A Pareto-efficient market-clearing mechanism for shared-mobility systems

Postprint of:

Le Vine, S. (2015) A Pareto-efficient market-clearing mechanism for shared-mobility systems. *International Journal of Automotive Technology and Management*.
http://dx.doi.org/10.1504/IJATM.2014.065293

Scott Le Vine
Imperial College London, Exhibition Road, London, SW7 2AZ, UK
Telephone: +44 20 7594 6105
Fax: +44 20 7594 6102
Email : slevine@imperial.ac.uk

Abstract

Shared-mobility services facilitate distinctive forms of personal mobility, and their pay-as-you-go business model has been shown to offer substantial benefits relative to use of privately-owned cars. Such systems in general operate one of two business models, in one case where customers make advance reservations and the other in which use is spontaneous and cannot be reserved with any certainty. This paper proposes a market-clearing mechanism that draws on the strengths and mitigates the weaknesses of each of these two prevailing operating models, by allowing reservations (the right to use the service at a particular time and place in the future) to be traded in a futures market. We show that there is a revenue-positive role for the market-maker of the secondary-exchange market as well as for investors in shared-mobility futures. Introducing a secondary exchange market is Pareto efficient in that shared-mobility services are allocated to customers on the basis of maximum willingness-to-pay rather than first-come-first-served. Finally, from the point of view of each individual customer there would be a step-change in the reliability of accessing shared-mobility vehicles when and where needed, which can be expected to increase overall demand for the service.

Key words: shared mobility; car sharing; market governance

1. Introduction

Shared-mobility services are emerging as a significant niche in urban transport. They facilitate 'judicious car use' (Cervero 2003) and can provide a wide range of benefits, including a reduction in spatial requirements for car parking, reduced vehicle-kilometres of travel, and emissions savings (Harmer and Cairns 2012, Martin and Shaheen 2012). There are now several million customers in a marketplace that barely existed at the turn of the century (Shaheen and Cohen 2013). In terms of demand, shared-mobility services offer customers greater choice and flexibility in how they travel, and can in principle deliver large monetary savings. Such services fall within broader trends of innovation and disruption in the automotive sector (Ceschin and Vezzoli 2010, Donada 2013. Gains in the economic efficiency of urban transport arise, including both private benefits to travellers as well as wider societal and environmental benefits due to a reduction in the negative externalities of private car use.

Shared-mobility services are delivered by a range of organisation types characterised by differing degrees of public-private sector interaction and a variety of types of private-sector entities. Structures include direct provision by the public sector, provision by private sector operators for compensation (either monetary or in-kind compensation) from the public sector, provision by private sector operators under licence from the public sector (frequently but not always with permit fees paid to the public sector), and provision by private sector operators with minimal ongoing interaction with the public sector. In general the degree of public-sector involvement is linked with the service's need for ongoing subsidies or privileged access to public property (space for vehicle parking in the public right-of-way.)

The blurring of functional relationships between incumbent firms in the transport sector is another particularly relevant aspect of shared-mobility. Automakers have traditionally sold vehicles to transport service providers (e.g. the taxi industry and car rental firms), but this business-to-business supplier-customer relationship is now being disrupted. Automakers are increasingly providing shared-mobility services themselves. Arguably the car rental sector has been selling 'shared-mobility' for decades without using this term (cf. Firnkorn and Muller 2012, Le Vine 2012), though major incumbent car hire firms are now providing services on a finer time-scale than previously and with different vehicle-access mechanisms than they typically have done (distributed fleets accessed via smartcard, in addition to storefront and airport locations), and competing in the transport-service marketplace with vehicle manufacturers.

This paper presents a market-clearing governance structure for shared-mobility that extends from prevailing operator practices. For the purposes of this paper we focus primarily on shared-mobility systems with the following characteristics. First, the shared-vehicle fleet is of a fixed number of vehicles, which are all owned by a central system operator. Second, when not in revenue use vehicles are stored at dedicated and fixed parking locations, with each vehicle having a 'home' location from which each usage episode begins and also ends. Third, customers must make an advance reservation for each usage episode, and this reservation includes the beginning and end time of the episode as well as the location at which it will begin (and therefore end). Customers therefore pay for the full duration of their usage episode, including the time that they are driving the shared-vehicle plus any time that it is parked but away from its home location, as well as any time at its home location that falls during the reserved period of time.

These characteristics describe what is generally termed 'round-trip' carsharing (Ciari et al. 2013, Rabbitt & Ghosh 2013, Jorge and Correia 2013). We are unaware of bikesharing systems in operation that have these features, but in principle the market governance mechanisms outlined in this paper are transferable to bicycles or vehicle types. Other variants of shared-mobility with characteristics different from those outlined above include one-way carsharing (where vehicles are in general used spontaneously, without an advance reservation that guarantees a vehicle at a particular location and time), bikesharing systems (which in general are also used without advance reservations) and peer-to-peer carsharing (where the fleet is not centrally owned) (Firnkorn 2012, Smith et al. 2013, O'Brien et al. 2013, Clark et al. 2014). By some definitions, shared-mobility can also encompass ridesharing (in which one person travels in a car which another person drives, possibly in exchange for compensation) and traditional car rental, where reservations may not be guaranteed as with carsharing (Agatz et al. 2012, Le Vine 2012).

For purposes of exposition this paper outlines the market governance mechanism in the context of round-trip vehicle-sharing. We discuss briefly later in this paper issues of applying the concepts discussed herein to shared-mobility services with other operational features.

The mechanism presented in this paper sits within a growing body of literature addressing management practices in shared-mobility systems. Early papers by Smeed (1964), d'Welles (1951), and Fishman and Wabe (1967) discuss conceptually the promise of shared-mobility systems in general to address traffic-related problems, and the system-level implications relative to privately-owned vehicles with relatively low costs of marginal usage. More recently, Barth and Todd (1999) employ simulation techniques for carsharing operators to optimally specify fleet size and operating characteristics, depending on the system manager's business strategy. Awasthi et al. (2007) analyse criteria to optimally site round-trip carsharing stations. Pavone et al. (2012), Kek et al. (2009) and Smith et al (2013) address the question of how to optimally balance fleets in one-way shared-mobility systems, in the first of these studies via autonomously-operating vehicles and in the latter two studies drawing on human drivers. Zhou (2012) investigates mechanisms for dynamic pricing to balance one-way-operation shared-vehicle systems, using principles modelled on Coulomb's Law for electrically-charged objects.

There is a parallel body of literature on the principles and operating characteristics of futures markets. Happel and Jennings (2002) discuss the prospects of a futures-trading marketplace for tickets to major events (major league sports, music concerts, etc.), concluding that consumer comfort with such a mechanism is an important unknown. In a study of the pricing of U.S. football tickets, Williams (1994) shows empirically that anti-resale laws are negatively associated, net of other effects, with tickets' face value. Swofford (1999) exposes the value of such markets to the original ticket seller as a risk-management mechanism.

The rest of this paper is structured as follows. Section 2 presents the conceptual framework, which is formalised in Section 3. Section 4 then presents simulation results of a stylised shared-mobility system which includes the new governance mechanism, and section 5 concludes the paper with a discussion of the implications of the governance mechanism.

2. Conceptual framework

At present users of round-trip shared-mobility services must make an advance reservation for each usage episode, while users of one-way services cannot in general make reservations well in advance and must instead check vehicle availability shortly ahead of their usage (i.e. spontaneously).[1] Both of these are undesirable from the customer's point of view, in different ways. Round-trip services frequently are booked for busy times by other users well ahead of time. This means that users who do not reserve first cannot access a vehicle at those times at any price; vehicle access is strictly first-reserved, first-served. The 'spontaneous' use of one-way systems, by way of contrast, means that users cannot rely at all on having access to a vehicle where and when they need one.

The innovation developed in this paper is the application of a secondary-exchange marketplace to shared-mobility services. It is shown that such a system would, subject to certain assumptions, deliver a Pareto improvement relative to the current operating practice in round-trip shared-mobility services. Users would be able to guarantee[2] access to a vehicle in advance of their planned usage episode, as is characteristic of today's round-trip services, as well as be able to reliably access a vehicle on little or short notice. The latter is characteristic of today's one-way shared-mobility services, and would be subject only to a) the user who wishes to access a vehicle on short notice being willing to pay a market-clearing price, and b) sufficient liquidity in the market.

There are several key aspects of current shared-mobility reservation systems which result in economic inefficiency. The first is that users cannot indicate that they would like to reserve a slot that is currently reserved, and the second is that a user who currently has a reservation at a time of high demand would receive no compensation from relinquishing the reservation to allow another user with a higher willingness-to-pay to take it over. Third, customers have no means to identify and coordinate with each other to arrange trades of reservations; the only market actor who knows customers' identities is the central system operator. For these reasons access to the shared-mobility fleet is apportioned on the basis of first-to-reserve rather than maximum willingness-to-pay. Unless willingness-to-pay is constant over time, the outcome will not in general be economically efficient. Willingness-to-pay would not be constant, for instance, when customers' plans for their future activity/travel patterns change.

It is noteworthy that there is a potential role for a class of actors not present in existing shared-mobility systems. These are 'investors', which we define as buyers of reservations from the SMSP who intend to sell on the reservations rather than to be end users of the system. There is a market opportunity for any actor willing to bet on the future spatio-temporal demand/supply conditions of the system. It can be viewed as an investment characterised by limited downside (the cost of purchasing the reservations from the central service provider is *a priori* known to the investor) but indeterminate upside (there is no natural limit to the price at which reservations may be sold on to

[1] The market-leading operator of one-way carsharing services allows users to place a reservation no more than 24 hours in advance of their planned usage. The reservation does not guarantee access to a vehicle at the time and place desired, but rather allows the user to access the nearest vehicle to the desired place at the time of the reservation. No guarantee is made of how proximate the offered vehicle will be to the desired location.

[2] Any guarantee of access to a vehicle that the shared-mobility service provider offers to a user is conditional on the previous user of a vehicle returning it at or before the agreed end of their usage episode. In practice such behaviour can be enforced through strong monetary dis-incentives for overrunning an agreed reservation timeslot.

end users). This role is economic if the investor is able to buy reservations at a lower average price than the price at which he/she is able to sell them.

There is nothing in principle to prevent the SMSP from selling reservations in a dynamic pricing model based on its expectations of future market conditions, but the SMSP may wish to sell reservations under a simple fixed-price model (as is generally the case in presently-operating systems). By choosing to sell reservations at a unit price which does not vary by time and place, however, the SMSP leaves open the possibility of other actors capturing value from trading in the secondary-exchange market that the SMSP could have retained itself. The governance mechanism does not require that the shared-mobility service provider have any predictive capacity regarding future system conditions. But if the service operator is able to predict the spatio-temporal patterns of future supply/demand conditions, and willing to sell at dynamic prices, they would be able to capture value that otherwise would accrue as consumer surplus or revenue to a combination of private individuals or the operator of the secondary-exchange market.

3. Formalisation

We develop a stylised round-trip-usage shared-mobility marketplace with the following elements:

- A single shared-mobility service provider (SMSP) who provides the fleet of shared-mobility fleet vehicles. It is assumed for the purpose of this discussion that the SMSP sells reservations at a fixed price per unit time, though this assumption can readily be relaxed.
- Shared-mobility fleet vehicles (SMFVs), each distributed at fixed parking locations.
- Timeslots, where time is discretised into finite time steps for ease of exposition.
- A single per-timeslot unit price for reserving any vehicle.
- Individual customers who purchase reservations from the SMSP.
- Reservations, each made by a single customer. A reservation provides the right to take a shared-mobility vehicle from its home parking location at a given point in the future, with a specified end-of-reservation time that the vehicle must be returned to its home parking location.
- A single operator of a secondary-exchange marketplace (OSEM) where reservations which take place in the future may be traded.
- Individual customers who buy and/or sell reservations through the SEM (from the OSEM).
- Buy (resp. sell) bids placed by individual customers through the OSEM. A 'buy' bid is placed by a customer wishing to purchase a reservation to use an SMFV, and is characterised by a desired timeslot and desired location, and a maximum price that the buyer is willing to pay. A 'sell' bid is characterised by the seller indicating that they are willing to sell their previously-purchased right to use an SMVF at a specific timeslot and location, and the minimum price which they are willing to accept for the reservation.
- Transactions, each of which is an agreement between a buyer and seller brokered through the OSEM. By definition both are willing participants, therefore the market-clearing price must be no more than the buyer's maximum willingness to pay and no less than the seller's maximum willingness to accept.

We attribute to each customer a willingness to pay for each vehicle-time slot, and write:

$$WTP^i_{tvu}$$

WTP^i_{tvu} represents customer i's willingness-to-pay at timeslot t to use vehicle v in usage timeslot u. At time t the customer can decide whether or not to make a reservation for (or, if already reserved, attempt to trade for) the right to use vehicle v at usage time u. Usage time-slot u cannot be earlier than time t; the willingness-to-pay for timeslots in the past is not relevant. From here forward we use the term 'vehicle-time slot' to refer to a specific combination of a given vehicle v and a given usage timeslot u. WTP^i_{vu} need not remain constant over time, and may vary to account for the customer's future plans changing; we therefore write WTP^i_{tvu}. We restrict WTP^i_{tvu} to be non-negative (i.e. zero or positive). For instance, on Tuesday a customer may be planning an activity for the upcoming Saturday that requires a car, but on Thursday she may decide that she wishes to spend her Saturday doing a different activity and no longer needs a car.

We assume that no reservations can be made before time $t = 1$, and that in any timestep t customer i reserves an available vehicle-time slot vu if their willingness-to-pay for it exceeds the price charged by the SMSP. If two customers both have a willingness-to-pay in timeslot t for an available vehicle-time slot vu that exceeds the cost, we specify that the customer having the higher willingness-to-pay makes the initial reservation.

It is specified that the SMSP allows customers to cancel reservations at no cost, therefore the reservation for vu is essentially an option to use vehicle-time slot vu that can be either exercised at time u or cancelled without cost at any time up to u. Any customer who has WTP^i_{tvu} between zero and the price to make a reservation simply does not desire at time t to hold the reservation for vu. If customer i holds the reservation for vehicle-time slot vu and their willingness-to-pay for it drops to below its price, it is specified that the customer simply cancels the reservation and pays no fee for doing so.

This section's discussion to this point has formalised the operations of the current generation of round-trip shared-mobility services. We now introduce the proposed secondary-exchange market for reservations.

Customer i holding a reservation for vehicle-time slot vu may choose to post a 'sell' bid in the secondary-exchange market, with the minimum price customer they are willing to accept for the reservation. The information contained in the sell bid would consist of the relevant details of the reservation, including the location of vehicle v, the timestep u, and the minimum price that customer i is willing to accept. Customers holding reservations are under no obligation to place 'sell' bids for their reservations; they would only do so if they wish. Nothing precludes them from either holding a reservation for vehicle-timeslot vu until time u arrives (and hence making use of it) or cancelling their reservation with no compensation. These are the two options generally available to them in presently-operating round-trip shared-mobility services.

A customer who wishes to reserve a vehicle-time slot but finds it unavailable through the SMSP (i.e. it is already booked by another customer) has the option to place a 'buy' bid on the secondary-exchange market, detailing the desired vehicle-time slot and the maximum price w that they are willing to pay.

The OSEM would match willing buyers and sellers, by continuously comparing buy and sell order to identify complementary bids. A trade is arranged by the OSEM if there exist in timestep t both a buy bid and a sell bid for a given future vehicle-time slot vu for which the prospective seller is willing to pay a price that is greater than the prospective seller is willing to accept. We assume that no trade occurs when prospective buyers and sellers are indifferent, and also that customers have symmetrical willingness-to-pay and willingness-to-accept values. In other words, a customer willing to pay some price to acquire a reservation is, in the next time-step (assuming their willingness-to-pay does not change in this timestep) willing to sell the reservation at any price in excess of their willingness-to-pay.

A few practical points require discussion. First, the OSEM can decide how much information to make available to potential buyers and sellers. For instance, the OSEM may decide to allow prospective buyers to view sell bids before placing a buy bid, or not. The mechanism would work in both instances, but with somewhat different properties (we leave a detailed discussion of these properties for future research). Second, the OSEM will require resources in order to operate; one logical mechanism is to retain a small percentage of all value exchanged through the marketplace. This is similar to the support-mechanisms used by peer-to-peer carsharing market-makers (cf. Shaheen et al. 2012), which retain a percentage of the value traded. Third, the OSEM would require either privileged secure access to the SMSP's computer systems and the right to change reservations on behalf of the buying/selling customers, or would require that buyers and sellers provide their login details to the OSEM so that the OSEM can add/cancel reservations in the SMSP's computer systems on their behalf. This is simplified if the OSEM is the same corporate entity as the SMSP, though this is not a requirement.

Table 1 shows a hypothetical example illustrating how the secondary-exchange market would provide a Pareto improvement relative to when such a marketplace does not exist.

<<Table 1 here>>

Table 1: Hypothetical example of the impact of introducing a secondary-exchange market

Column 'B' shows that in the initial timestep $t = 1$ (we specify that there is no prior reservation for vehicle-time slot vu) customer i has a positive willingness-to-pay for vehicle-time slot vu, whereas customer j does not. Customer i's willingness-to-pay exceeds the cost ($2), so the outcome in timestep $t = 1$ is that customer i makes the reservation. This outcome occurs regardless of whether the secondary-market is in operation.

We then increment a timestep to $t = 2$, and first consider the scenario shown in Column C. From timestep $t = 1$ to timestep $t = 2$, customer i's willingness-to-pay has dropped below the price of the reservation so they cancel it. Meanwhile, customer j's willingness-to-pay for the same reservation has risen to above the price, so they make the reservation. The outcome is the same with or without the secondary market; no trade would be made in this circumstance.

We now consider an alternative scenario in timestep $t = 2$, shown in Column D. Here customer i's willingness to pay has not changed between timesteps $t = 1$ and $t = 2$. But, customer j's has changed and it now exceeds both the price of the reservation and customer i's willingness to pay. If there is no secondary market, customer i will retain the reservation, because their willingness-to-pay exceeds the price. This is an inefficient allocation of the reservation, however, because customer j is willing to pay more for it. Therefore, if there is a secondary market which can facilitate trades between customers i and j, they may choose to trade it at a price which is between their two willingness-to-pay values. Both are better off when they trade relative to in the case when they could not trade, and hence the outcome is a Pareto improvement.

4. Simulation of market dynamics

To further expose the governance mechanism outlined above, simulations of a small-scale system were run using the following parameters:

- 24 one-hour-long timesteps (a representative day), with the simulation starting at time $t = 1$ with no prior reservations
- A fixed unit price of $2 per timestep
- 25 parking locations, each being the home parking location for a single vehicle.
- 10 customers who are able to reserve each vehicle, for a total of 250 customers. Their willingness-to-pay has the following parameters:
    - The willingness-to-pay for usage episodes beginning in all timeslots is uniformly distributed between -$100 and +$10/hour for each timeslot. Any draw of willingness-to-pay below zero is treated as zero, therefore the average person has a positive willingness-to-pay for 9% of the timeslots and zero for all others.
    - Subject to a customer having a positive willingness-to-pay for a given timeslot, the desired duration is distributed as: 1/3 are three hours in duration, 1/3 four hours, and 1/3 five hours. In the case of this algorithm generating two overlapping desired usage episodes for the same customer (i.e. a four-hour episode beginning at time t and a two-hour episode beginning at time t=1) , the one which begins first in time is retained and the second is eliminated.
    - In each timestep, there is a 5% probability of their willingness-to-pay for a given timeslot changing.
- Two scenarios:
    - Scenario #1 in which reservations can be made and cancelled (if one's willingness-to-pay drops below the price of the reservation) but not traded
    - Scenario #2 in which reservations can be traded in a secondary-exchange market

Table 2 shows the summary of results from 250 Monte-Carlo simulations of the two scenarios. Each realisation from the distributions listed above is used in both scenarios, allowing a paired comparison for statistical purposes. Three points in Table 2 are noteworthy.

First, the number of vehicle-hours sold by the SMSP is identical (519 of the available 600 vehicle-hours, or an 87% fleet utilisation rate) whether futures trading is allowed or not. This is because, in each timestep, vehicles are used if there is a customer with a willingness-to-pay *at that time* which exceeds the price, and they are not used if this is not the case. Customers' willingness-to-pay is, in this stylised model, independent of whether trading is allowed or not.

Second, consumer surplus is higher when the secondary exchange market is in operation. This is because vehicle-time slots are allocated on the basis of maximum willingness-to-pay rather than first-reserved/first-served.

Third, trades with an aggregate value of $1,891 are exchanged on the SEM through the course of an average simulated day, which results in the increase in consumer surplus of $81. More value is exchanged than the net increase in consumer surplus, and this is because the value of each trade is the total sum of money that changes hands, whereas the net change in consumer surplus from a trade is the difference in willingness-to-pay between the buyer and the seller.

<<Table 2 here>>

Table 2: Results from 250 Monte-Carlo simulations. Values are averages, standard deviations are in brackets.

Figure 1 shows the trading volume which is exchanged in each timestep. We see a rapid ramp-up in the beginning of the period, followed by a long decrease through to the end of the day. The simulation has a 'cold start, meaning that there are no reservations prior to time $t = 1$, and therefore no trades of reservations in the first timestep. In the first few timesteps there are therefore few people whose willingness-to-pay for a given vehicle-slot has changed from time $t = 1$. The decrease later on arises due to the limited duration of the simulation, such that as the end of the simulation is approached there are progressively fewer vehicle-time slots which remain possible candidates for trades.

<Figure 1 here>>

Figure 1: Number of vehicle-hours traded on the secondary-exchange market in each timestep. Error bars show ±1 standard deviation.

In the scenarios above, it was specified that there is a 5% probability that a customer i's willingness-to-pay in timeslot t for vehicle-time slot vu (WTP_{tvu}^{i}) changes in any given timestep increment. Figure 2 shows the results of a sensitivity analysis where this is allowed to vary, taking values [in addition to 5%] of 0%, 1%, 2.5%, 7.5%, 10%, 15%, 20% and 25%. We see that, in keeping with *a priori* expectations, greater volatility in people's willingness-to-pay is positively linked with trading volume on the secondary market. This is logical; gains from trading arise from customers' willingness-to-pay changing such that the person holding a given reservation no longer values it higher than other customers in the system.

<<Figure 2 here>>

Figure 2: Sensitivity analysis of the effect of varying volatility in willingness-to-pay on the number of vehicle-hours traded on the secondary-exchange market. Error bars show ±1 standard deviation.

5. Discussion and conclusions

This study shows that a secondary-exchange market in shared-mobility reservations would provide gains in economic efficiency relative to a market where trading is not possible, provided that customers' willingness-to-pay varies over time.

In the proposed mechanism there is a new revenue-positive role for the operator of the secondary-exchange market. There is also a role (which does not exist without a secondary market) for either small-scale or institutional 'investors' – people or entities who would reserve a shared-mobility vehicle with the sole intention of selling it on rather than using it themselves. They would be speculating that they will be able to find a customer willing to pay more than 'face value'. These investors are functionally similar to ticket scalpers, who acquire tickets to, for instance, sports events and then subsequently attempt to sell them later at a higher price. Interestingly, this activity has to a certain degree migrated in recent years away from physical transactions on street corners to online exchanges.

It is worth noting that the shared-mobility service provider may not wish to have a secondary futures market trading rights to use their services, and may attempt to prevent it from operating. At the other extreme, they may decide to operate the futures market themselves, which would provide it with additional revenue. It is likely that the possibility of market manipulation on behalf of 'investors' would be a concern; if this is the case this behaviour can be controlled to the desired degree by algorithms that would monitor reservation-making and trades to automatically identify patterns of manipulative behaviour. Alternatively, introducing a small penalty for cancelling reservations would deter investors from speculating on the shared-mobility futures.

The possibility of new types of outcomes from a secondary market in shared-mobility raises important public policy questions. The public does not necessarily have such a high degree of comfort with secondary-exchange markets that it is willing to allow an unregulated marketplace, particularly in one with the well-established public interests of safe and efficient mobility. Public institutions would also need to understand (and be comfortable with) how the proposed secondary-market system would work both in typical circumstances and at times when the transport network is under acute stress. Further, the public sector is likely to also be interested in the distributional (i.e. social equity) issues raised by a secondary-exchange mechanism. An example of public discomfort with dynamic pricing can be seen in the newly-emerging domain of real-time ride-sharing app services (e.g. Uber, Lyft, Sidecar, etc.). in many urban markets taxis traditionally operate according to fixed pricing structures. By contrast, the ride-sharing apps sometimes operate 'surge pricing'. For instance, during a snowstorm in New York City the cost of rides via one such service was reported to be eight times as expensive as the same rides during normal conditions. The service continued to operate on-demand, however, whereas it was reported to be difficult or impossible to find a traditional taxi during this weather event (Lowrey 2014). It is worth noting that ride-sharing app services have experienced sustained legal and regulatory challenges from public agencies that regulate traditional taxi services (California Public Utilities Commission 2012, 2013).

As with ride-sharing apps, the capacity and legal powers of public sector institutions to regulate a secondary-exchange market in shared-mobility is an open question. Further research is needed to identify such legal and institutional issues, as well as the implications of the various possible public/private relationships which are characterised by a range of types and intensities of interactions.

Mobility inherently has spatial features, and this would mean that the liquidity in the futures marketplace would be limited by customers' distaste for travelling to access a vehicle. Though we did not examine this aspect in detail in this paper, future research is needed to show that market liquidity is linked with customers' degree of willingness to travel to access a vehicle (following logic similar to that of Correia et al. 2013). Similarly, research is needed to expose the characteristic that the degree to which customers are flexible temporally (willing to adjust the timing of their usage pattern) is also associated with the degree of liquidity in the futures marketplace.

Choosing the price at which one wishes to bid to buy or sell reservations is a non-trivial task. Customers are likely to have limited information about other people's willingness-to-pay. As in many types of markets, there is a role for market intelligence – those with the best information on others' willingness-to-pay have an information advantage. Also, the market would operate continuously and market participants would have the opportunity to learn and adjust their bidding behaviour over time.

In situations where the willingness-to-pay of a buy bid materially exceeds the willingness-to-accept of a matching sell bid the OSEM can satisfy both the buy and sell bids and generate excess revenue. This revenue could be distributed to some combination of the actors in the system (buyer, seller, SMSP and OSEM), and how this is done would be subject to negotiated understandings. It would be expected that in general the terms of how such revenues are distributed would be determined by the relative market power of the actors.

This study evaluated a system based on fixed vehicle locations. If vehicles are free-floating (i.e. allowed to be used for one-way journeys), the operator cannot be certain about the distribution of vehicles available for customers to use in the future, and hence cannot offer guaranteed reservations. But, if the operator has predictive capacity that allow them to predict the probability distribution of possible spatial distribution of fleets at future points, they can use this to allow customers to make reservations. The operator could not guarantee the ability to meet the reservation, because they cannot know the future spatial distribution of the available fleet for certain, but they can know this to a probability and hence can offer the reservation with a probability. The operations of such a system must remain a matter for future research, and the same for the possibility of an operator in such a system charging variable rates according to how large a probability of meeting the reservation the customer wishes to have.

Finally, a key aspect of the secondary-market mechanism is that it provides liquidity. This means that people wishing to use the service benefit from a step-change in the reliability of being able to access the service, albeit at a dynamically-adjusting price. Such a market, with sufficient depth, would greatly reduce the possibility of being without a reservation when one is desired. Further research is needed to understand the precise implications of this step-change in reliability. This feature is likely to be highly-valued by prospective customers, and therefore can reasonably be expected to facilitate the overall growth of shared-mobility services.

References

Awasthi, A., Breuil, D., Chauhan, S.S., Parent, M., and Reveillere, T. (2007) *A Multicriteria Decision Making Approach for Carsharing Stations Selection*. Journal of Decision Systems, p.57-78.

Barth, M., and Todd, M. (1999) *Simulation model performance analysis of a multiple station shared vehicle system*, Transportation Research Part C, 7 (4), p.237-259.

California Public Utilities Commission (2012) *CPUS cease and desist letters sent to Sidecar and Lyft*. Accessed 13 January 2014 via: http://www.cpuc.ca.gov/NR/rdonlyres/03851232-DD84-47C1-B134-D90C8D15D3B7/0/CeaseandDesistLetters.pdf

California Public Utilities Commission (2013) *CPUC establishes rules for transportation network companies*. Accessed 13 January 2014 via: http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M077/K132/77132276.PDF

Cervero, R. (2003), *City CarShare: First-year travel demand impacts*, paper presented at the 82nd Annual Meeting of the Transportation Research Board, Washington DC.

Ceschin, F., and Vezzoli, C. (2010) *The role of public policy in stimulating radical environmental impact reduction in the automotive sector: the need to focus on product-service system innovation*. Int. J. Automotive Technology and Management. 10(3), p.321-341.

Ciari, F., Schuessler, N., Axhausen, K.W. (2013) *Estimation of Carsharing Demand Using an Activity-Based Microsimulation Approach: Model Discussion and Some Results.* International Journal of Sustainable Transportation. 7(1), p.70-84.

Correia, G.C., Jorge, D.R., Antunes, D.M. (2013) *The added-value of accounting for users' flexibility and information on the potential of a station-based one-way carsharing system: An application in Lisbon, Portugal*. Journal of Intelligent Transportation Systems: Technology, Planning and Operations, DOI:10.1080/15472450.2013.836928.

d'Welles, J. (1951), '*A propos de circulation urbaine*', Urbanisme Revue Francaise p. 56.

Donada, C. (2013) *Electric mobility calls for new strategic tools and paradigm for automakers*. Int. J. Automotive Technology and Management. 13(2), p.167-182.

Firnkorn, J. (2012) *Triangulation of two methods for measuring the impacts of a free-floating carsharing scheme in Germany*. Transportation Research Part A, p.1654-1672.

Firnkorn, J., and Muller, M. (2012) *Selling mobility instead of cars: New business strategies of automakers and impacts on private vehicle holdings*. Business strategy and the environment, p.264-280.

Fishman, L. and Wabe, S. J. (1967), *'Restructuring the form of car ownership: A proposed solution to the problem of the motor car in the United Kingdom'*, Transportation Research UK 3(4), 429-442.

Happel, S.K. and Jennings, M.J. (2002) *Creating a futures market for major events tickets: Problems and prospects*. Cato Journal, 21(3), p.443-461.

Harmer, C. and Cairns, S. (2012) *Carplus annual survey of car clubs 2011/12: England and Wales*. Prepared for Carplus Trust.

Jorge, D. And Correia, G. (2013) *Carsharing system demand estimation and defined operations: a literature review*. European Journal of Transport and Infrastructure Research, p.201-220.

Kek, A.G.H., Cheu, R.L., Meng, Q., and Fung, C.H. (2009) *A decision support system for vehicle relocation operations in carsharing systems*. Transportation Research Part E: Logistics and Transportation Review, p.149-158.

Lowrey, A. (2014) *Is User's Surge-Pricing an Example of High-Tech Gouging?* New York Times, 10 January 2014.

Martin, E.W. and Shaheen, S. (2010) *Greenhouse Gas Emission Impacts of Carsharing in North America.* Mineta Transportation Institute, San Jose State University.

O'Brien, O., Cheshire, J., Batty, M. (2013) *Mining bicycle sharing data for generating insights into sustainable transport systems*. Journal of Transport Geography. DOI: 10.1016/j.jtrangeo.2013.06.007

Pavone, M., Smith, S.L., Frazzoli, E., and Rus, D. (2012) *Robotic Load Balancing for Mobility-on-Demand Systems*. Journal of Robotics Research, p.839-854.

Rabbitt, N., Ghosh, B. (2013) *A study of feasibility and potential benefits of organised car sharing in Irelan*d. Transportation Research Part D, p.49-58.

Shaheen, S., and Cohen, A.P. (2013) *Carsharing and Personal Vehicle Services: Worldwide Market Developments and Emerging Trends*. International Journal of Sustainable Transportation, p.5-34.

Shaheen, S., Mallery, M.A., Kingsley, K.J. (2013) *Personal vehicle sharing services in North America*. Research in Transportation Business and Management, p.71-81.

Smeed, R. (1964), *'Road pricing: The economic and technical possibilities'*. Her Majesty's Stationery Office.

Smith, S.L., Pavone, M., Schwager, M., Frazzoli, E., and Rus, D. (2013) *Rebalancing the Rebalancers: Optimally Routing Vehicles and Drivers in Mobility-on-Demand Systems*. Paper presented at American Control Conference, annual conference of the American Automatic Control Council, Washington DC, 17-19 June.

Swofford, J.L. (1999) *Arbitrage, Speculation, and Public Policy Towards Ticket Scalping*. Public Finance Review, 27(5), p.531-540.

Williams, A.T. (2004) *Do anti-ticket scalping laws make a difference?*. Managerial and Decisions Economics, 15(5), p.503-509.

Zhou, S. (2012) *Dynamic incentive scheme for rental vehicle fleet management*. M.Eng thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science.

Tables and Figures

Column A	Column B	Column C	Column D
Unit price per vehicle-time slots	Fixed cost of \$2		
Timestep	$t = 1$	$t = 2$	$t = 2$
Willingness-to-pay of customers *i* and *j* for vehicle-time slot vt_u	$WTP^i_{1vu} = \$5$ $WTP^j_{1vu} = \$0$	$WTP^i_{2vu} = \$0$ $WTP^j_{2vu} = \$8$	$WTP^i_{2vu} = \$5$ $WTP^j_{2vu} = \$8$
Outcome when no trading possible	Customer i makes initial reservation in timestep	Customer i cancels reservation Customer j then makes the reservation	Customer i retains reservation Customer j cannot access the vehicle despite being willing to pay more for it
Outcome when secondary-exchange market in operation (i.e. trades possible)	Customer i makes initial reservation in timestep	Customer i cancels reservation Customer j then makes the reservation	Customer i sells reservation to customer j. Price at which trade is transacted between customers i and j is between \$5 and \$8 Welfare of both customers i and j improves from making the trade

Table 1: Hypothetical example of the impact of introducing a secondary-exchange market

	Scenario #1: No trades allowed	Scenario #2: Secondary-exchange market in operation
Number of vehicle-hours sold by SMSP	519 (12)	519 (12)
Aggregate consumer surplus	$2,606 ($107)	$2,687 ($106)
Number of vehicle-hours traded on secondary exchange	--	536 (39)
Aggregate value traded on secondary-exchange	--	$1,891 ($184)

Table 2: Results from 250 Monte-Carlo simulations. Values are averages, standard deviations are in brackets.

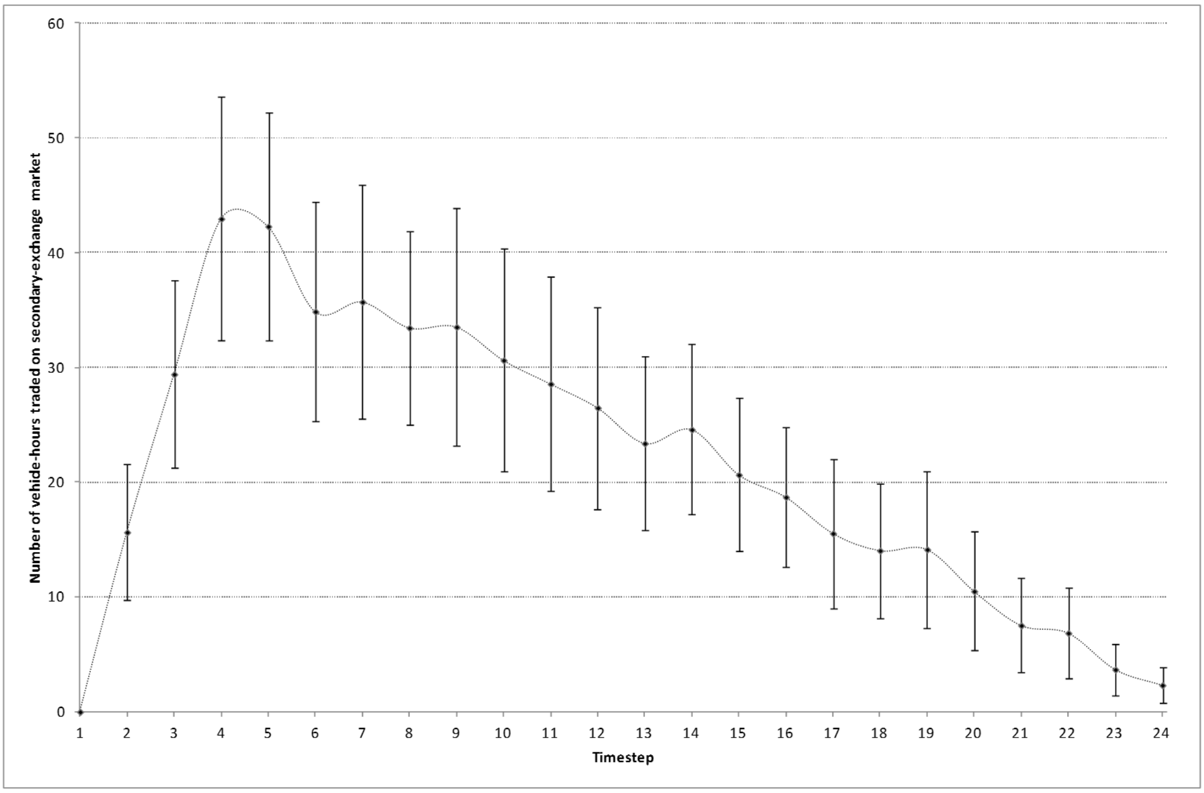

Figure 3: Number of vehicle-hours traded on the secondary-exchange market in each timestep. Error bars show ±1 standard deviation.

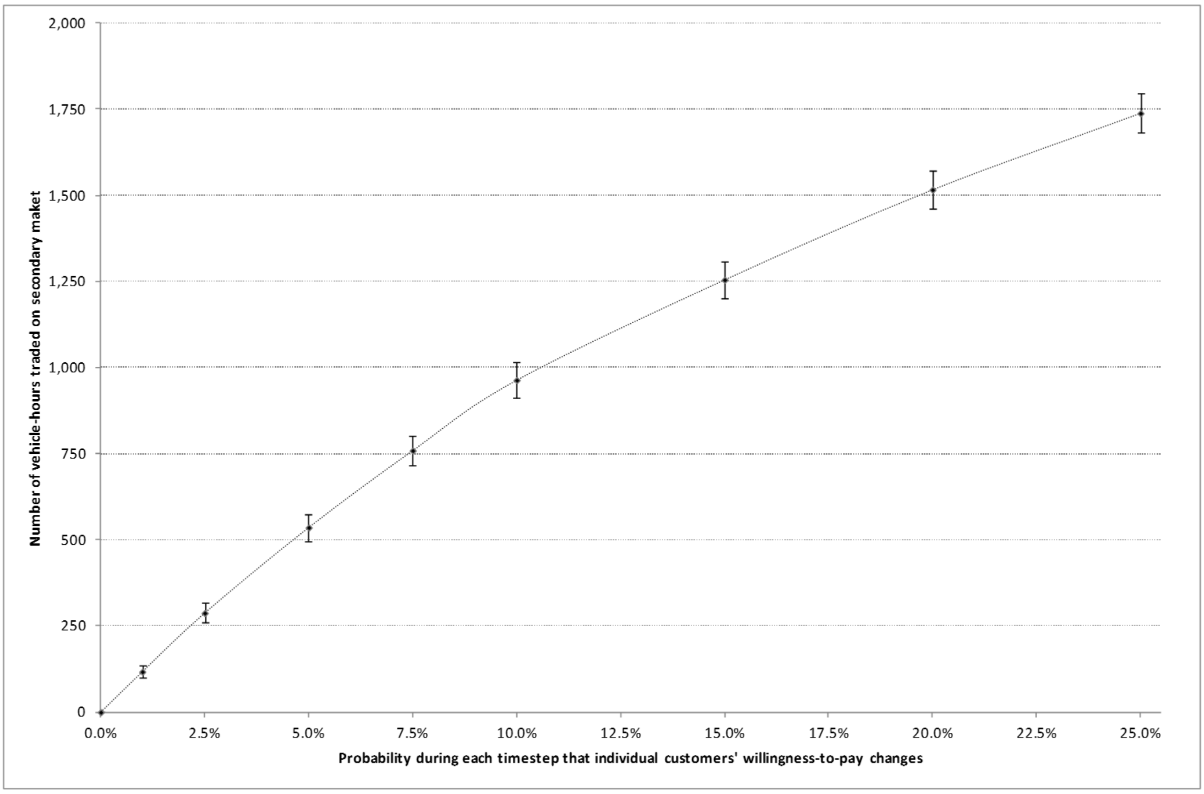

Figure 4: Sensitivity analysis of the effect of varying volatility in willingness-to-pay on the number of vehicle-hours traded on the secondary-exchange market. Error bars show ±1 standard deviation.