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# Bottleneck model with heterogeneous information

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ABSTRACT

This paper studies the effects of heterogeneous information on traffic equilibria and the resulting travel costs (both individual and social) when commuters make departure time choices to cross an unreliable bottleneck link. Increasing adoption and improved predictive abilities of Traveler Information Systems (TIS) enable commuters to plan their trips; however, there are inherent heterogeneities in information access and TIS accuracies. Our work addresses the open problem posed in Arnott et al. (1991) about the need to consider asymmetrically informed commuters in the bottleneck model of traffic congestion. We consider a Bayesian game with two heterogeneous commuter populations: one population is privately informed of the realized network state while the other only knows the public information about the distribution of states. We characterize the equilibrium of the game, in which each population chooses a departure rate function over time to minimize its expected cost based on its private belief about the state and the behavior of the other population. We provide a full equilibrium characterization for the complete range of values of link reliability, incident probability, and information penetration. The populations' equilibrium strategies can broadly be categorized into two distinct regimes. Specifically, when information penetration is above a certain threshold, the populations' equilibrium strategies are non-unique, and the relative Value of Information (VoI) is 0, i.e. the two populations face the same cost. On the other hand, when information penetration is below the threshold, equilibrium is unique, and VoI is positive and decreasing in information penetration. Importantly, we find that the lowest social cost is always achieved when a non-zero fraction of commuters are uninformed. The more unreliable the link, the higher the information penetration that achieves this minimum. We define the Value of Heterogeneity (VoH) as the difference between the minimum social cost and the cost under complete information penetration, and find that it can be significant under practically relevant conditions.



## 1. Introduction

In recent years, there have been significant advancements in the technology and penetration level of Traveler Information Systems (TIS), particularly smartphone navigation apps. These services provide commuters with information about

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network conditions, including uncertain network state and likely congestion. Commuters may use different TISs such as Google Maps/Waze, Apple Maps, etc. due to factors such as marketing, cost, and availability. The information provided by different TISs is generally not identical due to technological differences in traffic data collection and prediction between various providers. Moreover, some commuters may not have any means of gaining information about traffic conditions, or may choose not to use such means. This contributes to an inherently heterogeneous information structure among the population of commuters, with some having more accurate information about traffic conditions than others. One way to model this is to assume that commuters maintain private beliefs about traffic conditions such as network state, demand, etc. Furthermore, commuters may also include predictions of other commuters' decisions, and in particular other commuters' information, in their own decision making. From a practical viewpoint, if a commuter is aware that a significant number of other commuters have access to information about network state, she would be likely to consider how they will react based on their information, and make her decisions accordingly. Thus, to study the effect of heterogeneity of information, it is important to model commuters' beliefs about other commuters in addition to their own beliefs about traffic conditions.

The information structure (in particular its penetration and accuracy) has a significant effect on commuters' decisions and therefore their costs of commuting. Results obtained under symmetric information settings are not directly applicable to practical scenarios, since there is significant information heterogeneity between commuters in practice. However, heterogeneous information structures have not been studied as thoroughly in the literature as their importance merits. For example, despite the significant body of work on the bottleneck model of traffic congestion, there is no extension of the model to account for asymmetric information. In this paper, we address this gap in the literature and explore the effects of heterogeneous information. We focus on the following questions:

1. How does increasing penetration of accurate bottleneck state information affect commuters' time-of-travel decisions and costs?
2. In particular, what level of information penetration is socially optimal in minimizing total travel costs?

### *1.1. Our contribution*

To address these questions, we consider a Bayesian game played on an incident-prone bottleneck link. The state of the link determines its capacity. The link faces a fixed demand comprised of non-atomic commuters with identical preferences. Commuters have a single preferred arrival time at the destination, and incur a cost for arriving early or late, as well as a cost for time spent queuing at the bottleneck. Each commuter is costlessly[1] subscribed to one of two TISs; each TIS sends a signal of the state to its subscribers. In the case of a single bottleneck which we consider, all commuters subscribed to a TIS receive an identical signal; thus, they can naturally be modeled as one population. From a modeling perspective, we incorporate an asymmetric information structure with Vickrey (1969)'s seminal bottleneck model of traffic congestion.

In equilibrium, members of each population choose their departure times such that all members face the minimum expected cost based on their beliefs. We characterize the equilibrium strategies (i.e. departure rate functions) under certain assumptions on the information structure. Firstly, we assume that the accuracies of each TIS are common knowledge. Secondly, we assume that one population is perfectly informed about the state while the other is not informed. This assumption may seem restrictive, but, as mentioned before, some commuters may not use TISs at all, making them in effect an "uninformed population". On the other hand, those commuters who do use a TIS may have access to near-perfect information due to the exceedingly high accuracies of modern TISs. We show that these assumptions enable us to study the richness of equilibrium behaviors in even this most basic asymmetric information setting, and provide insights on the effect of information penetration on equilibrium strategies and costs relative to symmetric information.

We now mention our main results on equilibrium characterization. We characterize the equilibrium strategies for the complete range of values of link reliability, incident probability, and information penetration. We first provide the equilibrium strategies for the boundary cases of the game in which one or more of the parameters takes an extreme value, reducing it to a symmetric information setting. These boundary cases provide useful insights for solving the equilibrium for the general case with asymmetric information.

For the general case, we first show that all equilibria must satisfy certain necessary conditions, which helps narrow the search for equilibrium strategies. We show that equilibrium strategies can be broadly divided into two qualitatively different regimes depending on whether the information penetration is above or below a certain threshold. When information penetration is above the threshold, the populations' equilibrium strategies are non-unique, but the aggregate equilibrium departure rate function is unique and remains unchanged as more commuters gain access to information. We call this regime R0. On the other hand, when information penetration is below the threshold, we show that the populations' strategies are unique and sensitive to changes in the informed fraction. We call this regime R0'. Both R0 and R0' can be refined further in terms of the specific qualitative features of the equilibrium strategies. In particular, deriving the equilibrium strategies in R0' is rather involved and requires several stages of reasoning.

The equilibrium characterization allows us to analyze the travel costs faced by commuters in equilibrium. We specifically consider the effect of increasing information penetration on both the individual costs faced by commuters in each population as well as the social cost. To study the individual costs, we define the value of information (VoI) as the difference between

[1] This is true in many cases in practice, since several of the most widely adopted TISs are freely available through smartphone applications.