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Envy-free Pricing for Collaborative Consumption of Supply in Transportation Systems

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Abstract

Consumption of supply in transportation systems has generally always followed a First-Come-First-Served (FCFS) rule. This article proposes new control policies based on the concept of envy-freeness which outperform FCFS in both efficiency and fairness. We call an allocation envy-free when no agent feels any other agent's allocation to be better than their own, at the current price. Envy-free allocations are thus considered fair. Several new contributions are made: we first present a conceptual theoretical supply-demand framework which formally introduces the new supply paradigm. We propose and simulate a new problem, queue-jumping operations on highways, in which vehicles can skip positions in a queue and compensate the overtaken vehicles with a payment. We present a new concept, dynamic envy-freeness, and provide a new envy ranking criterion, Constant Elasticity of Substitution Envy Intensity (CESEI) that is applied to PEXIC, an exchange-based traffic signal control scheme.

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Keywords: envy-free pricing, queue-jumping, position auction, mechanism design, fairness, equity, envy-ranking, supply-demand framework;

1. Introduction

Consumption of transportation supply has generally always been on a First-come-first-served (FCFS) basis: queue positioning in traffic flow, pick-up of taxi customers, traffic signal approaches, etc, are some examples. FCFS was also a necessity when there was no real-time information available to do anything else, and it was acceptable as a fair option. FCFS can however be seen to be inefficient and unfair when we consider user heterogeneity in, for instance, users' valuation of time. With the advent of smartphones and connected vehicles, additional information transfer can be incorporated into the operation and operational rules that account for real-time user preferences can be implemented. This can lead to increase in efficiency and fairness in comparison to FCFS, as we show in this paper.

If non-FCFS concepts are introduced, our view of transportation supply can change rather radically. Implementing these new policies, however, opens new challenges such as understanding the degree to which the exchanges between

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users have to be regulated in order to prevent less efficient future states of transportation systems, avoiding inequities in utilities accrued by the users, and ensuring public acceptance which is fundamental to any transportation policy.

A concept we have found useful to prove policies which outperform FCFS in transportation systems, is envy-free (EF) pricing. We introduce this concept that is apparently unexplored in transportation literature but extensively studied in the fields of welfare economics and multiagent resource allocation in computer science. For the purposes of this paper, we assume a regulatory environment in which all the relevant information (users' valuations, regulations and prices) is publicly available and is common knowledge, though we realize that this will face many implementation challenges. The purpose of this framework is to assess the full potential of user heterogeneity in fairness and efficiency, and thus we do not focus extensively on implementation issues such as incentives to make such a system feasible. We do not see insurmountable technological challenges in this, however.

Under the assumption that users are utility maximizers, for a given price or cost vector, they would choose an allocation that maximizes their utilities. Envy-freeness actually captures such situations, since it ensures that no user is willing to swap their allocations at their current prices. The key aspect to note, is that the envy that any agent feels is a function of his or her own valuation of others' allocations, which would normally be different than the valuation done by the other agents for themselves. This could be under the presence of a central agent whose goal is to maximize a particular objective such as social welfare or revenue. Alternatively, one could allow users to trade with each other the supply of transportation that they each possess, in a decentralized fashion. These trades would be motivated by envy between agents as well and could eventually increase global social welfare. Nevertheless, the spatio-temporal nature of transportation systems makes distributed approaches more difficult to implement in practice than a more centralized allocative scheme. Thus, we will follow a centralized approach here.

It is important to note that we do not consider "envy" to be the same as, or similar to, "jealousy". To clarify, we do not refer to "envy" as a negative externality experienced by an agent due to someone else's allocation, but as the desirability of that allocation with regard to the current one. This is why we talk about an agent being "willing" to trade away the current allocation, as opposed to "wanting" to change it. Kolm (1995) presents a discussion on this finer point.

Envy-freeness started as a problem of fair division, with cake-cutting (Brams and Taylor, 1996) as a classic example, in which divisible goods have to be split fairly among agents. Economists showed that in the presence of a divisible good such as money, an envy-free Pareto efficient allocation always exists (Alkan et al., 1991). On the other hand, computer scientists explored the idea of profit maximizing envy-free pricing. The idea behind this is that, under envy-free pricing, both buyers and sellers maximize their utilities, and therefore do not have incentives to switch allocations. This pricing scheme also has proven useful as a benchmark for auctions (Hartline and Yan, 2011; Guruswami et al., 2005). In this paper, we explore the case of welfare-maximizing envy-free pricing, since we are interested in finding new policies which outperform FCFS as a new paradigm for fairness and efficiency in transportation systems.

Importing envy-freeness to transportation modeling presents challenges. In contrast with traditional settings found in multi-agent resource allocation, such as combinatorial auctions or task allocation, agents in transportation problems only wish for one particular bundle, their own trip. Thus we can say that transportation users are unit-demand agents. Since these trips cannot be shared, we say that our resources are indivisible and generally non-transferable.

Secondly, transportation problems have spatial-temporal complexity. While space can be included relatively easily in agents' valuations, including the temporal dimension, which leads to resource allocation settings that evolve over time, causes difficulties. To model envy dynamically, we will have to identify the specific points in time when envy is assumed to change from what it was in a previous state. A state change could be a change in the number of agents present in the system, changes in supply, or changes in actual valuation of the allocation. These changes can also be continuous-time or discrete-event phenomena, to use the terminology from systems modeling. A further complication is that the valuation is a function of how the modeler sets the points of reference when the preferences are time-dependent.

We first introduce, in the next section, a new conceptual framework for collaborative consumption of supply in transportation systems, which is essential before proceeding to explain the new operational paradigms. In section three, we introduce the concepts of envy-freeness and envy-free pricing, and the associated properties. In the fourth section, we propose a novel fair queue jumping mechanism for highway exit lanes that is inspired by position auctions, one of the most successful applications of envy-free pricing in internet advertising. In the fifth section, we describe a fair traffic signal control system in which users with high VDS (value of delay-savings) can obtain lower delays by