A VCG Mechanism for Ride-Share Pricing & Routing

David Adelberg, Eliot Levmore and Alan Liu

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1 Background

The intersection of market design and computer science promises to deliver superior outcomes in a variety of industries. One way to create these outcomes is to allow customers to express intensities of preferences for goods or services by introducing appropriate markets. In this project, we study how the efficiency of ridesharing services, such as Uber, could be significantly enhanced in one use case ("Airport to Downtown") if these platforms adopt a mechanism for their ride-pooling services that enables users to reveal the value they place on marginal delays and optimizes the order of dropoffs accordingly. This scheme would create additional value for platform users and shift demand from single-passenger vehicles to pooled rides, in turn reducing congestion, reducing carbon emissions, and increasing average trip revenue.

Existing ride-pooling servies like UberPool allow riders following approximately similar routes to share cars for some or all of their respective trips. Assigning riders to cars optimally is a computationally difficult problem assuming many riders and many cars; we assume that this is a topic of serious research in the industry. A somewhat more approachable problem is: given a set of riders who will share a car, what route should the car take pick up and deliver the riders from their respective origins to their respective destinations? Related questions include: How many riders should be in an UberPool at once? What is the correct relative price of an UberPool and and UberX, which guarantees a private car?

We focus on a speicfic case which has some nice properties: delivering passengers from an airport to a city that is reasonably far away. For demonstration we focus on trips from Chicago O'Hare airport to the City of Chicago.

2 The Problem

Two people, N and S, want to share a taxi from O'Hare Airport to two locations in the downtown area. Rider S is in a rush, even though she lives somewhat further south than the other passenger and would be dropped off last if the taxi follows the shortest path originating at the Airport and passing through the both destinations. We would like to enable S to express her hurriedness and pay more to be dropped off first, assuming that the resulting extended ride is optimal given individual's values for their own time. But we would also like S to share their car with N, because it is (environmentally and socially) inefficient for single-passenger vehicles to travel from the airport to downtown. Our mechanism should enable S to take the fastest route from O'Hare to her destination while also enabling her to share her car with N without fear of delay. For example, if the cost of capital/gas/labor for the driver is \$25/hr, N values her time at \$35/hr, and S values her time at \$140/hr, and the detour induces 5 minutes of extra driving time for the driver and 10 minutes of extra driving time for N while saving S 5 minutes, the detour would be optimal; if S valued her time at only \$50/hr, our mechanism would reject the detour.

The shortest-path UberPool would drop N off before S, so rider S would prefer to take UberX rather than the pool. Our allocation mechanism, which is sensitive to the riders' time valuations, would drop S off before N, and moreover would be cheaper for S than an UberX. This last point is a bit of a tautology; assuming a monopoly by Uber, UberX should not be a distinct service from an infinity bid in this UberPool mechanism. In the long term, shared rides (especially in the airport scenario) are overwhelmingly superior in terms of social utility; we expect other regulations to push consumers towards ride sharing in most situations (HOV lanes). We choose to ignore the question of passenger arrival times etc. at airports. This and other factors might marginally affect our analysis but they are distractions from the main point: Uber should phase out UberX from airports and instead offer UberPools with this superior routing mechanism.

In the existing system, riders like S who are unusually rushed are likely to choose not to participate in UberPool-type ridesharing and will instead hire a personal vehicle. This has contributed to substantial congestion at some airports, including O'Hare, leading to an overall reduction in utility.

Specifically, demand for Uber cars is so great at O'Hare that tens or hundreds of Uber drivers wait near the arrivals terminal. In response to this abundance of cars, O'Hare officials forced Uber drivers to move from a staging area 4 minutes from the terminal to a new lot 8 minutes from Arrivals. The Uber pickup lane is often full, and the process of getting an Uber from opening the application to leaving the airport takes significantly longer than it once did. In addition, because O'Hare is about 20 driving miles from downtown Chicago, large numbers of riders taking single passenger vehicles produce substantially more emissions and contribute to overall traffic on the highway. It is highly likely that these problems of congestion by Uber cars are exaggerated by inefficiencies in UberPool routing and relative mispricing of the UberPool and UberX services. Encouraging Uber users to substitute towards UberPool away from UberX would decrease congestion.

We would like to enable riders like S to share their cars without fear of being suboptimally delayed.

In general, given n passengers who want to share an UberPool from a single origin location to distinct destinations, we would like to extract accurate time valuations from riders and then choose the utility-maximizing route. Under such a mechanism, even riders in a rush would prefer UberPool to the existing UberX service.

3 The Solution

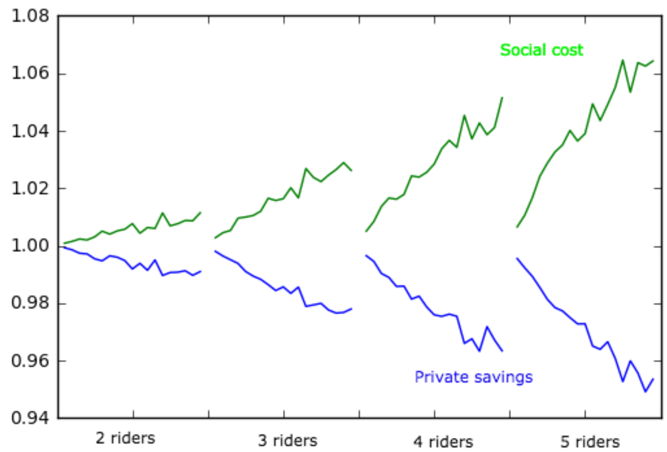
We propose a Vickrey-Clarke-Groves auction with additional flat payments to address the inframarginal cost of the shared journey. We suggest that each of n riders pay $A(n)*$(UberX rate of shared segment) where $A(n)$ is some decreasing function of n, in addition to the VCG payment.

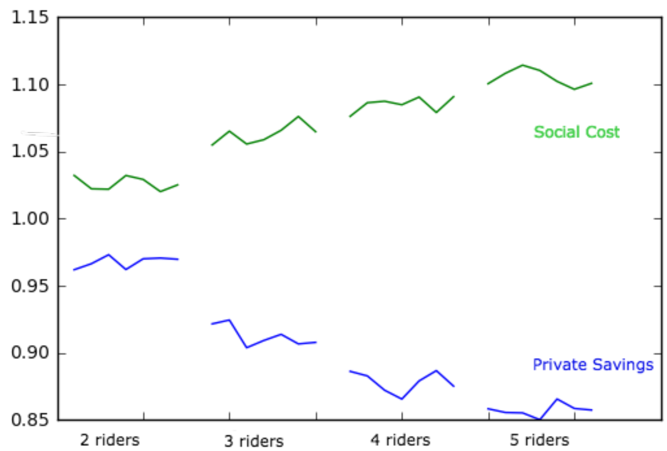
To compute VCG payments we did a brute-force search for the cost-minimizing path from the origin point (in the simulation, this was (0,0); typically it would be an airport) through the n destinations, and then did n further brute-force searches for the minimizing path through each possible subset of $n-1$ destinations. The payments from rider i are then equal to the cost of the optimal path through the n destinations minus the cost of the optimal path through the $n-1$ destinations (excluding rider i).

To solve this problem, we simulated the Vickrey-Clarke-Groves auction. This auction improves the efficiency of the ridepooling service because it allows the service to select the time-valuation optimal route. In addition, our mechanism is truthful. That is, riders will always be weakly better off if they state the true maximum rate they are willing to pay for an Uber. Further, even high time valuation users have an incentive to participate in ridesharing. Our mechanism would drop these people off first (unless someone else's destination is on the way), so ridesharing would not take additional time. Further, adding this feature will encourage some users to switch from taxis, creating economies of scale and density for Uber.

4 Implementation

First, we simulated riders traveling from the origin to destinations in the plane distributed around $(100, 0)$ using the Manhattan (or Taxi-cab) distance to determine travel time. Our output is unitless, but gives a sense of the scale of improvements and costs that might result from our new mechanism independent of the savings due to substitution from UberX to UberPool by consumers. We also simulated riders traveling from the origin to destinations distributed around the origin to obtain upper bounds on the usefulness of our new mechanism and to better understand the efficiency gains we hoped to obtain. To simulate the distribution of time-valuations among Uber drivers, we draw on the work of the University of California Transportation Center's paper "App-Based, On-Demand Ride Services" to estimate the distribution of annual income of Uber users. We used this distribution to estimate hourly wages and approximated the cost (capital, labor, and environmental) of operating an Uber to be \$25/hour.





The green lines track the "social cost ratio," which is computed as the ratio of the total driven distance of our time-value optimal path to the total driven distance of the shortest path; the blue lines track the "individual cost ratio," which is the ratio of the total time-weighted costs of the time-value optimal path to the time-weighted costs of the shortest path. There are a few clear patterns: percentage increases in total distance are approximately equal to percentage decreases in time-weighted costs; the payoff of the new mechanism is increasing in the dispersion of destinations relative to the length of the initial shared segment; and the payoff of the new mechanism is increasing in the number of riders.

The first point is not particularly surprising. We expected percentage increases in total distance to be approximately proportional to percentage decreases in time-weighted costs. Time-weighted savings are the result of taking longer paths. A key element of this proposed mechanism is that it would increase UberPool adoption rates, so we should not be particularly concerned with marginally (up to 10%) longer routes for UberPool cars. Moreover, the time-value for the Uber is an adjustable parameter and can be increased or decreased to reflect the costs of externalities, e.g. to incorporate a carbon tax or to further encourage carpooling through an insulating tariff strategy.

The second point mostly reflects the specifics of the airport situation, and supports our claim that any carpool from an airport to a downtown is better than single-passenger vehicles. On average, longer routes which respect individuals' varying preferences for speed are not much different from the socially optimal shortest route if the shared portion of the ride is substantial. In the case of riders traveling from airports to cities, then, we should not be too worried that it is socially optimal for individuals to have their own car.

We can inspect the second plot, which shows the value of our mechanism without an initial shared segment, to explain this third point. In short, a larger number of riders allows for more room for improvement over the shortest-path algorithm. This plot can be interpreted as the impact of the new mechanism after the riders have traversed their shared segment. It shows that pools with 5 riders (with time-values drawn from our distribution approximating the distribution of Uber riders) have average utility improvements of 15%. In many cases the mechanism-optimal path is also the shortest-path, and conditioned on being a different path the average time-value-utility improvement is much greater. This indicates that (as we hypothesized) riders frequently faced substantially suboptimal routes under the shortest-path algorithm, and that UberPool routes determined by this VCG mechanism will be more attractive to users.

Second, we developed a proof-of-concept web app that shows shortest-path and mechanism-optimal paths from O'Hare Airport to randomly generated locations in Chicago. We allow up to 8 riders to share an UberPool; although it is likely that most UberPools now can accomodate at most 3 or 4 passangers, it is plausible that the future of airport-to-downtown transport involves minibuses or other high capacity vehicles. In any case, we are only limited by the size of the search space which is roughly $\mathcal{O}(n! * n)$, and for $n \leq 8$ this is not too great. In addition, we expect that self-driving cars will allow up to 5 passengers to fit in an Uber, although Uber may prefer to limit the number of riders to improve passenger experience (this issue is beyond the scope of our proposal). For our simulation, we set the starting location of all of the travellers to Chicago's O'Hare International Airport. Next, we randomly generate up to n destinations by picking n arbitrary locations from a pre-selected list of 1000 locations in the Greater Chicago Area. Then, we independently select the riders' time valuations from our hand-coded distribution. While we think that in practice time valuations and locations might be correlated, we independently draw time valuations and locations for the purpose of demonstrating our concept.

To compute optimal paths from revealed preference intensity, we enumerate all possible paths through the five destinations and select the path that minimizes time-weighted cost, computed as the sum of the cost of the driver's time and that of the riders' times. This computation takes $\mathcal{O}(n! * n)$ time in general case ($n >> 10$ riders sharing a car), but because we limit the number of riders, this is not a computationally intensive step. We then compute Vickrey payments to the platform by calculating the marginal impact of each rider. We do this by computing the mechanism-optimal path for each subset of $n-1$ riders and subtracting the costs of these paths from the cost of the n rider path.

In the stats page, our web app displays the VCG prices paid by each rider and their time valuations. We have not included the proposed flat shared cost; instead we compare the revenue from the VCG mechanism to the estimated cost of operating the UberPool. The magnitude of the VCG revenues is a function of how well the Uber system in aggregate puts individuals with similar destinations in the same car, so the problem of deciding the level of the $A(n)$ fraction of the shared cost each passenger should pay has solutions which are idiosyncratic to different airports and levels of demands.

In addition, we display an example of a reasonable non-VCG payment scheme for the shortest path. We assumed that UberX prices equated to approximately \$40/hr, and charged each of n riders sharing an UberPool

$$\frac{3}{n+2} \times \text{[Price of an UberX to that riders' destination]}$$

We hope that comparison between these two schemes helps illustrate that the VCG mechanism charges different riders dramatically different prices, even though the service provided is superficially (or ex-ante, before choosing the route) similar. Our best guess is that Uber's pricing mechanism is even less outcome-driven than this one; Uber likely charges something like $\frac{3}{\overline{n}+2}$ of the price of an UberX, where $\overline{n}$ is the average number of riders in a Pool leaving from a given region.

Finally the "Surplus Calculations" tab displays the improvement for each occupant of the vehicle in surplus from the optimal VCG route over the shortest route. Then, we compute total surplus by adding all of the costs displayed on this tab and subtracting Uber's profit. Note that some of these improvements are negative; the driver takes a weakly longer route, so her surplus is weakly negative. For the most part, the riders with large positive surpluses also pay more than the other riders, redistributing the surplus as we would hope and expect (though in some cases correlated destinations interfere with this intuition).

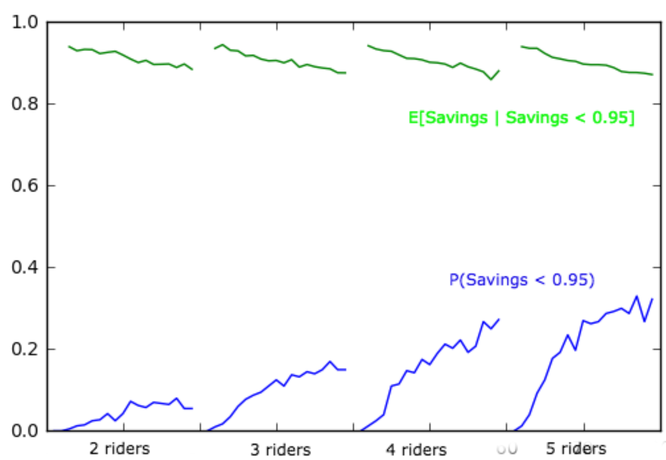
5 Conclusion

Our simulation indicates that Uber could create value for its users and encourage greater utilization of UberPool by adopting a VCG mechanism in the \$/hour space for determining UberPool routes, at least in our example use case of riders leaving a common origin point like airport. Our proof-of-concept web app suggests that, at least anectdotally, the sum of the resulting VCG-payments are reasonably close to the cost of operating the Uber. These payments are for the most part much lower than existing prices, so it seems like that our proposal would shift Uber's users away from UberX and towards UberPool. It is well-known that UberPool represents a superior profit opportunity to Uber, and it seems likely that some small additional flat payment to account for the shared distance could increase profits without dramatically affecting the dynamics of the auction.[1]

In the long term, our time-value-sensitive UberPool could replace UberX, at least in the airport-to-city use case. Under this system time-sensitive users would enter high bids and thus be the first person dropped off for an UberX-like-experience. At the very least, assuming a monopoly, Uber could analyze the payments from participants in the new UberPool mechanism and adjust prices for UberX accordingly to balance demand between the two services.

6 ...And More

In order to gain more insight into the potential benefits of implementing this mechanism, we measured the proportion of trips for which the impact of our mechanism is economically significant and the expected impact of our mechanism, given that the trip will be significantly effected by the change of mechanism. To do this, we measured the proportion of trips for which the individual cost ratio is less than 0.95. We also computed the expected individual cost ratio conditional on this cost ratio being less than 0.95.



[1]This is by far the least justified statement in this report. We could find only minimal work on the properties of VCG-mechanisms with entry fees. One paper from Microsoft Research suggests that they may have relatively nice properties in some situations: http://research.microsoft.com/en-us/um/people/nikdev/pubs/DualityAuctions.pdf

That said, we think that the proposed payments are sufficiently low that adding a surcharge will not unduly hurt demand given existing demand for Uber services, and would allow the lowest valuation consumers to substitute away to slower public transportation options. Existing transportation services do have a surcharge on transit to/from airports.

We can see that the proportion of trips for which the individual cost ratio is below 0.95 increases with the number of riders and dispersion. In particular, when four or more riders share an Uber, more than 20% of trips will be positively effected by the change of mechanism, for moderate levels of the dispersion parameter. In addition, our analysis indicates that when 4 or more riders share an Uber and their destinations are moderately dispersed, then one can expect a reduction of nearly 10% in the individual cost ratio. This means that Uber could significantly increase market share and/or improve margins by adopting this type of mechanism.