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Pushing towards shared mobility

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ABSTRACT

This paper provides a theoretical argument for preferential treatment of shared vehicles (SV) over private ones by municipal parking authorities. When all parked vehicles are treated equally, multiple equilibria may exist: (i) a "private" one, in which travellers are hesitant to switch to SV because the latter are hard to find, and (ii) a "shared" equilibrium, in which travellers use shared mobility because the city is saturated with vacant SV. The latter equilibrium, if it exists, is shown to yield higher welfare. Municipal parking discounts for SV reduce the amount of investment required for a "big push" towards the shared equilibrium, or even make it the only equilibrium.

1. Introduction

Commercial vehicle sharing (i.e. per-minute or per-hour vehicle rental via a mobile app, SV henceforth) holds great promise for the future of ground transportation. According to back-of-envelope calculation by Zakharenko (2023), in a large city, sharing cars enables the economy to satisfy the same transportation demand with one-sixth the number of vehicles and one-eighth of the parking space, dramatically reducing the capital costs of the industry. Jochem et al. (2020), by analysing survey data from multiple European cities, offer an even more optimistic conclusion that each free-floating SV can replace between 7 and 18 private vehicles, depending on the city. Jochem et al. (2020) also provide a substantial number of references to other studies measuring this ratio in various cities of the world.

While the SV technology has gained some momentum in many places, primarily in large cities of Europe, it still remains a fringe transportation option for most people in the world. For example in the U.S., the largest provider of round-trip SV (i.e. of vehicles that have to be returned to the same location) had only 12 000 vehicles in 2019[1]; the largest provider of free-floating SV (i.e. of those that can be dropped off anywhere within a certain area) has only 1000 vehicles and serves only a handful of cities.[2]

Shared vehicles, while serving a larger number of people daily compared to private ones, still spend a significant amount of time parked. Zakharenko (2023) estimates that in Moscow (Russia), a shared car is available for booking and parked 70% of the time. The success of shared mobility is therefore highly sensitive to municipal parking policy. For example Car2Go, a prominent SV provider of its time, chose to discontinue its service to 80,000 customers in Toronto (Canada) following the introduction of parking fees by the city hall.[3] The Carsharing Association, an organisation that promotes the interests of SV providers, emphasises simplified parking for SV (and also complicated parking for private vehicles) in the first three out of five suggested policies in its front-page policy proposal document.[4]

While it is obvious that preferential parking policies for SV will increase success of this particular industry, it is less clear whether they benefit the society as a whole or simply contribute to shared vehicles displacing other methods of transportation. An explicit discussion of this dilemma could not be found, neither in academic literature nor among relevant policy documents. The lack of consensus about socially optimal policy results in large heterogeneity of existing regulation practices. For example, the city of Los Angeles de-facto adopts a "carsharing as a business" philosophy (as defined in Shaheen et al. (2010), Table 4): its parking fees for shared automobiles are explicitly tied to foregone parking meter earnings.[5] In sharp contrast, San Francisco follows the

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[1] https://en.wikipedia.org/wiki/Zipcar.
[2] "GIG Car Share Thanking Members for Big Win with Big Expansion News", prnewswire.com, December 3, 2020.
[3] "Car2Go to shut down in Toronto, blaming new city rules", CBC News, May 24, 2018.
[4] "Five Foundational Carsharing Policies for Any City", carsharing.org, accessed on 18.05.2023.
[5] LA municipal code, SEC. 80.58.1 (e).

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"Carsharing as an Environmental Benefit" philosophy and requires developers to provide a certain amount of free parking spaces to qualified SV providers.[6,7] Shaheen et al. (2010) provide an early review of parking policy for SV by various governments.

The aim of this paper is to fill the theoretical gap in optimal SV parking regulation using a model of urban transportation market. The paper offers a theoretical analysis of how people with travel demand (*travellers* henceforth) make their choice between private and shared vehicles. Vehicle sharing allows to meet the same transportation demand with fewer vehicles and less parking space, but requires travellers to search for a vehicle before use. The cost of search depends on the density of vacant SV across space, which in turn depends on how many of other travellers choose shared mobility. Thus, vehicle sharing is a coordination problem with potential multiple equilibria. In the "private" equilibrium, the number of vehicles equals the number of travellers, which results in high costs of transportation (vehicle capital costs and parking), but allows to always have an available vehicle nearby. The "shared" equilibrium reduces the capital costs of transportation industry but introduces frictions of vehicle search. The model developed in this paper demonstrates that, when the shared equilibrium exists under a non-discriminatory parking policy, it results in a higher social welfare.

These results imply that the economy can get trapped in a bad "private" equilibrium, where travellers hoard vehicles due to expected difficulty in finding alternatives. Theoretically, transition to the better shared equilibrium can be achieved by a massive private investment (the "big push", cf. Murphy et al. (1989) for a theoretical discussion). However, securing the necessary venture investment on such a scale could hinder this transition. This paper shows that a local government parking policy favouring shared vehicles can push the economy towards the better equilibrium: such preferential treatment reduces the amount of investment required to make SV operations profitable. If parking discounts to SV are sufficiently high, the private equilibrium becomes unstable: even a small initial fleet of SV is profitable, so the market can gradually transition to the shared equilibrium.

Despite abundant literature on shared mobility in the fields of Management, Transportation and others, the attention to optimal government regulation of SV has so far been marginal. For example Nansubuga and Kowalkowski (2021), a review of nearly 200 papers on shared mobility, does discuss at length the hurdles limiting its success, but omits the municipal parking policy from the discussion. Besides the above mentioned Shaheen et al. (2010), Balac et al. (2017) simulate an SV market under various pricing schedules for *non-shared* vehicles, and Carrese et al. (2020) develop an algorithm to select locations of dedicated SV parking. None of these papers consider social welfare, thus offering limited normative insight.

A substantial body of economics literature on optimal parking regulations also does not address shared vehicles; for example Inci (2015), the most recent literature review in the field, implicitly assumes throughout the paper that each parked vehicle is used exclusively by a specific individual. The same assumption is made in existing theoretical studies of preferential parking policy, e.g. Zakharenko (2020) or Jakob and Menendez (2020). While some studies have discussed parking management for futuristic autonomous shared vehicles (e.g. Winter et al. (2021)), no study could be found that theoretically analyses optimal parking policy for existing non-autonomous SV services.

The general policy advice in the parking economics literature, e.g. in Zakharenko (2016), is that every parked vehicle should be charged the congestion externality it causes for other vehicles searching for parking. van Ommeren et al. (2021) apply this methodology to calculate optimal parking rates in Melbourne. Since the instantaneous externality of a parked vehicle is independent of whether it is private or shared, this approach suggests that per-minute parking rates should be uniform for all vehicles. This paper presents a theoretical counterargument, suggesting that endogenous choices between shared and private vehicles can result in multiple equilibria, and that parking discounts for shared vehicles can push the economy to the better equilibrium.

Because a larger number of users helps to increase density of vacant SV and thus attract even more users, this paper contributes to the literature on scale economies in transportation. A well-known Mohring effect (Mohring, 1972) is an observation that a larger number of users of mass transit allows to increase frequency of service, attracting even more users. Fielbaum et al. (2023) emphasise a similar effect in ridepooling services.

This paper also contributes to the economics literature on repeated matching. In transportation economics, numerous studies offered models of one-sided repeated matching, i.e. where the supplier, usually a taxi or ridehailing driver, is long-lived and matched repeatedly, while passengers are short-lived and matched once. Examples include Lagos (2000), Buchholz (2021) and Zakharenko (2023). This paper is probably the first paper in the field to analyse two-sided repeated matching, i.e. where both demand and supply side seek to be matched repeatedly. Two-sided repeated matching models have been proposed in other contexts (e.g. marriage and re-marriage, as in Kadam and Kotowski (2018)). These models typically assume that both sides are willing to be matched continuously and dissolve matches only to find a better match. In contrast, this paper makes this assumption only for the supply side, i.e. operators of shared vehicles; the demand side only needs to be matched to vehicles occasionally, rather than continuously.

2. The model

The model is based on that in Zakharenko (2023), but with some modifications. This is a dynamic model with infinite time horizon, where all parties do not discount the future. The reason for non-discounting is high frequency of transactions, e.g. each vehicle being used multiple times per day. It is implausible to assume, for example, that profit earned by vehicle operator in the evening has any lower value than profit in the morning. The objective of SV operators is therefore the average profit per unit of time, while that of travellers is minimisation of the average travel cost per trip.

The geographic space in the model consists of two infinitely long parallel *streets* with symmetric travel demand between them. Travellers have a specific origin location on the origin street and destination location on the destination street, for each trip. They can walk along the origin street to search for an SV, but require a vehicle to reach the destination street. Vehicles can be private (i.e. always used by the same traveller) or shared (available for hire by anyone when not in use). To simplify the analysis, we will assume that vehicles of both types can be dropped off exactly at the destination point and no further walking costs are incurred upon arrival. In case of shared vehicles, this assumption corresponds to the free-floating mode of service. Fig. 1 illustrates travel demand by an SV user. All results of the model are also applicable to a single street, with round-trip travel demand, such that the destination location is on the same street. We assume the destinations of inbound trips are distributed uniformly along each street, such that an exogenous mass L of travellers arrive per unit of street length, per unit of time.[8]

Unlike Zakharenko (2023) who considers one-time trip demand, here we assume that all travellers have recurrent demand, i.e. will demand another trip, originating from the location of previous arrival,

[6] San Francisco planning code, Sec. 166.

[7] Not surprisingly, the success of carsharing in San Francisco far exceeds that in Los Angeles despite much smaller population. For example, Zipcar has about 200 carsharing stations in the former, versus about 60 in the latter. This estimate is based on count of Google Maps results for "Zipcar San Francisco" and "Zipcar Los Angeles", respectively.

[8] All notation used in the model is catalogued in Table 1.

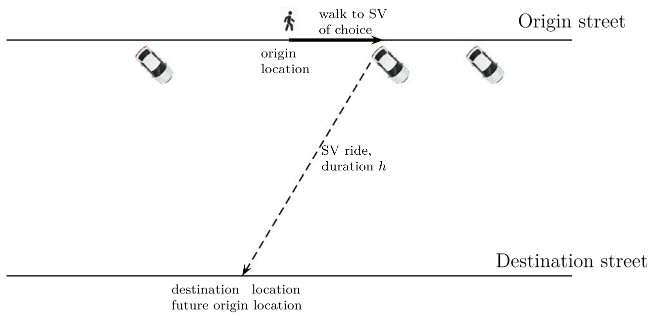

Fig. 1. Illustration of a typical trip. Vehicle image courtesy of Macrovector/Freepik.

Table 1
Notational glossary.

Notation	Description	Units
C	Social cost of transportation (excl. vehicle movement)	\$/h
c_0	Cost of private vehicle use	\$/h/veh[a]
c_1	Excess cost of shared vehicle use	\$/h/veh[a]
g	Social cost of parking	\$/h/veh
$g_r(g_v)$	Parking tariff for reserved (vacant) vehicles	\$/h/veh
h	Duration of travel	h
L	Travel demand	per[b]/h/km S[c]
p	Shared vehicle trip fare	\$
q	Poisson rate of SV reservation by walkers	1/h
t	Duration of stay at destination	h
w	Cost of walking	\$/h
λ	Share of travellers using shared mobility	
μ	Density of vacant vehicles	veh/km S
π	SV operator profit	\$/h/km S
τ	Mean duration of stay at destination	h
ϕ	Vehicle standing cost	\$/h/veh

[a] Per vehicle or number of vehicles.
[b] Number of persons.
[c] km of street space.

after some period of stay. For mathematical tractability of the results that follow, we will assume that the duration of stay t of a traveller in each zone is distributed exponentially with mean τ. The assumption of stochastic traveller departure process implies that the departure process of vacant SV is also stochastic and, importantly, independent of trip history of these vehicles. Given these assumptions, the origins of outbound trips are also distributed uniformly with density L, per km of street space per hour.

Every ride between streets takes h units of time, which may also include cruising for parking at the destination.[9] Vehicle costs include, per unit of time: capital cost ϕ at all times; social cost of parking g, when the vehicle is vacant or reserved; cost of use c_0 when in transit.

We also assume that use of shared vehicles is more costly, with additional cost of $c_1 > 0$ per unit of time. Bösch et al. (2018) argue that such excess cost may be due to the need to clean shared vehicles more often; an additional cause may be moral hazard on the part of travellers, i.e. their lower level of care about vehicles they do not own. At the same time, we assume the excess cost of an SV ride is not too high:

$$c_1 h < (g + \phi)\tau, \tag{1}$$

i.e. it does not exceed the expected social cost of a private vehicle parking session.

[9] A more general model could assume a distribution of travel times with mean h. Such generalisation can be shown to have no effect on all results in the model, particularly on the chosen mode of vehicle use. It is also immaterial how accurately travellers can predict their time in transit. Assuming uniform travel time helps to focus on key results of the model.

Denote by λ the endogenous share of travellers who use shared mobility, so the share of private vehicle users is $1 - \lambda$. The latter group always has a vehicle at hand and thus never has to incur the search cost.

Users of SV release their vehicle at the end of each trip, and search again at the beginning of the next trip. With a positive probability, the previously released vehicle remains available. In such cases, since the next trip origin is the same as the previous trip destination (and also the location of parking of previously released vehicle), the traveller can avoid any search cost. With the remaining probability, the previously used vehicle is no longer available and a new one has to be found. In the latter case, almost surely, another vehicle is located some distance away, and the traveller has to walk to the vehicle, incurring a positive search cost. Denote by w the disutility of walking, per unit of time/distance. The vehicle has to be *reserved* while a traveller is walking towards it.

Among travellers who previously released a vehicle, those who return to the same vehicle are referred to as *returnees*, while those who search for another one are *walkers*. Denote by μ the endogenous density of vacant vehicles. Assuming unitary walking speed, the expected walking distance/time to the nearest vacant vehicle is $\frac{1}{2\mu}$; the coefficient 2 is due to two available directions of search from the origin location.

For a representative vacant vehicle, denote by q the endogenous booking rate by walkers.

3. Social optimum

What are the socially optimal release decision λ and vacant vehicle density μ? Because the number of passenger-kilometers travelled (and therefore the number of vehicles in transit) is assumed exogenous, maximisation of social welfare amounts to minimisation of transportation costs. For private vehicles, such cost is $(c_0 + \phi)h$ per movement event and $(g + \phi)\tau$, in expectation, per parking event. Vehicles enter each of these two modes at rate $(1 - \lambda)L$ per hour per km of street space.

Shared vehicles fall into one of three categories:

- Vacant: density μ per km of street space. The social cost of every such vehicle is $g + \phi$ (parking, vehicle capital cost) per hour.
- Vehicles reserved by the walkers. The flow of travellers who use shared mobility is λL, per Little's law. It is socially optimal that travellers always walk to the most proximate vehicle. For a traveller who stayed t units of time before the next trip, the probability that the previous vehicle is still vacant is $\exp(-qt)$. In this case, the traveller is a returnee and zero walking time/cost is incurred. With the remaining probability $1-\exp(-qt)$, the traveller becomes a walker. Given exponential distribution of t with p.d.f. $\frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)$, the flow of new walkers is
$$\lambda L \int_{t=0}^{\infty} (1 - \exp(-qt)) \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) \mathrm{d}t = \lambda L \frac{q\tau}{1 + q\tau}.$$
As discussed at the end of Section 2, the expected walking distance (and time) is $\frac{1}{2\mu}$. The associated social cost per unit of time is $\phi + g + w$ (vehicle capital cost, parking, walking).
- In transit: cost $(c_0 + c_1 + \phi)h$ per vehicle per trip. The flow of new trips initiated is λL.

Given this analysis, the total social cost of transportation, per hour per km of street space, is given by

$$C \equiv (c_0 + \phi + \lambda c_1)Lh + (g + \phi)(L(1 - \lambda)\tau + \mu) + (g + \phi + w)\lambda L \frac{q\tau}{1 + q\tau} \frac{1}{2\mu}. \tag{2}$$

The equilibrium value of q is found as follows: it is equal to the flow of newly emerging walkers, $\lambda L \frac{q\tau}{1+q\tau}$, divided by the density of vacant vehicles μ. Thus, the value of q is determined from the following equation:

$$q \equiv \lambda L \frac{q\tau}{1 + q\tau} \frac{1}{\mu}. \tag{3}$$

One solution to this equation is $q = 0$; it corresponds to the scenario where travellers who release their vehicles always return to the same ones. We will refer to such state as *quasi-shared*, because it essentially makes all vehicles private: even if they are in the vacant status, they will not be demanded by anyone except their previous user. This means that, in the quasi-shared economy, the density of vacant vehicles should be no less than the flow of SV users times their expected duration of stay, $\mu \geq \lambda L\tau$.

Replacing $q = 0$ into (2) trivially yields

$$C = (c_0 + \phi + \lambda c_1)Lh + (g + \phi)(L(1-\lambda)\tau + \mu).$$

Minimisation of this cost, subject to the above inequality constraint on μ, yields the solution of $\mu = \lambda = 0$, i.e. purely private transportation. Intuitively, excess vehicle supply $\mu > \lambda L\tau$ can never be optimal. One vehicle per traveller $\mu = \lambda L\tau$ implies that the parking cost $(g+\phi)(L(1-\lambda)\tau + \mu)$ does not depend on fraction of travellers λ who are (quasi) sharing. At the same time, (quasi) sharing incurs higher running cost relative to private vehicles, hence cannot be optimal as well.

Can the society do better than that? When $q > 0$, the solution to (3) is

$$q = \frac{\lambda L}{\mu} - \frac{1}{\tau}, \tag{4}$$

which is only possible when

$$\mu < \lambda L\tau. \tag{5}$$

Intuitively, q is equal to the ratio of SV users flow λL to vacant SV density μ, minus the rate of SV booking by the last user (the returnee) $\frac{1}{\tau}$. Given (4), the problem of minimisation of (2) is $\min_{\lambda,\mu} C(\lambda,\mu)$, where

$$C(\lambda,\mu) \equiv (c_0 + \phi + \lambda c_1)Lh + (g+\phi)(L(1-\lambda)\tau + \mu) + \frac{g+\phi+w}{2}\max\left\{\frac{\lambda L}{\mu} - \frac{1}{\tau}, 0\right\}. \tag{6}$$

When (5) holds, $\frac{dC}{d\lambda}$ equals zero when $\mu = \bar{\mu}$ such that

$$\bar{\mu} \equiv \frac{1}{2}\frac{g+\phi+w}{(g+\phi)\tau - c_1 h}, \tag{7}$$

which is well-defined thanks to (1). Then, given a value of μ, the optimal share of SV users λ is as follows. When $\mu < \bar{\mu}$, it is optimal to have at most one traveller per vehicle, i.e. to quasi-share, $\lambda = \min\left\{\frac{\mu}{L\tau}, 1\right\}$. When $\mu > \bar{\mu}$, it is optimal that all travellers use shared mobility, $\lambda = 1$. Note that truly shared mobility, where (5) holds, can be locally optimal only if

$$L\tau > \bar{\mu}, \tag{8}$$

i.e. the density of demand L and traveller duration of stay τ are high enough, while walking cost w or excess SV use cost c_1 are low enough.

Given $\lambda \in [0,1]$, the optimal vacant SV density μ is the larger of the two values, $\mu = \lambda L\tau$ and the one defined by

$$\frac{dC}{d\mu} = g + \phi - \frac{g+\phi+w}{2}\frac{\lambda L}{\mu^2} = 0. \tag{9}$$

The former quantity is larger if and only if $\mu \leq \frac{1}{2}\frac{g+\phi+w}{(g+\phi)\tau}$; this threshold is always below $\bar{\mu}$. Fig. 2 illustrates the social cost of transportation, as functions of endogenous parameters λ and μ.

As is evident from Fig. 2, there are two possible local optima. The private local optimum $\lambda = \mu = 0$ always exists. There can also exist a shared local optimum with $\lambda = 1$ and $\mu = \mu^*$, with the latter defined by (cf. (9))

$$\mu^* = \sqrt{\frac{L}{2}\frac{g+\phi+w}{g+\phi}}. \tag{10}$$

The shared local optimum can exist if and only if $\bar{\mu} < \mu^*$, which is equivalent to

$$c_1 h < (g+\phi)\tau - \sqrt{\frac{(g+\phi+w)(g+\phi)}{2L}}. \tag{11}$$

Note that when the right-hand side of (11) is positive, μ^* and $\lambda = 1$ also satisfy (5), which also means that (8) is satisfied.

If both local minima exist, the global social cost minimum is determined by comparison of $C(0,0)$ (private local minimum) and $C(1,\mu^*)$ (shared local minimum). The latter delivers lower social cost if and only if

$$c_1 h < \left(\sqrt{(g+\phi)\tau} - \sqrt{\frac{g+\phi+w}{2L\tau}}\right)^2. \tag{12}$$

Note that if $c_1 = 0$ (i.e. there is no excess cost of SV use) and shared local optimum exists ((11) holds), it is necessarily the global social optimum ((12) also holds).

To summarise, the social cost function (6) may have multiple local minima. One local optimum is a pure private-vehicle economy. If demand L and parking duration τ are sufficiently high while walking cost w and excess SV use cost $c_1 h$ are sufficiently low, there is also a local optimum where all travellers use shared vehicles, and $\mu = \mu^\star$. The existence of multiple local optima is due to problems of coordination: when few travellers use shared mobility, there are few vehicles available for hire, finding a vacant SV is difficult, which makes it optimal to use private vehicles. When $c_1 h$ is low enough and shared local optimum exists, it is also the global optimum, regardless of other model parameters.

4. Market equilibrium and optimal policies

This section studies decentralised equilibrium with provision of SV by a single operator, and government policies that help to achieve the global optimum. The focus on a single operator is due to three reasons: (i) empirically, most cities indeed have at most one SV operator with non-negligible market share; (ii) this paper focuses on the conditions for the survival of the SV industry — the monopoly power maximises the chance of such survival; (iii) the monopoly assumption simplifies the mathematical model. We will focus on the case with sufficient density of travel demand for SV operations to be viable, i.e. when (11) is true.

The government can regulate the market by varying fees for parked shared vehicles; denote by g_r the parking rate for reserved vehicles, and by g_v the rate for vacant vehicles. We will assume that the parking fee for private vehicles is equal to its social cost g.[10]

4.1. SV demand

The travellers decide whether to use private or shared mobility. Define by the *traveller cycle* the period of time from the end of the previous traveller trip until the end of the next traveller trip. When using a private vehicle, the expected cost of a traveller cycle is (cf. Section 3) $(c_0 + \phi)h + (g+\phi)\tau$. When using shared mobility, the cost per traveller cycle includes the monetary cost denoted p, as well as the walking cost. The latter is the product of the probability of having to search for a new vehicle (cf. Section 3) $\frac{q\tau}{1+q\tau}$, the expected walking duration $\frac{1}{2\mu}$, and walking cost w. Thus, the participation constraint for joining shared mobility is

$$p + \frac{q\tau}{1+q\tau}\frac{w}{2\mu} \leq (c_0+\phi)h + (g+\phi)\tau. \tag{13}$$

This constraint serves as the upper bound on per-trip operator price p. Since we assume a monopolised SV market, the operator will extract the consumer surplus entirely, (13) holds as an equality, which uniquely defines the operator revenue per trip p.

[10] If the parking rate for reserved SV, g_r, is sufficiently lower than g, travellers may be incentivised to hold a shared vehicle continuously for private use, instead of using their own vehicle. Such strategy obviously prevents the vehicle from being shared, and therefore defeats the purpose of SV parking discounts. To mitigate the problem, reduced parking rate g_r could apply only if the vehicle was previously vacant, rather than used by the same traveller.

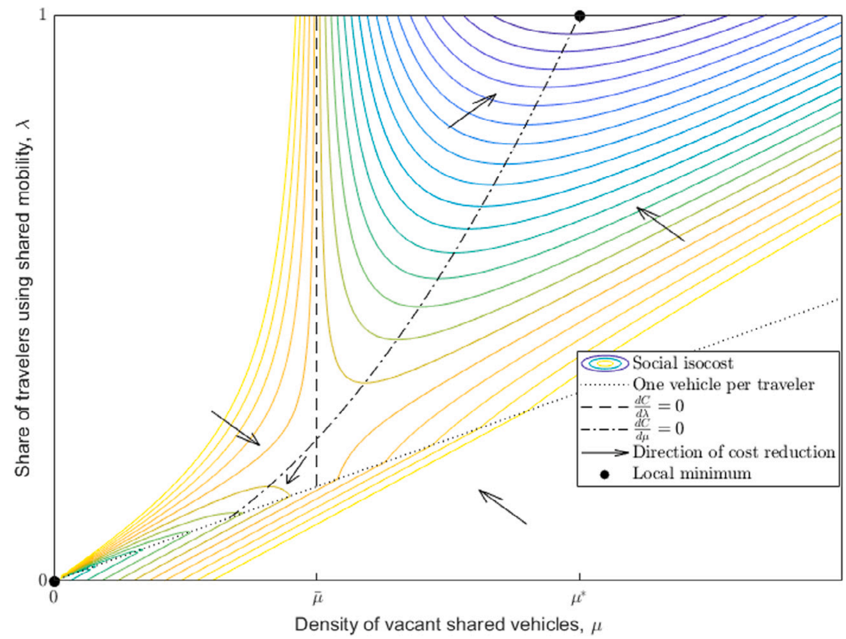

Fig. 2. Social cost of transportation as functions of SV density and traveller decisions.

4.2. SV supply

Define by *vehicle cycle* the time from the end of the previous vehicle trip until the end of the next trip. Vehicle cycle coincides with traveller cycle when there is private mobility, and each vehicle is attached to a traveller. Vehicle cycle may be shorter than traveller cycle when vehicles are shared. The SV cycle consists of three phases: vacancy, (possible) reservation, and use.

The SV operator costs per vehicle cycle include (cf. Section 3):

- The cost of vacancy is $\phi + g_v$ per hour. As the rate of vacant vehicle booking is $\frac{1}{\tau}$ by the last traveller (the returnee) and q by the walkers, the expected vacancy duration is $\frac{1}{\frac{1}{\tau}+q} = \frac{\tau}{1+q\tau}$.
- The cost of reservation is $\phi + g_r$ per hour. The probability that the vehicle was booked by a walker and has to be reserved for a positive amount of time is (cf. Section 3) $\frac{q\tau}{1+q\tau}$; the expected duration of such reservation is $\frac{1}{2\mu}$.
- The cost of vehicle movement: $(c_0 + c_1 + \phi)h$.

The revenue per vehicle cycle p is defined by (13) held with equality; the flow of trips/cycles initiated is λL, per hour per km of street space. Therefore, the flow of SV operator profit can be defined by

$$\pi = \lambda L \left[(g+\phi)\tau - (g_v+\phi)\frac{\tau}{1+q\tau} - \frac{g_r+\phi+w}{2\mu}\frac{q\tau}{1+q\tau} - c_1 h \right]. \tag{14}$$

In a quasi-shared case $q = 0$, profit simplifies to $\pi = \lambda L \left[(g-g_v)\tau - c_1 h \right]$. Profit does not depend on reservation parking rate g_r, as in such quasi-shared state, travellers repeatedly use the same vehicle and never have to reserve vehicles for the walk towards them. Profit does depend on vacant SV parking rate g_v, as vehicles are formally vacant while not in use. Without parking discounts ($g_v = g$), the profit is necessarily negative, as SV operators incur the same parking costs as users of private vehicles, but higher movement costs. SV operations become profitable if parking of vacant SV is sufficiently subsidised:

$$g_v \le g - \frac{c_1 h}{\tau}. \tag{15}$$

In a truly shared state (cf. (4)) $q = \frac{\lambda L}{\mu} - \frac{1}{\tau} > 0$, profit (14) becomes (cf. (6))

$$\pi = \lambda L \left[(g+\phi)\tau - c_1 h \right] - (g_v+\phi)\mu - \frac{g_r+\phi+w}{2}\left(\frac{\lambda L}{\mu} - \frac{1}{\tau}\right). \tag{16}$$

Suppose the SV operator has control over supply μ, and can also gradually adjust demand λ by setting the price p marginally below the participation constraint (13). Which combination of λ, μ maximises the operator profit?

Given a value of μ, profit-maximising choice of λ depends on comparison of μ to a threshold that equates $\frac{d\pi}{d\lambda}$ to zero (cf. (7)), $\bar{\mu}(g_r) \equiv \frac{g_r+\phi+w}{2[(g+\phi)\tau - c_1 h]}$. When $\mu < \bar{\mu}(g_r)$, quasi-sharing is optimal: $\lambda = \min\left\{\frac{\mu}{L\tau}, 1\right\}$. When $\mu > \bar{\mu}(g_r)$, it becomes optimal that all travellers join shared mobility, $\lambda = 1$. Parking discounts for reserved SV, i.e. lower g_r, reduce the threshold for μ when vehicles become truly shared. This is because such discounts reduce the cost of search for vacant vehicles, which is positive when there are multiple users per vehicle.

Given the value of λ, profit-maximising μ is the larger of $\mu = \lambda L\tau$ and the value defined by (cf. (9))

$$\frac{d\pi}{d\mu} = -(g_v+\phi) + \frac{g_r+\phi+w}{2}\frac{\lambda L}{\mu^2} = 0. \tag{17}$$

The latter value is greater when $\mu \ge \frac{1}{2\tau}\frac{g_r+\phi+w}{g_v+\phi}$. Profit-maximising μ coincides with socially optimal when there are no parking discounts ($g_r = g_v = g$). It decreases with g_v (meaning that lowered cost of vacancy g_v increases vacant SV supply) and increases with g_r (i.e. lowered cost of reservation decreases vacant SV supply).

The SV operator profit is characterised by two local maxima: one with no operations ($\lambda = \mu = 0$) and zero profit $\pi = 0$; another with serving all travel demand: $\lambda = 1$ and (cf. (10)) $\mu = \mu^*(g_r, g_v) \equiv \sqrt{\frac{L}{2}\frac{g_r+\phi+w}{g_v+\phi}}$. The operator profit (16) in the latter local maximum can be shown to equal

$$\pi^*(g_r, g_v) = \left(\sqrt{L(g_v+\phi)\tau} - \sqrt{\frac{g_r+\phi+w}{2\tau}}\right)^2 + L((g-g_v)\tau - c_1 h). \tag{18}$$

4.3. Equilibria and regulation

Absent parking discounts ($g_r = g_v = g$), the SV operator profit $\pi^*(g, g)$ can be positive if and only if shared mobility is socially optimal, i.e. (12) holds. In other words, the economy cannot end up in the shared equilibrium when the private equilibrium is socially superior, unless pushed by government subsidies.

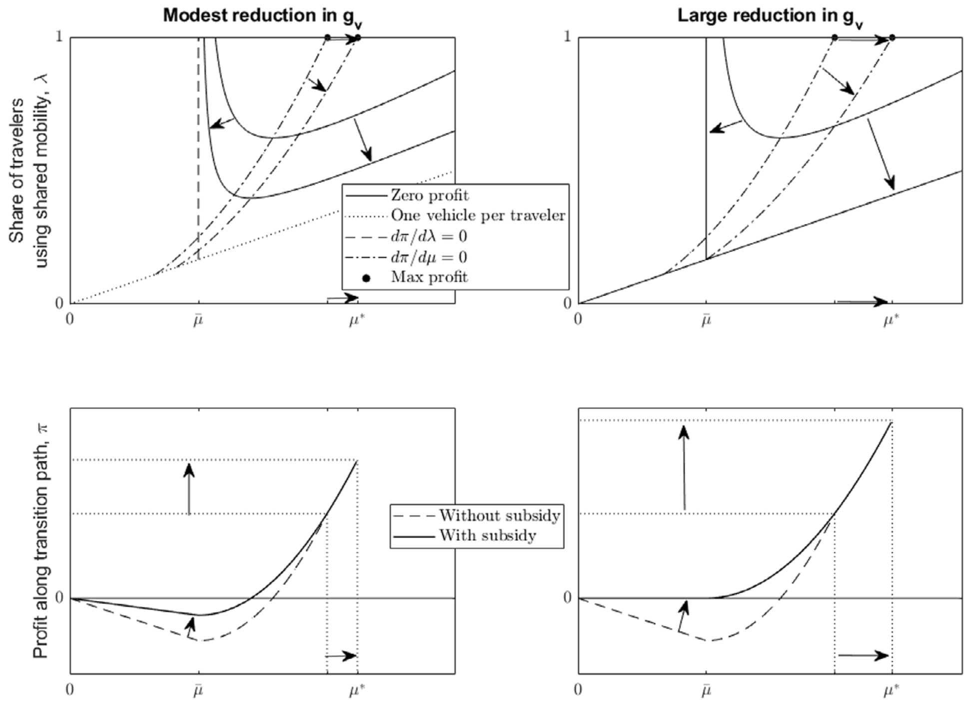

Fig. 3. Effects of parking discounts for vacant vehicles.

But what about the reverse scenario: can the economy remain in the private equilibrium when shared equilibrium is socially desirable, i.e. when $\pi^*(g, g) > 0$? Absent parking discounts and assuming λ and μ can increase only gradually, the SV provider would have to live through a period of negative profits before reaching the global profit maximum. With perfect capital markets, the supplier should theoretically be able to borrow until positive profit is achieved. However, the scale of such investment (to saturate a sufficiently large urban area with a sufficient density of shared vehicles, and convince a sufficient number of residents to forego their pre-existing private vehicles) may be too high for a start-up industry. This section demonstrates how discounted parking rates g_r, g_v reduce or eliminate the period of negative profit on the path to the shared equilibrium.

Fig. 3 illustrates the effects of discounted rate g_v for vacant SV. The left-hand panels illustrate effects of a modest discount, such that g_v remains above the cutoff defined by right-hand side of (15). This means that the SV operator will continue to make a loss at the initial stage of the industry growth, but the magnitude of the loss is decreased. The right-hand panels of Fig. 3 illustrate effects of a larger reduction in g_v, such that (15) holds with equality and there is no loss from SV operations even in early stages of industry growth. Note that a discount in g_v has a distortional positive effect on the density μ^* of vacant vehicles in the shared equilibrium.

The bottom panels of Fig. 3 illustrate the dynamics of operator profit along a transition path from private to shared equilibrium. The optimal transition path depends on relative speed of adjustment of endogenous parameters λ and μ, not defined explicitly in this paper. The illustration of Fig. 3 assumes that traveller transition to shared mobility, λ, is more inert (e.g. because travellers have pre-existing private vehicles) while SV supply μ is easier to adjust. Given this assumption, as λ gradually increases from zero to unity, the operator adjusts μ to maximise profit for each intermediate value of λ. The transition path then implies quasi-sharing (dotted line on top panels of Fig. 3) for $\mu < \bar{\mu}$, and then following (17) (a dash-dotted line) beyond $\bar{\mu}$.

In the early stages of industry growth, $\mu < \bar{\mu}$, operator losses are minimised when vehicles are quasi-shared, i.e. effectively always used by the same individual. This theoretical finding is corroborated by empirical evidence: Zakharenko (2023) in their Fig. 4 demonstrate that in lower-density markets (as proxied by city population size), shared vehicles spend more time being vacant. This is because low density of vehicles implies high spatial frictions of sharing, making such sharing more difficult in the early stages of the industry. Note that reduced g_v does not affect the cutoff $\bar{\mu}$ where the operator profit reaches its bottom and beyond which vehicles become actually shared.

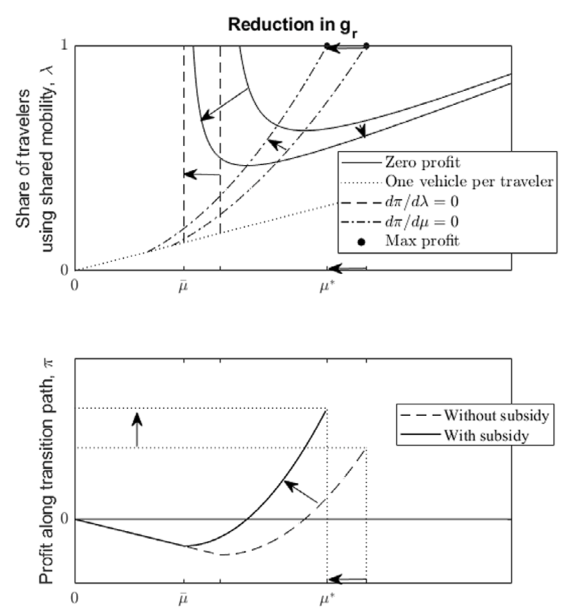

Fig. 4. Effects of parking discounts for reserved vehicles.

Fig. 4 shows the effects of discounted parking g_r for newly hired vehicles, reserved while travellers are reaching them. Because such discount reduces the spatial friction of sharing, it also reduces the cutoff $\bar{\mu}$, meaning a higher number of travellers per vehicle. This leads to a reduced density of vehicles in the shared equilibrium μ^*, relative to the social optimum. At the same time, discounted g_r is ineffective for the initial stages of industry growth ($\mu < \bar{\mu}$): without multiple travellers per vehicle, g_r has no impact on operator profit.

As a summary, discounted parking fees g_v for vacant SV are effective for boosting operator profit at all stages of industry growth, but they do not contribute to actual vehicle sharing and lead to excess supply of SV in the shared equilibrium. Discounted fees g_r for reserved SV are ineffective in the early stages of industry growth, where vehicles are repeatedly used by the same individual rather than shared. At the same time, they bring closer the moment when the vehicles actually become shared, and reduce the density of vehicles in the shared equilibrium. Therefore, it is recommended to use both types of discounts simultaneously, to add up the encouraging effect for the SV operator and to cancel out the distortionary effect on the equilibrium vehicle density μ^*. When the equilibrium is reached and sufficiently many users join the SV service, parking discounts can be abolished to reduce transfers of public welfare to the SV operator.

5. Extensions

5.1. Traveller heterogeneity

One possible extension is heterogeneous walking cost w. Travellers with lower w would be more inclined to use shared mobility. That would imply that the share of travellers using SV, λ, changes more gradually as the supply of vehicles increases (i.e. the dashed line on Fig. 2 is upward sloping, rather than vertical). If the upper bound of the walking cost distribution is sufficiently high, shared mobility cannot capture the entire transportation market. In particular, it is unlikely that disabled travellers will use shared mobility, unless technological progress allows to deliver vehicles to customers autonomously (without a driver) or using a remote driver.

Travellers may also differ in their expected duration of stay τ at each destination, with similar equilibria outcomes: shared mobility would be preferred by long-term stayers (those with high τ); SV demand would rise gradually with vehicle availability.

5.2. Convex social cost of parking

The model above has assumed that the marginal social cost of a parked vehicle does not depend on aggregate parking demand. It is likely though that such marginal cost is increasing: as the number of parked vehicles rises, the economy has to transition from cheaper surface parking lots to more expensive multi-story garages. But then, transition of the economy towards the shared equilibrium, by reducing overall demand for parking, will allow to make parking cheaper for all. This further increases the social value of shared mobility and the government incentives to push towards such mobility.

5.3. Traveller risk aversion

One simplifying assumption made in the above model is that travellers are risk-neutral with respect to their walking distance to the next vehicle. If any risk aversion exists, it may have a negative impact on the willingness to use shared mobility, thus making the shared equilibrium more difficult to achieve. However, SV operators may counter this problem by offering some kind of insurance for the next vehicle reservation. For example they could offer free or even subsidised reservation time for the walk, in excess of some distance, from the location of previous vehicle drop-off to the nearest available vehicle for the next ride. Further research is needed to formulate the optimal insurance policy to counter uncertainty in the location of the next vehicle.

5.4. Public transit

While public transit (PT) is generally viewed as a substitute to personal car, it may in some circumstances become a complement to shared vehicles. For example CoMoUK, a British non-profit organisation that promotes shared mobility, argues in its website that “Car sharing schemes generally work best where there are good public transport links”.[11]

In the context of the model developed in this paper, PT could be modelled as a fixed-cost transportation option that is inferior (more costly) than a private car. Then, PT would have no effect on the private equilibrium, when everyone uses the same vehicle repeatedly and there are no vacant SV available.

But in the presence of actual vehicle sharing (i.e. when $q > 0$ in the notation of this paper), PT would be used by travellers who found themselves without a vehicle within certain walking distance, effectively imposing a cap on the walking time. This would have a twofold effect on optimal decisions. First, the fact that a fraction of travellers use another method of transportation would lead to a reduction of equilibrium density μ of vacant SV, for every given release decision λ. At the same time, existence of alternative transportation method would hedge SV users from worst-case outcomes (very long walking times). That would increase the SV demand λ for every given SV supply μ.

To sum up, public transit reduces the long-term scope of SV popularity; at the same time, it makes it easier for the industry to overcome coordination failures and take off from the private equilibrium. Empirically, cities of Europe with better public transit have seen far more success in shared mobility (especially its free-floating form) than car-friendly American cities: there are several European free-floating SV operators with 5000+ vehicles each, compared to a single U.S. operator (GIG carshare) with estimated fleet of 1000 vehicles. In the future however, car cities like Los Angeles can become global leaders in shared mobility, provided that they overcome the coordination problems discussed in this paper.

6. Conclusion

This paper analyses whether preferential treatment of shared vehicles by local governments is socially optimal. The answer is positive: in the early stages of industry growth, such preferential treatment helps to overcome coordination problems in transition from private to shared use of vehicles. In later stages, when the density of shared vehicles becomes sufficiently high, such preferential treatment can be removed to avoid excessive redistribution of welfare to SV operators and/or distortions in the supply of shared vehicles.

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