The Potential of Public Transit: Evidence from Mobile Phone Data*

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Motivation

Despite the drastic growth of cities during the second half of the 20th century, the technology of urban transportation essentially remained unchanged. In the year 2000, just as in the 1960s, a city dweller who did not want to walk, bike, or drive had two options to get to her destination: she could take a taxi, or she could use some form of mass transit operated on a fixed schedule such as a bus or subway. However, in recent years, the internet, and the ability to track locations through widely adopted smartphones have drastically reduced the cost of coordination between commuters. These technologies, so far, are mostly used and developed by private transportation providers, such as Uber, Lyft, and various other companies.[1] However, it stands to reason that these advances have also shifted the production possibility frontier of public transit, making the old fixed-route, fixed-schedule paradigm no longer optimal.

In this project, our aim is to measure to what extent the *production possibility frontier* of *public transit* has shifted and, hence, whether it can be organized more efficiently than currently. The benefits and drawbacks of different forms of urban transportation are to a large extent summarized by the trade-off between convenience, flexibility, and immediacy on the one hand and cost efficiency on the other hand (see figure 1). Private transportation (private cars, taxis, and ride-hailing) and mass transit are the extreme points of this trade off. The former is convenient, immediate, and expensive while the latter is typically associated with long waits and low costs. More recently, we have seen the appearance of pooled ride-sharing services like UberPool or Lyft Line. They offer a completely new alternative to commuters and are a third option that sits in between private rides and mass transit: Prices tend to be around two thirds the prices of taxis, and they provide a degree of comfort and travel time intermediate between those of taxis and

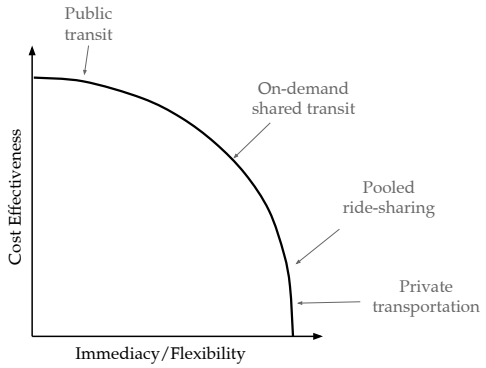


Figure 1: Spectrum of modes

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[1]Some cities have also seen large-scale improvements in their public transit system (Tsivanidis, 2018).

mass transit. Moving one step closer to public transit, we find a fourth option, services such as Via that offer on-demand public transit. Vans or small buses take riders to their destination using routes that are optimized on the go instead of using pre-specified time schedules. Thus, pooled ride-sharing and on-demand public transit have the feature of pooling many riders together; we refer to them collectively as *shared transit*.

There are important reasons to believe shared transit might play a crucial role in the future of urban transportation. First, they exhibit large returns to scale and network effects—maybe even more so than ride-hailing. Second, they offer higher capacity utilization than private transportation and, hence, offer a realistic pathway towards more sustainable urban transportation. Traditional buses and subways are much more efficient than individual cars, but a large share of the population might be unwilling to switch to them on a daily basis, especially in sprawling cities. Shared transit might provide a form of transportation that has a small carbon footprint but is still convenient enough that most of the population might be willing to use it every day.

To understand whether shared transit can reduce congestion and carbon emissions, it is essential to understand substitution patterns both from private transportation as well as from from traditional subways and buses. While substitution from the former increases capacity utilization and efficiency, the latter might be detrimental. The extent to which both forms of substitution occur may be city-specific and could be determined by the existing transport infrastructure. While most American cities have underdeveloped public transit, some cities have efficient bus and rapid transit networks, so substitution away from those networks might be a concern.

To what extent shared transit will be adopted depends not only on technical details of the implementation but also on subsidy schemes that account for the positive externalities that arise from network effects. Quick trips with minor detours can only be offered if there is a thick enough pool of riders that enables good matches. A higher quality of matches also allows for more riders per car, using drivers' time more efficiently. Taxes on less efficient transportation and subsidies for more efficient transportation might be necessary to enable widespread use of shared transit.

Research objectives

The first goal of this project is to understand to what extent shared transit enabled by new technologies can help achieve more efficient transportation with lower congestion and a smaller carbon footprint. Concretely, we would like to understand whether citizens' movement patterns and preferences over modes are such that the market could shift towards large scale usage of shared transit. Part of this first goal is to measure to what extent social welfare, which includes consumer surplus and any externalities, could increase with shared transit. Our work is thus related to previous papers such as Baum-Snow and Kahn (2000) and Winston and Maheshri (2007) that analyze the welfare effects of introducing new forms of transportation.

Our second goal is to understand what local governments should do in order to implement shared transit systems. They have two main policy instruments at their disposal: investment and prices. Investment takes the form of purchases of shared-transit vehicles, while prices refer to subsidies and taxes on different modes of transportation. Our exer-

cise will allow us to determine the welfare-maximizing mix of instruments, in a similar vein to Glaeser and Ponzetto (2018) and Winston and Maheshri (2007).

Data and methodology

Data The long-run goal of this study is to map the shared transit potential for many large urban areas in the US. However, in our initial analysis we will focus on Chicago because of two reasons: it is a large city for which detailed data is available, and it has a significant public transit infrastructure while also relying heavily on cars.

There are two data sources we use for our analysis. First, a large dataset based on cell-phone locations, which records people's movements over time. The dataset is ideally suited for our study as it covers about 40% of active cell-phone devices in the U.S. and the panel nature allows us to describe individual-level behavior over time, similar to Miyauchi et al. (2020) and Glaeser et al. (2020). With these data we are able to study people's movement patterns, including mode of transportation, and we can measure substitution patterns between modes, as in Hall et al. (2018). The second source of data is administrative data from the City of Chicago including bus and subway ridership, taxi and ride-hailing trips, traffic counts, and survey data on people's commuting needs.

We are currently in the first step of our analysis. We are analyzing the cell phone location data by defining whether individuals are moving as well as their home and work locations. We are also developing a protocol to identify public transit rides through various clustering techniques. Eventually we will put together our data into a dataset of individual trips taken by citizens, including the time, origin, destination, and the mode of transportation. This dataset will be the starting point for the rest of our analysis.

Conceptual framework We now present a simple model that serves as a conceptual framework for our analysis. The main market participants are commuters, who wish to move from some origin to some destination, and decide which mode of transportation they want to use. There is also a central planner who determines prices and chooses how much to invest in each mode of transportation, which reducing travel times.

We assume that agents—i.e., commuters—going from origin o to destination d arrive at an exogenous rate λ_{od}. If some agent i, who wishes to go from o to d, chooses transportation mode j among a set J of transportation modes, her utility is[2]

$$u^i_{odj} = \xi^i_{odj} - \alpha^i_t \cdot t_{odj} - \alpha^i_p \cdot p_{odj} + \epsilon^i_{odj}, \tag{1}$$

where:

- ξ^i_{odj} captures unobserved features that make mode j more desirable, such as the degree of comfort or whether the agent needs to share a car with someone else.
- α^i_t and α^i_p are coefficients that represent agent i's disutility of time and price.
- t_{odj} is the expected time to get from o to d using mode of transport j.

[2]We suppress time variation for simplicity, but allowing for it is straightforward.

- p_{odj} is the price for using mode of transport j to get from o to d.
- ϵ^i_{odj} is an idiosyncratic shock, which we assume follows a type I EV distribution.

There is also an outside option $j = 0$ with utility ϵ^i_{od0}, which represents not going to the destination. Rider i chooses transportation option $j = \text{argmax}_j \, u_{odj}$.

Integrating over individuals, the previous maximization problem leads to the demand (or flow) from origin o to destination d for mode j:

$$q_{odj}(\mathbf{t}_{od}, \mathbf{p}_{od}) = \lambda_{od} \int \mathbb{1}\{\underset{j}{\text{argmax}}\, u^i_{odj} = j\} dF(i|o,d), \tag{2}$$

where $\mathbf{t}_{od}$ and $\mathbf{p}_{od}$ denote the vectors of prices and travel times for all options j if the agent goes from o to d.

While agents take the vector of travel times $\mathbf{t}_{od}$ as given, these are in fact a function of overall demand, and thus, an equilibrium object. In particular, there is a matching technology T that maps demand into travel times,

$$t_{odj} = T_{odj}(\mathbf{q}_j, I_j), \tag{3}$$

where $\mathbf{q}_j$ is the vector of all flows q_{odj} using mode j. Travel times also depend on investment I_j in transportation mode j, which involves expenditure in buses, trains, and cars, all of which lower transit times.[3,4]

A market equilibrium is a set of flows q_{odj} and travel times t_{odj} that satisfy equations 2 and 3. In order to define welfare, let $U^i(\mathbf{t}_{od}, \mathbf{p}_{od}) = \frac{1}{\alpha^i_t} \log\left(\sum_j \exp u^i_j(t_{odj}, p_{odj})\right)$ be the expected utility of agent i, measured in dollars. Also let $C_j(\mathbf{q}_j)$ be the social cost function for mode j, which involves direct costs, such as fuel, car depreciation, and driver salaries, and let $E_j(\mathbf{q}_j)$ be the externalities caused by mode j, which includes congestion and carbon emissions (as in Allen and Arkolakis, 2020). Welfare is given by:

$$W(\mathbf{p}, \mathbf{I}, \mathbf{t}, \mathbf{q}) = \sum_{o,d} \lambda_{od} \int U^i(\mathbf{t}_{od}, \mathbf{p}_{od}) dF(i|o,d) + \sum_{o,d,j} p_{odj} q_{odj} - \sum_j \left[C_j(\mathbf{q}_j) + E_j(\mathbf{q}_j) + I_j\right].$$

The planner's problem is to maximize welfare $W(\mathbf{p}, \mathbf{I}, \mathbf{t}, \mathbf{q})$ subject to equations (2) and (3). The planner might face a budget constraint $\sum_j \left(C_j + I_j\right) - \sum_{odj} p_{odj} q_{odj} \leq \bar{I}$. Note that this model allows for subsidies: mode j is subsidized if $C_j > \sum_{od} p_{odj} q_{odj}$.

Estimation and counterfactuals The core of our data analysis will be to recover the main elements in our model. The first element are agents' preferences, which means estimating a distribution of parameters $\xi^i_{o,d,j}$, α^i_t and α^i_p across individuals i. With that, we can also compute demand $q_{odj}(\mathbf{t}_{od}, \mathbf{p}_{od})$, which accounts for rich substitution patterns across modes of transportation. The second key element is the matching technology

[3]The function $T_{odj}(\mathbf{q}_j, I_j)$ implicitly assumes that the amount spent is invested efficiently.

[4]We treat roads and railroads as exogenous, although they could be part of investment. This longer-run question is outside the scope of this work.

$T_{odj}(\mathbf{q}_j, I_j)$, which we compute by simulation, using similar techniques to those used in recent papers in the transportation literature, such as Frechette et al. (2019), Buchholz (2020), and Castillo (2020). With those two elements, we will be in a position to simulate market equilibria and compute welfare for different counterfactuals, each one of which is characterized by the policy set by the planner.

In our first exercise, we aim to understand the degree to which the introduction of shared transit can increase welfare. We compare two counterfactuals. In the first one, we find the welfare maximizing policy when the set of modes J includes all modes except for shared transit. In the second one, J also includes shared transit. The increase in welfare gives us a measure of the potential gains that can be obtained from shared transit.

The second counterfactual in the previous exercise will also tell how the government should invest and set prices in an ideal world. The optimal policy, however, might not be feasible, since it will likely require significant expenditure on subsidies and investments. For that reason, in our second exercise we compute the optimal policy when the planner is subject to a budget constraint. That way we can inform local governments about the policies they should set, and about the gains in welfare that can be achieved with the introduction of shared transit in a realistic way.

References

Allen, Treb and Costas Arkolakis, "The welfare effects of transportation infrastructure improvements," Technical Report, National Bureau of Economic Research 2020.

Baum-Snow, Nathaniel and Matthew E Kahn, "The effects of new public projects to expand urban rail transit," *Journal of Public Economics*, 2000, *77* (2), 241–263.

Buchholz, Nicholas, "Spatial Equilibrium, Search Frictions and Efficient Regulation in the Taxi Industry," *Working paper*, 2020.

Castillo, Juan Camilo, "Who Benefits from Surge Pricing?," *Working paper*, 2020.

Frechette, Guillaume R, Alessandro Lizzeri, and Tobias Salz, "Frictions in a competitive, regulated market: Evidence from taxis," *American Economic Review*, 2019, *109* (8), 2954–92.

Glaeser, Edward L and Giacomo AM Ponzetto, "The political economy of transportation investment," *Economics of Transportation*, 2018, *13*, 4–26.

_ , Caitlin Gorback, and Stephen J Redding, "JUE Insight: How Much does COVID-19 Increase with Mobility? Evidence from New York and Four Other US Cities," *Journal of Urban Economics*, 2020, p. 103292.

Hall, Jonathan D, Craig Palsson, and Joseph Price, "Is Uber a substitute or complement for public transit?," *Journal of Urban Economics*, 2018, *108*, 36–50.

Miyauchi, Yuhei, Kentaro Nakajima, and Stephen J. Redding, "Consumption Access and Agglomeration: Evidence from Smartphone Data," *Working Paper*, 2020.

Tsivanidis, Nick, "The aggregate and distributional effects of urban transit infrastructure: Evidence from Bogotá's transmilenio," *Unpublished manuscript*, 2018.

Winston, Clifford and Vikram Maheshri, "On the social desirability of urban rail transit systems," *Journal of urban economics*, 2007, *62* (2), 362–382.