a common situation during the morning rush hour, where a fixed and very large number of identical (homogeneous) commuters travel from a single origin (e.g. home) to a single destination (e.g. workplace) along a same stretch of road. This road has a single bottleneck with a fixed and commonly known capacity. If the arrival rate at the bottleneck exceeds its capacity, a queue forms. Although all the commuters wish to arrive at the common destination at the same time, this is not physically possible because the bottleneck capacity is finite. Consequently, some commuters may choose to depart earlier or later to avoid the cost of waiting in the queue, and pay the penalty cost for doing so. As noted by Arnott et al. (1990, 1998), in determining his/her departure time, each commuter faces a trade-off between journey time and schedule delay (early or late arrival at the destination). Vickrey's model provides a theoretical base to gain qualitative insights into alternative policy measures and to improve our understanding on congestion management possibilities.

Vickrey's model has been extended in various ways (see comprehensive reviews in Arnott et al., 1990, 1998; Lindsey, 2004; de Palma and Fosgerau, 2011). Smith (1984) and Daganzo (1985) proved the existence and uniqueness of the bottleneck equilibrium. The so-called equilibrium refers to a state at which no one can reduce his/her commuting cost through changing the departure time. Arnott et al. (1993a) extended the basic bottleneck model to consider elastic demand. Huang (2000) investigated the pricing and modal split in a system of transit and highway with heterogeneous commuters who differ in their disutility from travel time, schedule delay and transit crowding, whilst Tian et al. (2013) discussed the efficiency

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of a tradable credit schemes for managing bottleneck congestion and modal split with heterogeneous users. Most of the existing literature, however, is based on deterministic settings, with either a fixed capacity and demand (Arnott et al., 1990; Huang and Lam, 2002; Huang et al., 2007), or a pre-defined elastic demand function (Arnott et al., 1993a; Yang and Huang, 1997). Lindsey (1994) was the first to investigate the optimal departure scheduling when capacity is uncertain. Chen et al. (2002) developed a probability model to represent the variations and their impacts on system performance. Along this line of direction, several other developments on bottleneck models with uncertain capacity have been made (see, for example, Arnott et al., 1999; Fosgerau, 2008, 2010; Siu and Lo, 2009, 2013; Li et al., 2008; Xiao et al., 2013).

On the morning commute problem, most of the existing studies assume that each commuter passes only one bottleneck during the commuting trip. However, along a congested commuter route, it can be often observed that some commuters may pass through two or more bottlenecks during their commute journeys, and en-route they may merge with other traffic streams from a different origin. This research follows the pattern of the previous bottleneck analyses but relaxes the above assumption to analyze possible equilibrium queuing patterns in a network with more than one bottleneck. Kuwahara (1990) developed the equilibrium queuing patterns at a two-tandem bottleneck during morning peak. Arnott et al. (1993b) considered a Y-shaped travel corridor, in a configuration shown in Fig. 2, which consists of two origins, one destination and three links. Two groups of commuters use the corridor, one entering each arm and passing through the corresponding upstream bottleneck and the bottleneck downstream which is common to both groups, on their way to work. Different to the usual ramp-mainline merging configuration where there is only metering control for the ramp, in the Y-shaped network, both upstream links can be controlled. Arnott et al. (1993b) obtained the analytical equilibrium solutions and discussed the capacity paradox arising from users' departure time choice in this Y-shaped corridor. Lago and Daganzo (2007) adopted a similar Y-shaped highway corridor to study the spillovers of merging traffic. Daniel et al. (2009) conducted a behavioral experiment in a controlled environment with human subjects taking part in their departure time choice in a setting similar to that of Arnott et al. (1993b) and confirmed the theoretical bottleneck paradox by laboratory behavior. Based on the perspective of the deterministic settings, however, all these existing studies assumed a fixed capacity at the downstream bottleneck.

In reality, merging on highway is a major source of conflict and potential causes of flow breakdown, in other word, the capacity downstream of the merge is an exogenous variable in the merge model. Concerns have been raised in recent years about the inadequacy of conventional traffic models in representing the complex interactions at highway merges (Liu and Hyman, 2012). Several models have been proposed to account for capacity fluctuations at merge. For example, Evans et al. (2001) and Kerner (2002) postulated the stochastic approaches. Leclercq et al. (2011) applied the Newell–Daganzo model (Newell, 1982; Daganzo, 1995) to analyze the capacity drops at merges. Wang et al. (2005) and Huang and Sun (2009) employed microsimulation models to investigate merging behavior. Fig. 1 displays two observed speed-flow relationships from a busy motorway network in England. The data are from two MIDAS (HA, 1994) loop detectors on the M25 motorway in England, and are 5-min aggregated speed and flow data. Both diagrams show the stochastic maximum flows.

To highlight the contribution of this paper relative to the literature, Table 1 provides a summary of the existing research on modeling morning commute with bottleneck congestion, categorized in terms of modeling scenarios, characteristics of the models, and selected key references. It is clear that, whilst the integrated problem with consecutive bottlenecks congestion and stochastic capacity is prevalent in reality, it has largely been ignored in the literature. Therefore, the aim of this paper is to understand the departure time choice of commuters travel through two consecutive bottlenecks and how the individual and total travel cost vary with the variability of capacity degradation, and based on which to propose and compare different traffic control strategies under this morning commute problem.

In this paper, we adopt the Vickrey's bottleneck theory to develop a model which consists of two upstream links with fixed capacity and one downstream link with a stochastic bottleneck capacity. We investigate the morning commute problem from two origins to one destination and derive the traffic departure pattern under two merging strategies. Our model setting is similar to that of Arnott et al. (1993b) on a Y-shaped network (shown in Fig. 2), where two groups of commuters

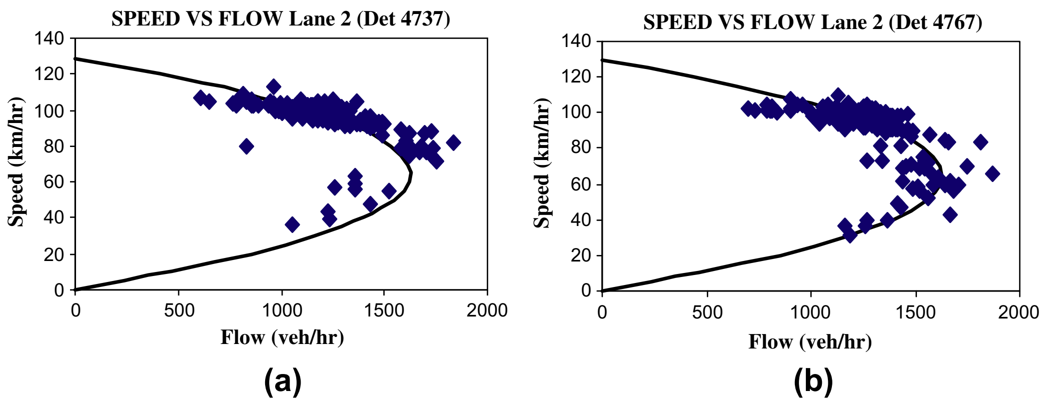

Fig. 1. Observed speed-flow relationships from the M25 motorway in England.