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Departure Time and Route Choices with Bottleneck Congestion: User Equilibrium under Risk and Ambiguity

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Abstract

This paper examines commuters' departure time and route choices in the morning commute problem when travel time is described as a bounded distributional uncertainty set. The preferences towards risk and ambiguity are distinguished by adopting the ambiguity-aware constant absolute risk aversion travel time criteria. We first examine the dynamic user equilibrium for a single-route model with homogeneous risk/ambiguity preference. Compared with risk-neutral commuters, we find that departure time window is shifted earlier for the risk-averse commuters and shifted later for the risk-seeking commuters. We then study the single bottleneck with a risk-averse class and a risk-seeking class. It is shown that with a larger gap between the two classes' preferences, the congestion pattern will change from one peak to two peaks. It implies that preference heterogeneity may stagger the departure time choice and thereby relieve the average congestion. At last, we examine a two-routes problem with homogeneous preference towards risk and ambiguity. The commuters will choose between a faster route (highway) and a less risky route (local arterial). We prove that the flow distribution between the two routes will monotonically change with the maximum variation in travel time. That is, the highway flow will decrease with uncertainty on the highway for risk-averse commuters. In contrast, it will increase with uncertainty on the highway for risk-seeking commuters. The price of anarchy is analyzed in the numerical section by varying the risk preference and the ambiguity preference.

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Keywords: risk preference, ambiguity preference, bottleneck model, uncertain travel time, dynamic user equilibrium

1. Introduction

In the real world, it is common that a residential area in a suburb and the central business district (CBD) area are connected by a freeway and local arterial routes running in parallel. The classic bottleneck model, first proposed by Vickrey (1969), has been extended to study the departure time choices and congestion evolution over time in the morning commute problem. Travel time is one of the important attributes which greatly influence commuters' departure time and route choices. Travel times in transportation network are generally uncertain due to inevitable variability in both demand and supply side. Given a travel time distribution, the risk can be explicitly evaluated with

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the travelers' preference towards risk. One typical approach is the mean-variance measure (Markowitz, 1952) which combines the mean travel time and the risk (measured by travel time variance). Another approach is the expected utility theory where travelers make the decision so as to maximize their underlying utility functions. The implications of uncertain travel time in transportation network have been extensively studied in stochastic routing problem (Nie and Wu, 2009; Miller-Hooks and Mahmassani, 2003, to name a few), and in user equilibrium problem (Yin et al., 2004; Connors et al., 2007; Tan et al., 2014, to name a few).

Consider those unpredictable or exceptional events on roads, such as traffic accident and natural disaster, the perfect information of the travel time distribution is rarely available to the commuters. In this study, we consider the ambiguity in travel time and the ambiguity preference to represent the commuter's subjective perception of uncertain travel time. Ellsberg demonstrates the experiment results that violate the principle of maximizing the subjective expected utility for modeling decision choices when precise information of the probability distribution is not available (Ellsberg, 1961). Ellsberg paradox provides evidence to support the existence of ambiguity aversion in decision-making. Additionally, Hsu et al. (2005) use functional brain imaging to present physiological evidence that human has heterogeneous attitudes towards risk and ambiguity. Sikka (2012) studies the travelers' choices under uncertainty using stated preference data and finds ambiguity heterogeneity (ambiguity seeking and ambiguity aversion) exists among risk-seeking drivers. Kemel and Paraschiv (2013) propose an estimation method using prospect theory to compare travelers' attitudes towards risk and ambiguity respectively. Their numerical studies show the estimation at individual level produces more reliable values of risk and ambiguity compared with estimation in aggregate level when Prospect Theory elicitation method is used. de Palma and Picard (2005) calibrate the traveler's risk preference by collecting survey data and reveal the exponential disutility function which exhibits constant absolute risk aversion (CARA). Qi et al. (2016) propose a unified framework to model decision-making when there are both risk and ambiguity by blending the CARA model using exponential disutility function (i.e., the risk preference given the travel time distribution) and Hurwicz model (Hurwicz, 1951) (i.e., the ambiguity attitude when travel time distribution belongs to a distributional uncertainty set).

This paper studies the impacts of the risk preference and the ambiguity preference on commuters' departure time and route choices in the morning commute problem. To distinguish the impacts of risk (the travel time probability distribution is known) and ambiguity (the travel time probability distribution is unknown), travel time is described as a bounded distributional uncertainty set. We adopt the ambiguity-aware CARA travel time (ACT) in (Qi et al., 2016) because of its analytical tractability and introduce ambiguity-aware CARA commute cost (ACC). ACC commute cost represents a commuter's perception of commute cost (consisting of the cost of uncertain travel time and the cost of schedule delay) by incorporating individual commuter's risk and ambiguity preference. Therefore, we extend the work by Qi et al. (2016) to explore the impacts of risk and ambiguity on the temporal and spatial equilibrium of the bottleneck model.

Using the ACC commute cost, we first examine the user equilibrium (UE) and the system optimum(SO) for a single-route model with homogeneous risk/ambiguity preference. Comparing with risk-neutral commuters, we find that departure time window is shifted earlier for the risk-averse commuters and shifted later for the risk-seeking commuters. The preference towards ambiguity affects the magnitude of the movement of the departure time window. For the risk-averse commuters, their perceived uncertainty cost is higher and the movement of their departure time window is greater when they are more pessimistic towards ambiguity. If the risk-seeking commuters are more optimistic towards ambiguity, they will also perceive larger uncertainty and choose to depart later. We then study the single bottleneck with a risk-averse class and a risk-seeking class. It is shown that with a larger gap between the two classes' preference, the congestion will change from one peak to two peaks. It implies that preference heterogeneity may stagger the departure time choice and thereby relieve the average congestion (measured by the expected total time). At last, we examine the two-routes problem with homogeneous preference towards risk and ambiguity. The commuters will choose between a fast route (highway) and a less risky route (local arterial). We prove that the flow distribution between the two routes will monotonically change with the maximum variation of travel time on highway or local arterial. That is, the highway flow will decrease with uncertainty on the highway for risk-averse commuters. In contrast, it will increase with uncertainty on the highway for risk-seeking commuters. The total expected travel time will increase with uncertainty on highway regardless of the commuters' risk attitude but decrease with uncertainty on the local street. The system ACC commute cost will decrease with the uncertainty on highway for risk-seeking