Dissolving the Segmentation of Shared Mobility Markets: A Unified Theoretical Framework and Four Examples

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Word Count: 7216 words + 1 table(s) × 250 = 7466 words

Submitted: April 8, 2022
**ABSTRACT**

In mobility sharing markets, there are two conflicting principles: 1) the healthy competition between platforms, such as Uber and Lyft, and 2) economies of network scale, which leads to higher chances for trips to be matched, and thus higher efficiency. The status quo mobility sharing markets are either monopolistic or largely segmented with significant efficiency loss. In this paper, we first introduce a unified theoretical framework to describe the shared mobility market, and then use it to propose four market structure designs to dissolve the market segmentation to different extents. Using a formal analysis framework, we analyze the following aspects of the two status quo and four proposed market structures: demand and supply information collection, service delivery and payment flow. For each proposed market, detailed mechanisms are introduced and feasibility for market realization is also discussed.

*Keywords:* Shared Mobility, Efficiency, Market Structure, Game Theory, Mechanism Design,
INTRODUCTION

Over the past decade, shared mobility service providers such as Uber and Lyft have grown rapidly in many cities across the world. These providers, known as Transportation Network Companies (TNCs), offer convenience to many travelers, but their proliferation has led to a significant increase in urban vehicle travel. In this paper, a TNC is also referred as a “platform,” which is used in the platform economy literature (1).

Schaller (2) estimated that TNCs are responsible for adding 5.7 billion vehicle-miles of travel (VMT) annually in just nine U.S. metropolitan areas. This rise in travel, in turn, increases urban congestion, travel delay and carbon emissions. In San Francisco, TNCs have been responsible for a 51% increase in daily vehicle hours of delay between 2010 and 2016, comprising 36% of the total delay (3). While recognizing the benefits that TNCs provide to urban residents, such as offering more convenient and accessible transportation services, urban policy makers also need to actively improve the efficiency of TNC markets. In this paper we focus on improving efficiency of TNC markets by improving and redesigning the current market structures.

The ride hailing markets in most cities are divided among several uncooperative platforms, which reduces the opportunities for matching trips between drivers and customers, or pooling trips with proximate origin and destinations if they use different platforms. Due to this market segmentation, the spatial “densities” of passengers and drivers are both lower for each platform in the market, and the unloaded driving distance for pick-up is longer compared to that in a non-segmented market.

There is an implicit “dissolve” of this segmentation between platforms enabled by multi-homing drivers and customers, who serve customers or request trips with multiple platforms. Nevertheless, this passive collaboration leads only to marginal efficiency improvement since they cannot fundamentally change the market structure.

The market fragmentation results in a critical tension between two principles in economics: 1) to cultivate healthy competition between multiple players—in the mobility sharing market, between platforms; and 2) the economies of scale—if a shared mobility platform serves more trips, there is a higher probability that these trip requests will be matched with a nearby driver, and a higher probability that two or more trips can be pooled together (5 6). The Mohring Effect (7) is the observation that there are returns to scale for public transportation. A recent study found that this effect also applies to the ridesharing market (8).

At the moment, the majority of TNC trips are not shared and drivers must spend many empty miles to pick up distant requests. Sperling (9) pointed out that pooling rides to fill the empty seats in all vehicles is the most important strategy for achieving more sustainable TNC services. Market segmentation reduces the size of each platform’s network, limiting the opportunity of any one operator to match or pool. Fréchette et al. (6) found that the market segmentation between a taxi company and a TNC or between two TNCs generates lower total consumer surplus, lower driver revenue, and longer waiting times compared to the monopoly case. Similarly, our preliminary investigation using New York City taxi data found that a 50/50 market split between two TNCs leads to 5% more VMT than if trips were served by a single company.

Rather than advocating for a monopolistic market, we seek to improve the efficiency of the current competitive but segmented market by incentivizing cooperation between platforms in a way that reduces VMT and provides better services for travelers.

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1 Multi-homing customers account for nearly 9% of total customers in the US, May 2020 (4).
Cities around the world have started to realize the benefits of collaboration among mobility service providers. The city of Zürich, for instance, is exploring the opportunity of improving collaboration between transport providers (10). Coordination between shared mobility platforms could take many forms, and the design of the collaboration mechanism may bring substantial impact on the outcomes.

In freight transportation, collaboration among multiple carriers is usually realized by the reassignment of transportation requests among the carriers to minimize their total transportation cost or to maximize their total profit gained by serving requests. Studies have shown that collaboration between carriers can reduce CO2 emissions from 8 to 33% (11, 12), with other scholars estimating the saving to be up to 60% (13). Such remarkable results only underline the importance of realigning the shared mobility market structure such that it encourages and enables collaboration among the service providers.

In this paper, we propose a unified theoretical framework for the shared mobility market structure and discuss four potential market structure designs together with two existing ones. We use formal analysis for each market structure under a unified theoretical framework, and then investigate it from multiple angles, including demand and supply information, service delivery and payment flows. We will also discuss the feasibility of implementation of each market structure.

LITERATURE REVIEW

Wang and Yang (14) proposed a general framework and conducted a comprehensive literature review on ridesourcing systems, which is also generalizable to other types of shared mobility systems. As they pointed out in the paper, many previous economics studies haven been focused on the competition between two-sided platforms in the shared mobility market. Séjourné et al. (15) quantified the efficiency loss of Mobility-On-Demand (MOD) system induced by market fragmentation. Zha et al. (8) analyzed the shared mobility market with an aggregate model focusing on the customer-driver matching. They investigated the competition between multiple ride-sourcing platforms, and recommended that the regulatory agency should even encourage the merger of competing platforms if the matching friction between customers and drivers was sufficiently large. Cohen and Zhang (16) discussed the competition between two-sided platforms with a Multinomial Logit (MNL) choice model and illustrated the existence and uniqueness of equilibrium of the competing market. They further proved that the “coopetition,” which is synonymic to the concept of cooperation in our paper, leads to a win-win situation where platforms, drivers, and customers all benefit from the partnerships.

While cooperation between competing platforms brings additional benefit to the shared mobility system, few papers have explored competition with collaboration in shared mobility markets under different market conditions and regulations. Shaheen and Cohen (17) highlighted the business models and partnerships as one of core enablers for facilitating the MOD system. However, how to redesign the shared mobility market structure to facilitate collaboration between competing platforms, to establish feasible market mechanisms to allow such collaboration, and to impose appropriate regulations still remain as open questions.

Outside the shared mobility field, market structures to enable collaboration between competitors have been studied. Verdonck et al. (12) conducted a survey on the horizontal cooperation in logistics, which could improve companies’ productivity and level of service. Horizontal cooperation in the paper refers to sharing customer orders (demand side) or sharing vehicle capacities (supply side). Multiple operation-level techniques are introduced to facilitate the horizontal co-
operation, including auction-based mechanisms and bilateral swapping. In forestry transportation, Frisk et al. (18) proposed a collaboration mechanism for cost allocation, and demonstrated that this mechanism leads to an additional 9% saving to each company while better planning strategies could only save around 5%.

Learning from the theories and experiences in other fields, in this paper we aim to provide market structure designs to facilitate the collaboration of mobility sharing platforms, in order to improve the efficiency of mobility sharing markets. In following sections, we first introduce a unified theoretical framework to describe the shared mobility market, and then propose four market structure designs illustrating four different levels of collaboration between platforms.

A UNIFIED THEORETICAL FRAMEWORK FOR SHARED MOBILITY MARKET

The essence of a shared mobility market is a set of rules to conduct an assignment between drivers and customers. Therefore, there are three layers of abstraction in this formulation process: 1) the underlying supply and demand, 2) the actual assignment between them, or what we call “matching” in all prior papers (19, 20), and 3) the “market structure” or “market mechanism,” which rules how this assignment is going to be, after supply and demand are given. Typically, this rule set is driven by an objective, e.g., profit maximization, customers’ travel time minimization or VMT minimization, and is constrained by a list of factors, e.g., market segmentation, and how the segmentation could be “dissolved” to different extents.

More formally, let’s denote a bipartite set \( \mathcal{Q} := \mathcal{R} \cup \mathcal{T} \) in a shared mobility market, where \( \mathcal{R} \) represents drivers and \( \mathcal{T} \) corresponds to customers (who request trips from origins to destinations). A feasible “matching” between customers and drivers, and between customers is defined as \( m \subset \mathcal{Q} \), and the collection of feasible matchings is represented by \( \mathcal{M} = \{m|m \subset \mathcal{Q}\} \). Trivially, we have \( \mathcal{M} \subset 2^\mathcal{Q} \). Here for generality, we do not put any prior constraints on \( m \), but it is worth mentioning that restrictions embedded in \( m \) are determined by the type of service provided, or the legitimate combination of trips in the shared mobility market. For instance, Santi et al. (19) quantified the benefits of vehicle pooling. A feasible matching \( m \) in their paper satisfies maximum delay time and maximum vehicle capacity (equals to 2) constraints. In Alonso-Mora et al.’s paper (21), where they studied the on-demand high-capacity ride-sharing problem, a feasible matching \( m \) satisfies the maximum vehicle capacity (varies from 2 to 10), maximum waiting time and maximum delay time constraints.

In addition to the underlying supply, demand and assignment, a market structure puts other constraints on \( \mathcal{Q} \) and \( \mathcal{M} \). For example, in a segmented market, driver set \( \mathcal{R} \) is partitioned into several non-overlapping subsets \( \mathcal{R} = \mathcal{R}_1 \cup \cdots \cup \mathcal{R}_n \), and vice versa for customers. The matching \( m \) in this case can only occur for \( \mathcal{R}_j \) and \( \mathcal{T}_j \) with the same index. A market structure (or mechanism) is also equipped with an objective, which not only permits some assignments to be feasible, but can point directly to one or several assignments which possess some unique properties, e.g., leading to the minimum VMT. The assignment here indicates a collection of individual matchings; formally defined as a subset \( \mathcal{M} \subset \mathcal{M} \), or \( \mathcal{M} \in 2^\mathcal{M} \), with non-overlapping single feasible matchings. Let us denote the evaluation process (or objective function) as \( f(\mathcal{M}) \), which evaluates the goodness of each assignment. A market structure equipped with an objective can be explicitly expressed as an optimization process (or more generally solving or converging processes):

\[ 2 \] We use \( 2^A \) to represent all possible subsets, named power set, of \( A \), or the set of all subsets of \( A \).
\[ \mathcal{M}^* = \arg\min_{\mathcal{M} \in 2^\mathcal{Q}} f(\tilde{\mathcal{M}}). \]

This process maps the underlying set \( \mathcal{Q} \) to one or several “optimal” or “equilibrium” assignments given the market structure. From another perspective, we make the argument that market structures actually \textit{act as the mapping process}, and market structure not only works on specific instances of the underlying \( \mathcal{Q} \), but all possible combinations of demand and supply. Therefore a market structure (or mechanism) \( \mu \) can be defined as:

\[ \mu : \mathcal{Q} \rightarrow \mathcal{M}^*. \]

Given a fixed objective function \( f(\cdot) \) and underlying set \( \mathcal{Q} \), different market structures \( \mu \) lead to different feasible matching sets \( \mathcal{M}_\mu \), which are used as inputs for the optimization process and generate optimal matching \( \mathcal{M}_\mu^* \). The main distinction between different shared mobility markets is the market structure \( \mu \).

**MARKET DESCRIPTION**

In this section, we will discuss basic assumptions for the shared mobility market studied in this paper. Six different market structure designs are described from demand and supply information collection, service delivery and payment flow perspectives. A summary of six market structures is also presented at the end of the section.

In microeconomics, a market is defined as a collection of buyers and sellers that, through their actual or potential interactions, determine the price of a product or set of products (22). A shared mobility market can be treated as two separate markets linked by platforms: a market with drivers being service sellers and platforms being service buyers; a market with customers being service buyers and platforms being service sellers. Let \( \mathcal{P} \) denote the set of platforms and \(|\mathcal{P}| > 1\) represents a segmented shared mobility market. In this paper, without losing generality, we formulate the competing market under the two platform scenario, i.e., \( \mathcal{Q} = (\mathcal{R}_1 \cup \mathcal{T}_1) \cup (\mathcal{R}_2 \cup \mathcal{T}_2) \).

A competing market comprising of more platforms can be extended from the formulation easily, and thus is not given in detail for simplification. A single-platform market is indicated by \( \mathcal{Q} = \mathcal{R} \cup \mathcal{T} \). Assume all customers \( \mathcal{R} \) need to be served by one platform in the platform set \( \mathcal{P} \). First, we make the following assumptions and definitions for the shared mobility market studied in this paper.

1. The shared mobility market is an open market where customers could leave the market if the price is unacceptable.
2. A homogeneous fleet of vehicles with capacity of 2 operated by a set of drivers.
3. Each driver contracts with at most one platform and each customer requests rides from only one platform (no multi-homing customers and drivers).
4. The pricing scheme for a platform \( i \in \mathcal{P} \) can be represented by \((p_i, q_i, o_i)\). Platform \( i \in \mathcal{P} \) charges a customer with an OD-pair \((s, t)\) the price \( p_i(d_{st}) \) for a dedicated trip and \( q_i(d_{st}) \) for a shared trip, where \( d_{st} \) is the shortest path distance between the origin \( s \) and the destination \( t \). For the driver who serves a trip which consists of either a single customer or two customers, the platform \( i \in \mathcal{P} \) pays \( o_i(\hat{d}) \) to the driver, where \( \hat{d} \) includes both non-occupied (pick-up) and occupied driving distance related to this trip.

Under this assumption of pricing scheme \((p, q, o)\), the assignment \( \mathcal{M}^* \) with minimum VMT
provides each platform with the largest revenue. For all markets throughout the paper, the objective function equipped with market structures \( \mu \) is VMT minimization, and \( f(\tilde{\mathcal{M}}) \) denotes the overall VMT for an “assignment” \( \tilde{\mathcal{M}} \).

**Structure of Status Quo Markets**

In this subsection, we describe two existing *status quo* shared mobility markets. While the shared mobility platforms provide massive convenience to travelers, limited and outdated interventions and regulations are imposed from governmental authorities \( \text{(23)} \). There are two types of *status quo* markets: single-platform market and multi-platform market. A typical single-platform market is the Chinese ride-hailing market, where DiDi served 93% of total daily active users in 2019 \( \text{(24)} \). As for the multi-platform market, the American market with Uber and Lyft competing for the market share is an emblematic one. The latest data shows that Uber served 71% of market share nationwide while Lyft serving the remaining 29% for April, 2020 \( \text{(4)} \). In certain cities and neighborhoods, the gap may be even smaller (Detroit has a nearly 50/50 market share between Uber and Lyft).

There are three components in the shared mobility market: Driver, Customer and Platform. To describe the structure of each shared mobility market, we introduce four flows between these components:

- **Demand information flow**: Flow of customer request information.
- **Supply information flow**: Flow of driver location and occupancy information.
- **Payment flow**: Flow of money paid by customers to use shared mobility services.
- **Physical service delivery flow**: Flow of physical service delivery from drivers to customers.

Physical service delivery flow is trivial to discuss since it always directly runs from drivers to customers in any shared mobility market. Thus, in the following discussions, we only focus on demand information, supply information and payment flows, which are denoted by red, blue and orange arrows, respectively, in the following figures. Figure 1 illustrates the *status quo* markets, which are obvious and straightforward. In both single-platform and multi-platform *status quo* markets, platforms collect demand information from customers and supply information from drivers, and allocate drivers to customers. The payment flow goes from customers to drivers via platforms.

In the *status quo* single-platform market, market structure \( \mu \) does not put any constraints on \( \mathcal{Q} \) and \( \mathcal{M} \). For the *status quo* multi-platform market with \( n \) platforms, market structure \( \mu \) divides driver set into \( \mathcal{R} = \mathcal{R}_1 \cup \cdots \cup \mathcal{R}_n \) and customer set into \( \mathcal{T} = \mathcal{T}_1 \cup \cdots \cup \mathcal{T}_n \). Any feasible matching \( m \in \mathcal{M} \) is a subset of \( \mathcal{T}_i \cup \mathcal{R}_i, \forall i = 1, \ldots, n \).

Assuming a set of demand and supply \( \mathcal{D} \) in a shared mobility market with a set of platforms
offering both dedicated and ride-pooling services, each platform $i \in P$ tends to maximize its profit under a pricing scheme $(p_i, q_i, o_i)$. Considering all possible markets under this assumption but with different market structures, the status quo single-platform and multi-platform markets serve as two extreme cases regarding the system efficiency (or overall VMT). To gain the largest revenue in a single-platform market, the platform tries to find the optimal driver-customer and customer-customer matchings within $Q$ to minimize the overall VMT while serving all passengers. For any fragmented market, where the set of customers and drivers $Q$ are divided into multiple disjoint subsets, each platform $i \in P$ solves the optimal matching problem with its own set of customers and drivers $Q_i$. The market fragmentation leads to VMT losses compared to single-platform markets. Although the monopoly in a market is typically considered as the source of inefficiency, we analyse the market efficiency purely from the overall VMT perspective, and a monopoly (single-platform) market lead to the minimum VMT among all shared mobility markets. A single-platform market induces an unfair and unhealthy market due to a lack of competition.

Facing the situation that the status quo multi-platform market yields the worst system efficiency, we proposed four markets with different market structures. In each of the proposed market structures, the hard boundaries between segmented platforms are partially "dissolved." This dissolution of platform boundaries reduces the constraints of cross-platform trip matching, thus enables more sharing opportunities and further reduces VMT.

### Bilateral Trading Market

The first proposed market, bilateral trading market, improves the system efficiency of the status quo multi-platform market by allowing the trading, in an encrypted way to protect data security, of customer or driver information between platforms. Bilateral trading market offers platforms with choices for trading supply or demand information that they can not efficiently serve. Supply or demand information are traded between any two platforms if both platforms can improve their revenues, which also reduce the overall VMT. For example, in a market with two platforms $A$ and $B$, a passenger requests a ride with platform $A$ and all available drivers from platform $A$ are far away from this passenger. There is an available driver from platform $B$ who is close to this passenger. By allowing the bilateral trading in the market, platform $A$ could trade the customer request information to platform $B$ in an appropriate price such that both platforms and the passenger gain benefits from the trading. Figure 2 illustrates the bilateral trading market with Figure 2a showing the demand and supply information flow and Figure 2b indicating the payment flow. Based on relationships in status quo multi-platform market, all three types of flow can move between platforms in the bilateral trading market.

![Figure 2: Bilateral trading market illustration.](image)

3Drivers or customers that give platforms low or negative revenues.
For the bilateral trading market, the market structure $\mu$ allows feasible matchings $m_{ij}$ between $S_i$ and $T_j, \forall i, j = 1, \ldots, n$. In theory, bilateral trading markets can be as efficient as single-platform markets with infinite number of datings. However, only a limited number of platform pairs $(i, j)$ will trade in practice and feasible matchings $m_{ij}$ between $S_i$ and $T_j$ can be infeasible if trading information does not bring extra benefits to both platforms even though the system efficiency can be improved. The order of trades also matters. Given an order of trades, the optimization process acts in sequence: At each round of trading between any two platforms $i, j$, an optimal assignment between $R = R_i \cup R_j$ and $T = T_i \cup T_j$ is found; depending on whether platforms trade supply or demand information, driver and customer sets are updated according to the assignment for both platforms $i$ and $j$; after all rounds of trading have finished, an optimal assignment among $n$ platforms is calculated with feasible matchings as a subset of $R_i \cup R_i, \forall i = 1, \ldots n$.

With three existing components, drivers, customers and platforms, in the shared mobility market, possibilities for deriving different market structures are tightly restricted. In the following three proposed markets, we introduce a new component, central broker, which represents non-profitable governmental authorities, U.S. Department of Transportation (DOT) for instance, or non-governmental organizations to facilitate the cooperation between platforms.

**Central Trading Market**

*Central trading* market is generalized from bilateral trading market by introducing the central broker to conduct the supply or demand information trading between multiple platforms. Instead of trading bilaterally, multiple platforms can trade simultaneously with the help of the central broker. Figure 3 explains the central trading market. Demand information, supply information and payment flow are moving between platforms through the central broker. The central trading market is the most common type of market structure in reality, stock market for instance. In the stock market, issuing companies sell stocks (a share of ownership) and investors buy stocks. The stock exchange has similar role as the central broker in the shared mobility market, which offers a platform for stock tradings between issuing companies and investors.

![Figure 3](image.png)

**FIGURE 3**: Central trading market illustration.

Similar to bilateral trading market, the market structure $\mu$ of the central trading market permits feasible matchings $m_{ij}$ between $S_i$ and $T_j, \forall i, j = 1, \ldots, n$. The feasibility of matchings depends on both spatiotemporal constraints and whether information tradings which lead to cross-platform matchings are beneficial for platforms. In a shared mobility market with multiple platforms, the central trading market gains extra benefit regarding the system efficiency compared to bilateral trading market by incorporating more trading opportunities.
Cooperative Market

Cooperative market is a market where multiple platforms form an alliance and contribute their driver and customer information to a common pool. Platforms make an agreement on a common pricing scheme and profit distribution mechanism for the alliance. A central broker assigns drivers to customers in the common pool and distributes profit to platforms. This market can be as efficient as the status quo single-play market when all platforms in the market form a “grand” platform. Two markets with the same level of efficiency imply that they produce identical overall VMT. Figure 4 illustrates the cooperative market. Figure 4a shows that the central broker collects demand and supply information from drivers and customers via platforms. Payment flow is displayed by Figure 4b, where the central broker receives payments from customers and distributes them to platforms and then to drivers. For central trading market, the market structure $\mu$ allows feasible matchings $m_{ij}$ between $S_i$ and $T_j$, $\forall i, j \in \bar{N}$, where $\bar{N}$ indicates the set of platforms in the alliance.

![Diagram of Cooperative Market](image)

**FIGURE 4**: Cooperative market illustration.

Shared Mobility Marketplace

The central broker could also play a more fundamental role which gathers demand or supply information in the shared mobility market. For the next proposed market, we assume that the central broker gathers demand information$^4$ and platforms gather supply information.

Shared mobility marketplace is a market where the central broker acts as an auctioneer and sells demand information to platforms based on certain mechanisms, such as single-item VCG (Vickrey-Clarke-Groves) mechanism. Given the location of their available drivers, platforms bid for customers and the central broker distributes customers to platforms and charges price of information in order to maximize system efficiency. Platforms assign drivers to customers after getting demand information via the auction. The detailed mechanisms are discussed in the next section. Figure 5 explains the shared mobility marketplace. As shown in Figure 5a, platforms collect supply information from drivers and receive demand information from the central broker, who gathers demand information from customers. Figure 5b describes the payment flow, where platforms receive payments from customers and a proportion of their revenue are used to pay drivers’ salary and another proportion to pay the price of information charged by the central broker.

For shared mobility marketplace, the driver set is split by $n$ platforms, i.e., $\mathcal{R} = \mathcal{R}_1 \cup \cdots \cup \mathcal{R}_n$. The market structure $\mu$ enables feasible matchings between $\mathcal{T}$ and $\mathcal{R}_i$, $\forall i = 1, \ldots, n$. When platforms bid truthfully, indicating that platforms submit bids based on their true revenue for serving customers, the objective function $f(\cdot)$ is bona fide VMT minimization.

$^4$The case where a central broker collects the supply information can be treated as an equivalent case.
Summary
Table 1 summarizes key elements of the two existing and four proposed market structures, and enumerate roles of platforms and central brokers in each market structure. There are two major factors to distinguish between different market structures: market segmentation and mediation of a central broker. Furthermore, roles of platforms and central brokers are diverse across all markets. For status quo single-platform and multi-platform markets, platforms are in charge of contracting drivers, collecting customer requests, matching and setting pricing. For each proposed market, we allow a central broker to take over tasks form platforms.

| Market | Segmentation | Central broker |
|--------|--------------|----------------|
| I. Status quo single-platform | ✓ | ✓ |
| II. Cooperative | ✓ | ✓ |
| III. Shared mobility marketplace | ✓ | ✓ |
| IV. Central trading | ✓ | ✓ |
| V. Bilateral trading | ✓ | × |
| VI. Status quo multi-platform | ✓ | × |

| Role of platform/central broker | Platform | Central broker |
|---------------------------------|----------|----------------|
| 1. Contracts with drivers | I, II, III, IV, V, VI | - |
| 2. Receives customer requests | I, II, IV, V, VI | III |
| 3. Matches customers and drivers | I, III, IV, V, VI | II |
| 4. Supply/Demand information buyer | III, IV, V | - |
| 5. Supply/Demand information seller | V | III, IV |
| 6. Pricing | I, II, IV, V, VI | III |
| 7. Profit distribution | - | II |

TABLE 1: Summary of different markets.

MARKET MECHANISMS
Based on the high-level structure of each proposed market, we discuss the possibilities for market realization by proposing detailed and feasible mechanisms for proposed markets in this section.
Cooperative Market
The cooperative market is a market in which platforms form a multilateral alliance while each platform remains their own user base and fleet. Platforms contract with drivers and receive customer request information while the central broker assigns drivers to customers. Platforms make an agreement on the pricing structure \((p^*, q^*, o^*)\) and a central broker is responsible for assigning drivers to customers to maximize the overall profit, which is equivalent to VMT minimization. In order to incentivize platforms to cooperate and participate in the alliance, a fair profit allocation mechanism has to be established. Three different profit allocation mechanisms can be applied in the cooperative market: Shapely value (26), Equal Profit Method (EPM) (18) and contribution-based allocation mechanism (27).

Market Feasibility Discussion
The cooperative market exists in numerous industries, forestry transportation and logistics for instance (18 27). For the cooperative market, we discuss the feasibility from four market components’ perspectives:

- **Platforms**: For the shared mobility market, the cooperation among multiple platforms improves individual platform’s revenue. The key issue lies in the fairness of profit assignment. Platforms might not be willing to join the alliance if their market share will decline after the cooperation, especially for large platforms. Since a cooperative market unify the pricing schemes across multiple platforms, platforms in small-scale have larger relative profit improvement compared to large platforms.
- **Central broker**: The central broker in the cooperative market will be supported by platforms in the alliance, each platform can contribute to operations of the central broker. The central broker requires the ability to assign drivers to customers and calculate the profit allocation according to the agreement made by all participating platforms.
- **Drivers**: Drivers have more opportunities to be matched with customers in the cooperative market, which brings extra benefits to drivers.
- **Customers**: In the cooperative market, customers can choose whatever platforms they want without worrying about paying extra price for the same service. However, forming an alliance is similar to the single-platform case, where the “unified” platform, i.e., a cartel, set higher price to gain monopolist-like benefit. Customers’ interests can be hurt in the cooperative market. Therefore, government regulation is necessary for cooperative markets.

Shared Mobility Marketplace
In the shared mobility marketplace, a central broker serves as an auctioneer, collects and sells demand information to platforms according to certain mechanisms. Assuming that platforms bid for trip information based on their valuations, which are denoted by their net profits for serving a given trip. The central broker distributes customers to platforms to maximize the overall valuations and charges platforms the price of information. Under this market structure, platforms contract with drivers, buy demand information from the central broker and assign drivers to customers. The central broker collects customer requests, set pricing scheme \((p^*, q^*, o^*)\) and sell demand information to platforms.

In this section, we propose two auction mechanisms for two different types of auctions: single-item auction and combinatorial auction.
In the single-item auction, the central broker first creates shared trips for customers who request pooling services based on their pooling potentials. Then, the central broker sells a dedicated trip or pooling trip at a time to platforms. For the combinatorial auction, the central broker sells a set of customers’ trip request information to platforms and platforms bid for a bundle of trip requests according to their service capabilities.

**Single-Item Auction Mechanism Design**

Consider the situation where a trip is auctioned among \( n \) platforms through a sealed-bid auction. In the sealed-bid auction, bidders place bids in sealed envelopes, simultaneously submit envelopes to the auctioneer, and the bidder with the highest price wins the item. A pooling trip is created by matching customers who request shared service to maximize the overall travel distance savings \( (19) \). For a trip, each platform \( i \) has a valuation \( v_i \) based on information of their drivers, indicating the net profit for serving it\(^5\). We would like to design an auction mechanism such that platforms bid truthfully (according to their valuations).

Charging platform that wins the trip with price of information \( p \) is a necessary condition for designing such a mechanism. Since platforms will bid as large as possible to win the trip if they have positive valuations whatever their valuations are. Then, we introduce the VCG mechanism into the shared mobility market context to design a single-item auction mechanism. Under the VCG mechanism, bidders (or platforms) bid truthfully according to their true valuations \( (28) \). The difference between the general auction and the auction in the shared mobility marketplace is that platforms have to serve customers to earn profit instead of owning them as assets. Considering a situation where player \( i \) wins the item with valuation 100 and payment 98 in a general auction, it is reasonable for him/her to buy the item since he/she pays less money to get an item with higher valuation. However, if the same case happens in the shared mobility marketplace auction, it is extremely unfair for platforms to participate in the auction because 98\% of their net profit goes to the central broker as the price of information. To maintain a fair marketplace, we propose the following single-item auction mechanism:

**Proposition 1.** *In the single-item auction in the shared mobility marketplace, the central broker sells dedicated and pooling trips in sequence to platforms with the highest bid, and the winning platform pays a price of information equals to \( \gamma \) proportion of the second-highest bid, where \( \gamma \) represents the rate for price of information.*

In the shared mobility marketplace, the central broker’s intention for collecting payments from platforms is to maintain a truthful-bidding auction instead of obtaining its own profit. Given such an auction mechanism, each platform will bid truthfully and the revenue of platforms can be protected.

**Combinatorial Auction Mechanism**

In the combinatorial auction case, \( n \) platforms bid for customers given \( m \) trip request information collected by the central broker within a time period \( \Delta \). This type of auction with multiple items and players is termed as a combinatorial auction in the literature, and it has been studied intensively in recent years \( (29) \). The ideal mechanisms for the combinatorial auction is VCG mechanisms where platforms bid truthfully. One major limitation for the VCG mechanism is that its truthfully

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\(^5\)Platform has zero valuation if the trip can not be served or the net profit is negative.
bidding property depends on the unlimited bidder budget condition. For each platform in the shared mobility marketplace, it has limited budget in the auction because of limited number of drivers. This is an idealization of real-world case—in reality, the number of drivers is not infinite, but in most cases, it won’t reach the limit. Hence, a practical combinatorial auction procedure incorporating the budget constraint, the ascending proxy auction, proposed by Ausubel and Milgrom (30) can be applied in the shared mobility marketplace.

Market Feasibility Discussion
There are several transportation-related markets implementing auction mechanisms. In the truckload transportation auction market, retailers, manufacturers, distributors and other companies which need to move freight are auctioneers, and the trucking companies that own the transportation assets serve as bidders (29). For the bus routes market in Greater London area, the London Regional Transport (LRT), which is succeeded by Transport for London (TfL), acts as an auctioneer and sells rights for carrying out bus services to private operators (29). These instances suggest possibilities for introducing auction mechanisms in the shared mobility market, and we discuss the feasibility of this market from four perspectives:

• **Platforms:** For the shared mobility marketplace, platforms are strongly affected due to the loss of control for demand information. Large platforms lose advantages comparing to small platforms, and they are unlikely to join the shared mobility marketplace unless receiving external interventions. The distribution of customer information is entirely based on driver locations of each platform.

• **Central broker:** The central broker under this market requires technological competences for gathering enormous demand information and distribute demand information rapidly to maintain a satisfying service for customers, which is required by the on-demand nature of mobility sharing services. Also, the central broker need to be regulated because of its power of setting the pricing scheme and collecting all customers’ information.

• **Drivers:** Drivers have more chances to be matched with customers and earn more incomes.

• **Customers:** In this market, customers experience lower waiting time while taking shared mobility service with satisfying price. Since the central broker, who decides the pricing scheme, is a non-profit authority.

Central Trading Market
For platforms in the shared mobility market, they can not efficiently serve their drivers and serve all customers because of the imbalance between supply and demand. In this market, the central broker serves as the demand (trip request) information seller while platforms buy demand information from the central broker. Given a set of customer information \( T_i \) for each platform \( i \) within a time period \( \Delta \), the central trading market works as follows:

• A central broker receives demand information \( T_i \) with selling prices from each platform \( i \) and offers a list of available demand information \( T = \bigcup_{i=1}^{n} T_i \) to all platforms.

• Each platform \( i \) evaluates demand information in \( T \) and requests customers which bring platform \( i \) profit after paying driver cost and price of information.

• The central broker sells demand information to platforms and distributes price of information back to sellers. For the situation where multiple platforms request a same
customer, the central broker randomly assigns the demand information.

- The remaining trip request information in the current round will not be traded in the future rounds of central trading.

**Market Feasibility Discussion**

Central trading market is the most common type of market in the real world, the stock market and rental market for instance. The essence of a central trading market is that it allows all participants to be "faceless," but only price is relevant in all transactions. In a stock exchange, for instance, no buyers or sellers care about whom they are buying to or selling from. As long as the price can meet their requirements, the transactions can be fulfilled. However, there are rarely transportation-related markets with the central trading structure. For the shared mobility market, we discuss the feasibility for applying central trading market from four perspectives:

- **Platforms**: In a central trading market, platforms reduce their possibilities for offering customers services with unacceptable waiting time. Both large and small companies benefit from this market without worrying about decline of their market shares. For large-scale platform, owning more customer or driver information expanding the possibility for earning profit by selling information to other platforms.

- **Central broker**: The central broker in this market need the technological competences for maintaining a trading platform to exchange demand information with platforms. Also, fairness has to be included as a criteria when distributing demand information. For example, when multiple platforms request a same trip, each platform should have a equal probability to buy this trip request information.

- **Drivers**: Drivers have more opportunities to serve customers and gain extra revenues.

- **Customers**: In the central trading market, customers receive better services with lower waiting time.

**Bilateral Trading Market**

The bilateral trading market improves the system efficiency of status quo multi-platform market without introducing any third-party organization. In the bilateral trading market, platforms trade demand information directly with each other. For each platform \( i \), let \( T_i \) denote the set of customer information given a time interval \( \Delta \). For any two platforms \( i, j \), a random sequence is generated for \( U = \{ (t_i, t_j) \mid \forall t_i \in T_i, t_j \in T_j \} \), indicating a series of demand information pairs to be traded. A trading mechanism is designed for the selling platform to decide whether to receive the offer proposed by the buying platform. A practical framework for bilateral trading proposed by Myerson and Satterthwaite (31) can be applied in the bilateral trading market, and we skip the details of this mechanism in this paper.

**Market Feasibility Discussion**

Most real-world markets contain multiple participants, leading the bilateral trading becomes inefficient compared to in the central trading scenario due to the lack of information sharing. However, this type of market is close to daily life since most trading between people can be treated as bilateral trading. The biggest advantage of this market compared to the first three proposed markets is its feasibility because it does not need a central broker. In bilateral trading market, platforms increase their profit by trading customer information. Similar to central trading market, large-scale platforms do not need to worry about losing market share and benefit from trading information. Both
drivers and customers receive marginal benefit in the bilateral trading market since only limited number of tradings can be conducted.

**SUMMARY AND DISCUSSION**

In this paper we proposed a unified theoretical framework to describe the shared mobility market. Two status quo market structures, single-platform market and multi-platform market, are discussed from the efficiency perspective, which is indicated by total VMT. Facing the efficiency gap between the two status quo market structures while avoiding monopoly, we proposed four different market structure designs to facilitate cooperation between platforms.

We analysed two existing and four proposed market structures in terms of four flows: demand and supply information flows, payment flow, and physical service delivery flow. Each existing and proposed market structure can be interpreted with our unified theoretical framework and the main distinction between different markets is reflected by the specification of the market structure $\mu$.

Our proposed unified theoretical framework is to the best of our knowledge the first attempt of designing a theoretical framework on shared mobility market and discussing different market structures based on it.

In this paper, we only consider the market efficiency represented by the total VMT, but we acknowledge that efficiency can incorporate a much richer set of different objectives, including total travel time, total carbon emission, total energy consumption, etc., each of which is worth of a further investigation. Besides, equity of platforms, passengers, and drivers in the mobility sharing markets, and the redistribution of gained surplus from market efficiency improvement also asks for detailed discussion in future research.

In the next step of our research, we will conduct simulation to evaluate the efficiency improvement of each proposed market structure. The numerical results can provide practitioners, regulators, and policy makers with detailed measures of improvements on VMT, which can be further translated to energy saving and emission reduction.

While in this paper, all our models are highly abstract and stylized, in further discussion of each mechanism, more rigorous design is needed to make the model operable. We believe that the market design in the mobility sharing field could be a powerful tool to facilitate the reduction of inefficiency due to the segmentation of different platforms, and to promote healthy competition with collaboration between them.

**ACKNOWLEDGEMENTS**

The authors thank the Singapore–MIT Alliance for Research and Technology (SMART) Centre for their financial support of this project, and thank Nicholas S. Caros and Shenhao Wang for their comments on the paper.

**AUTHOR CONTRIBUTION STATEMENT**

The authors confirm the contribution to the paper as follows: study conception and design: X. Guo, H. Zhang, P. Noursalehi, J. Zhao; modeling: X. Guo, H. Zhang; draft manuscript preparation: X. Guo, H. Zhang, P. Noursalehi, J. Zhao. All authors reviewed the results and approved the final version of the manuscript.
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