EPFL

October 16, 2025

Introduction to on-demand and shared mobility

École polytechnique fédérale de Lausanne

Our lab

Members

Head

Postdoc

PhD

Visiting

Lab for human-oriented mobility eco-system

At HOMES, we develop human-centric solutions to emerging mobility challenges.

Our lab

HOMES

Topics

Shared mobility

- ride-hailing & ride-pooling
- ride-sharing
- micro-mobility

\+ integration into mass transit

Traffic demand management

- network design
- incentives design

Methodologies

- network modeling
- game theory
- min F(x) optimization
- data-driven & learning

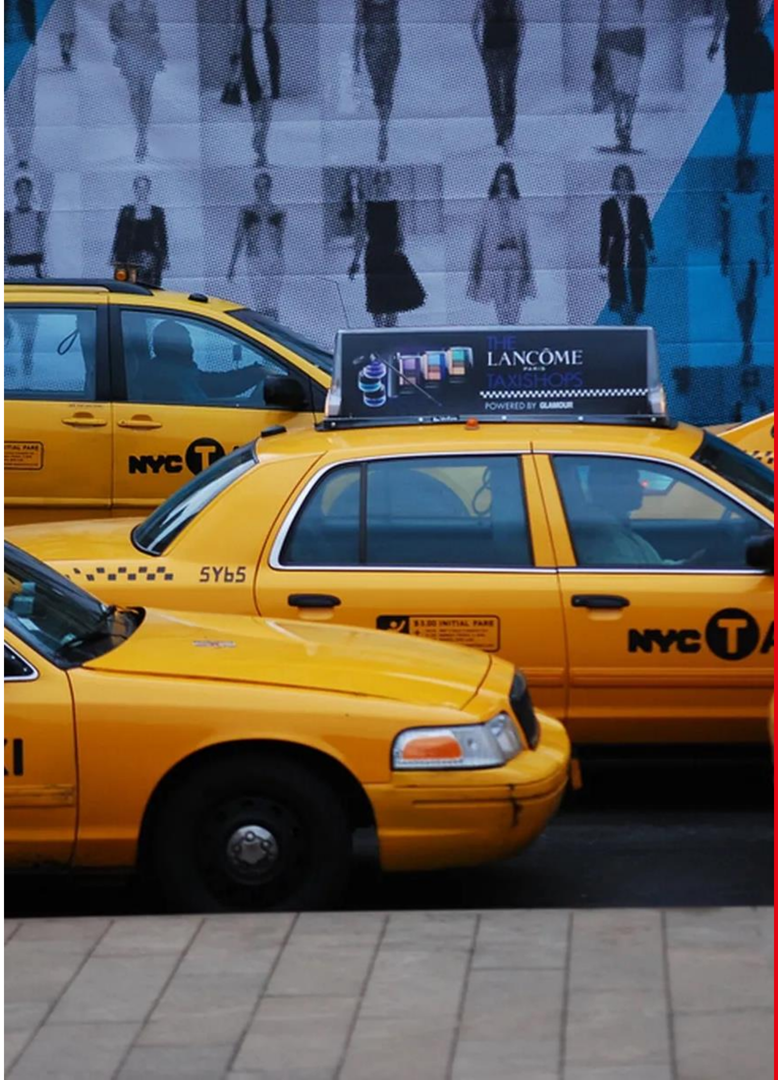
Kenan Zhang

Our lab

- Courses
  - CIVIL 324 (BA6) Urban public transport systems
    - transit system and on-demand service design
  - CIVIL 477 (MA2) Transportation network modeling & analysis
    - traffic assignment and network equilibrium

- Student projects
  - Modeling
    - Route choice, accessibility, shared-mobility
  - Data-driven analyses and machine learning
    - Individual and vehicle trajectories, meal delivery orders, environmental sensing data, transit operation data
  - Simulation
    - On-demand mobility, day-to-day commute

HOMES @ EPFL



Agenda

- Basics
- Matching
- Operations
- Regulations

What is on-demand and shared mobility

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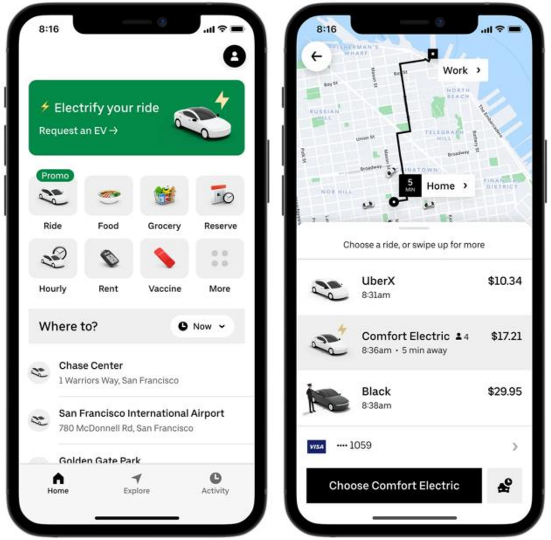
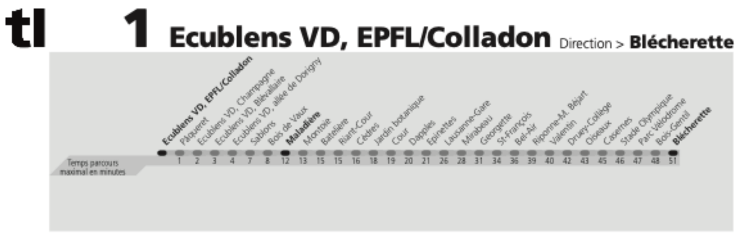
- "On-demand" means…
  - the service can be requested at any time and any location
  - there is no fixed schedule or route (e.g., bus and train)



book a Uber trip



Lundi-Vendredi — **Ecublens VD, EPFL/Colladon** Direction > **Blécherette**

Ecublens VD, EPFL/Colladon									06 30	06 37	06 42	06 47	06 54	07 00	07 06	07 12	07 18	07 25	07 32	07 38	07 44	07 51
Ecublens VD, allée de Dorigny									06 34	06 41	06 46	06 51	06 58	07 04	07 10	07 16	07 22	07 29	07 36	07 42	07 48	07 55
Sablons									06 37	06 44	06 49	06 54	07 01	07 07	07 13	07 19	07 25	07 32	07 39	07 45	07 51	07 58
Maladière	05 10	05 25	05 40	05 53	06 05	06 17	06 29	06 35	06 41	06 48	06 53	06 58	07 05	07 11	07 17	07 23	07 29	07 36	07 43	07 50	07 56	08 03
Montoie	05 12	05 27	05 42	05 55	06 07	06 19	06 31	06 37	06 42	06 49	06 54	06 59	07 06	07 12	07 18	07 24	07 30	07 37	07 44	07 51	07 57	08 04
Jardin botanique	05 16	05 31	05 46	05 59	06 12	06 24	06 36	06 42	06 47	06 54	06 59	07 04	07 11	07 17	07 23	07 29	07 35	07 42	07 49	07 56	08 02	08 09
Epinettes	05 18	05 33	05 48	06 01	06 14	06 26	06 38	06 44	06 49	06 56	07 01	07 07	07 14	07 20	07 26	07 32	07 38	07 45	07 52	07 59	08 05	08 12
Lausanne-Gare	05 21	05 36	05 51	06 04	06 17	06 29	06 41	06 47	06 53	07 00	07 05	07 11	07 18	07 24	07 30	07 36	07 42	07 49	07 56	08 03	08 09	08 16
Georgette	05 24	05 39	05 54	06 07	06 20	06 32	06 44	06 50	06 56	07 03	07 09	07 15	07 22	07 28	07 34	07 40	07 46	07 53	08 00	08 07	08 13	08 20
St-François	05 26	05 41	05 56	06 09	06 22	06 34	06 46	06 53	06 59	07 06	07 12	07 18	07 25	07 31	07 37	07 43	07 49	07 56	08 03	08 10	08 16	08 23
Bel-Air	05 28	05 43	05 58	06 11	06 24	06 36	06 48	06 55	07 01	07 08	07 14	07 20	07 27	07 33	07 39	07 45	07 51	07 58	08 05	08 12	08 18	08 25
Riponne-M. Béjart	05 30	05 45	06 00	06 13	06 26	06 38	06 50	06 57	07 03	07 10	07 16	07 22	07 29	07 35	07 41	07 47	07 53	08 00	08 07	08 14	08 20	08 27
Casernes	05 34	05 49	06 04	06 17	06 30	06 43	06 55	07 02	07 08	07 15	07 21	07 27	07 34	07 40	07 46	07 53	07 59	08 06	08 13	08 20	08 26	08 33
Blécherette	05 38	05 53	06 09	06 22	06 35	06 48	07 00	07 07	07 13	07 20	07 26	07 32	07 39	07 45	07 51	07 58	08 04	08 11	08 18	08 25	08 31	08 38

bus route and schedule

What is on-demand and shared mobility

Kenan Zhang

- "Shared" means…
  - trips are served by a dedicated fleet of vehicles
  - you share the vehicle with someone, but not necessarily in the same trip

"sharing" in a narrow sense

"sharing" in a broad sense

What is on-demand and shared mobility

- Putting “on-demand” and “shared” together…

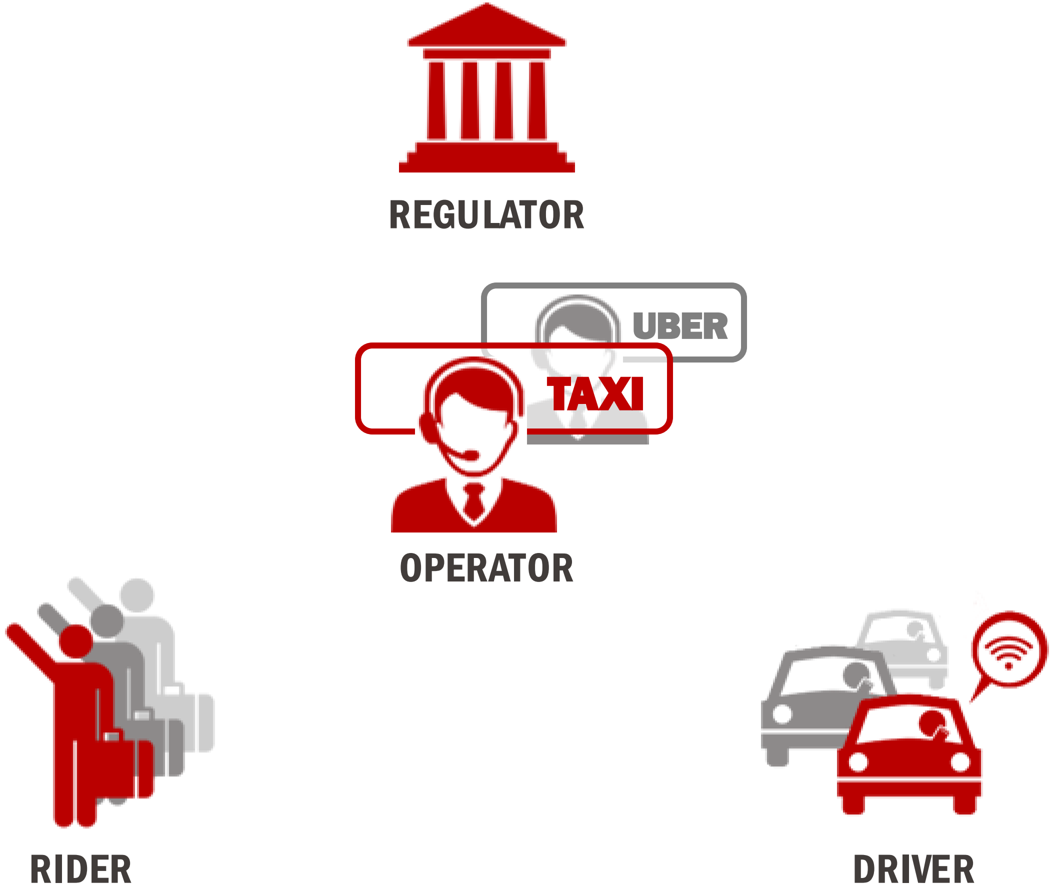
ride-hailing
- taxi
- e-hailing
- ride-pooling
- micro-transit

micromobility
- bike-sharing
- scooter-sharing

ride-sharing
- carpooling

(on-demand) car-sharing

Who are the stakeholders?



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Who are the stakeholders?

REGULATOR

Pursuits

- get to my destination asap
- price is reasonable
- trip is comfortable
- ….

OPERATOR

Costs

- trip fare
- waiting and in-vehicle time
- detours in shared trips
- ….

RIDER

DRIVER

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Who are the stakeholders?

REGULATOR

Pursuits
- high hourly earning
- short search time
- equal dispatch opportunity
- ….

OPERATOR

Costs
- operation cost
- other job opportunity
- fatigue after long work hours
- ….

RIDER

DRIVER

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Who are the stakeholders?

REGULATOR

Pursuits
- high profit
- dispatch efficiency
- large market share
- reliable supply
- ….

OPERATOR

Costs
- payment to drivers
- incentives to passengers
- operation cost
- ….

RIDER

DRIVER

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Who are the stakeholders?

REGULATOR

Pursuits
- max social welfare
- min traffic congestion
- equity and accessibility
- ….

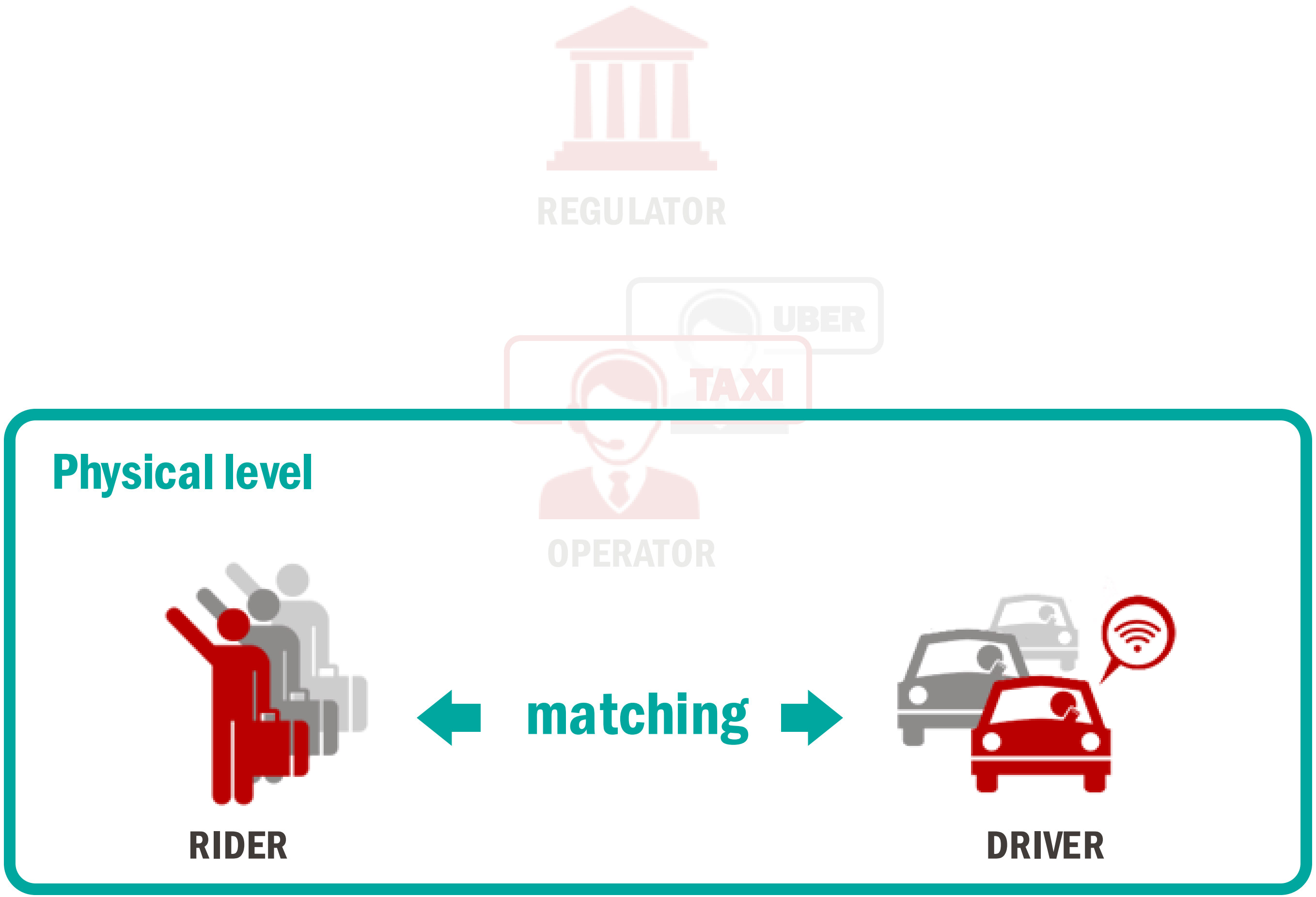
OPERATOR

Instruments
- subsidy and tax
- regulation and incentive mechanism
- ….

RIDER

DRIVER

What problems do we study?



What problems do we study?

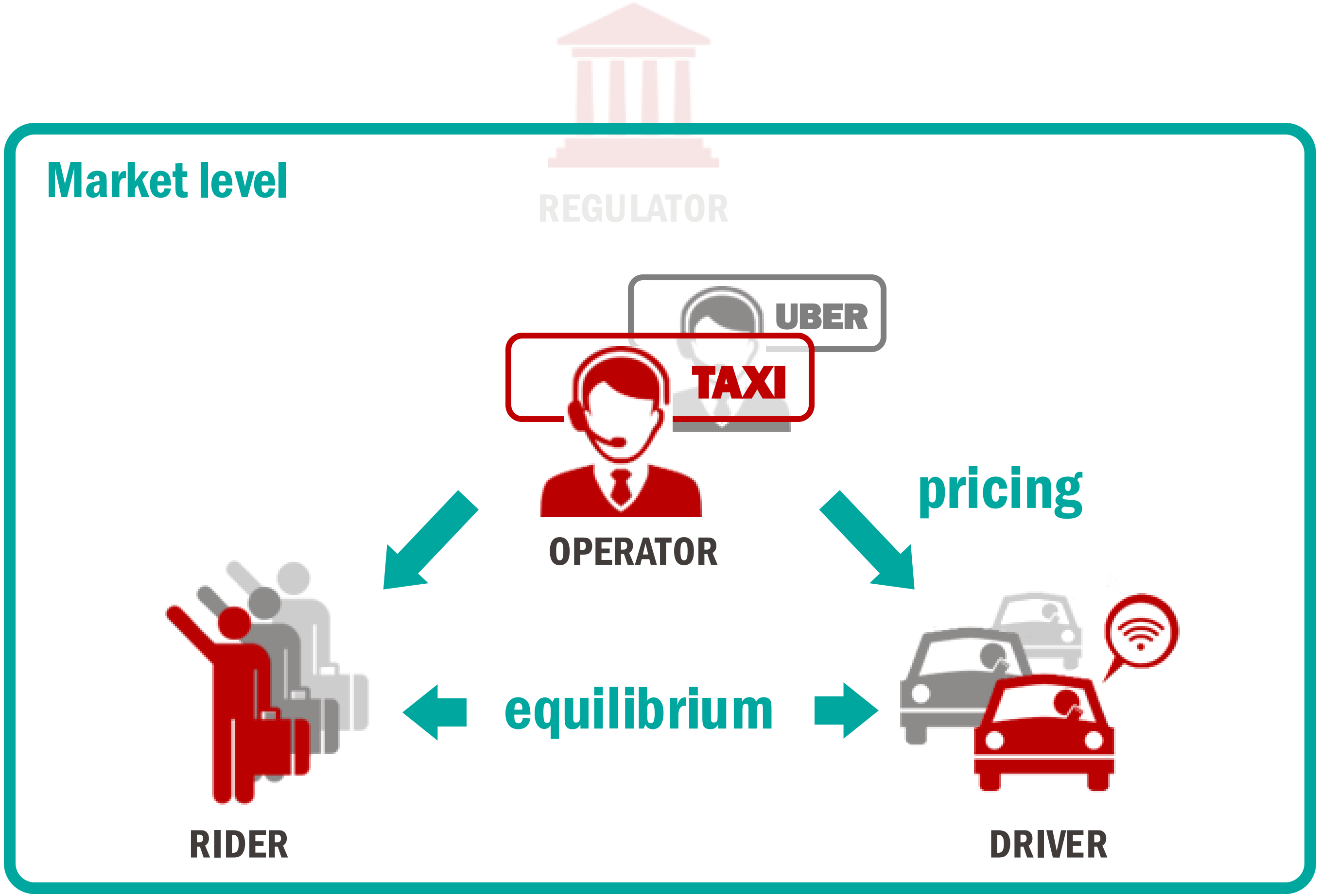
street-hailing

e-hailing

taxi stand

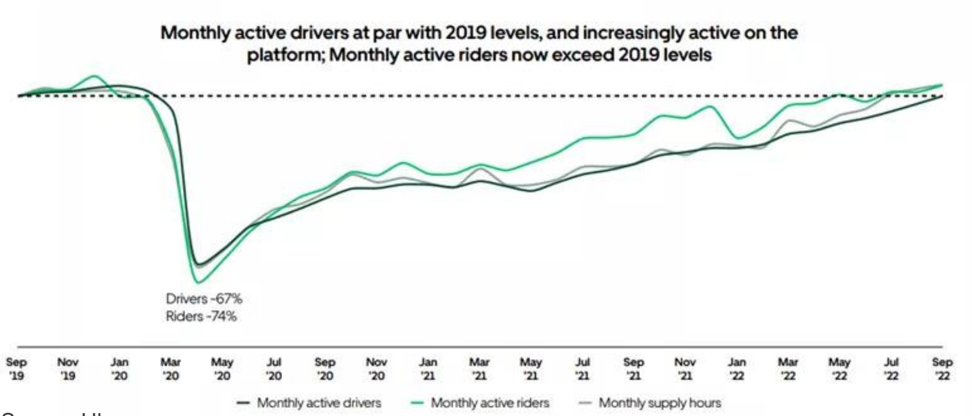
Ride-sharing with meeting point

What problems do we study?



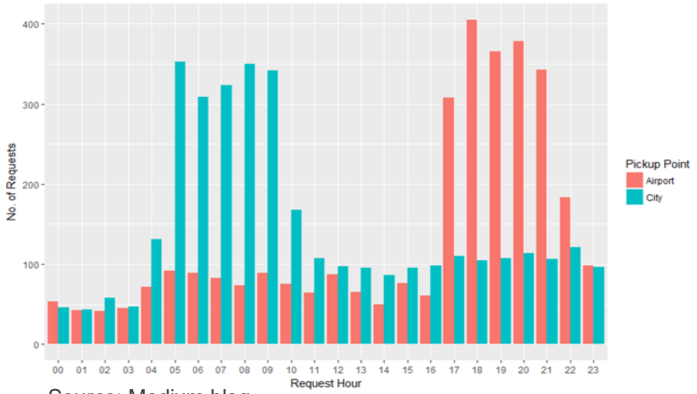
What problems do we study?

Active riders and drivers



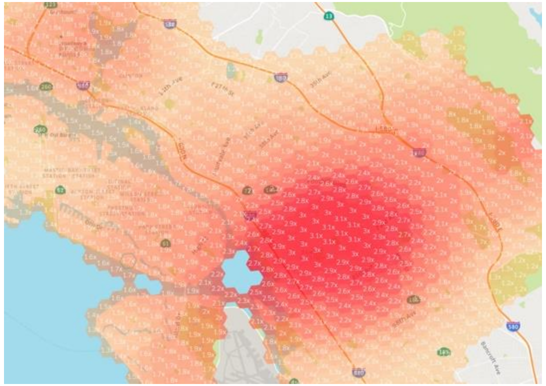
Source: Uber

Temporal demand pattern



Source: Medium blog

Peak-hour surge pricing



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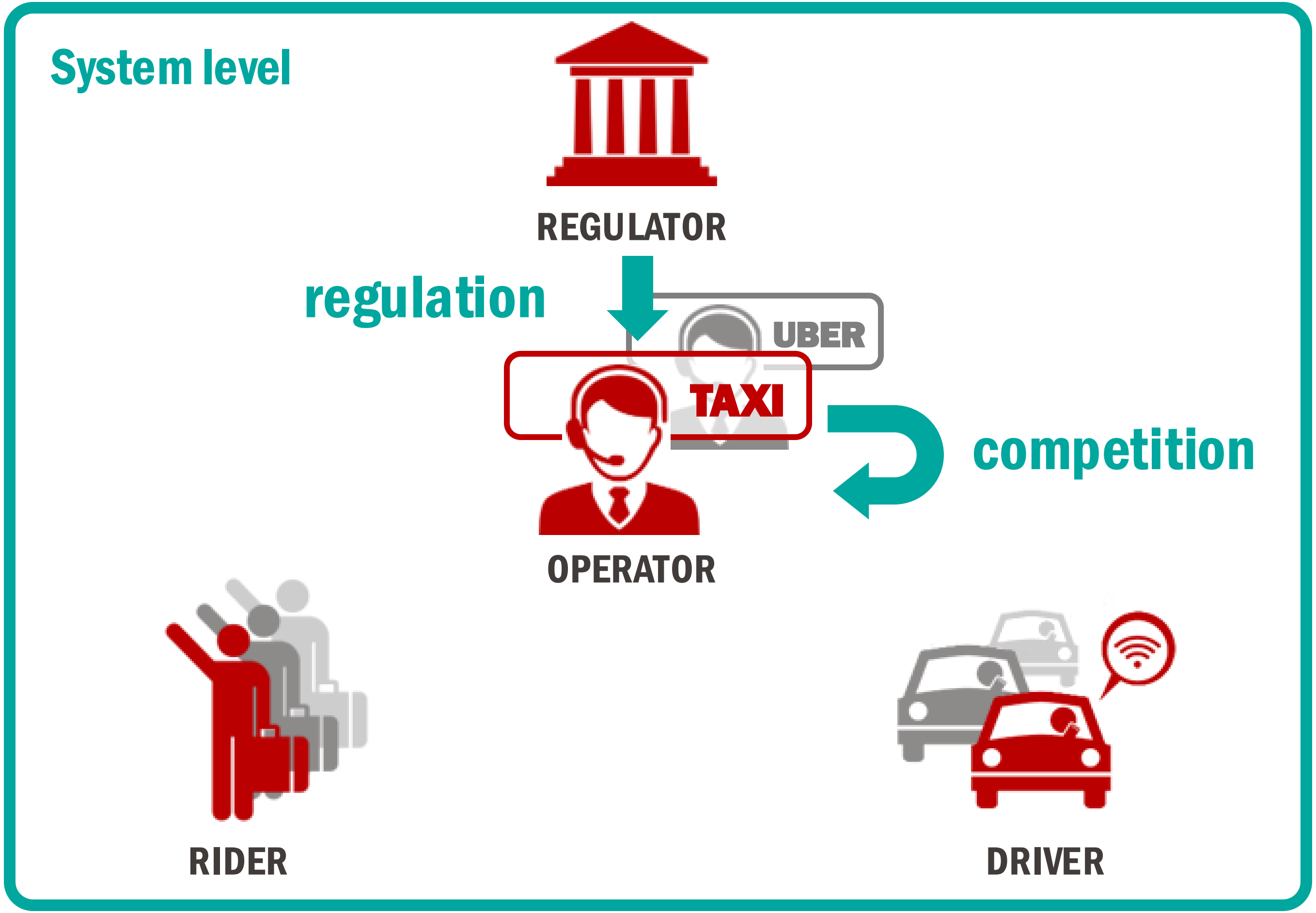
What problems do we study?



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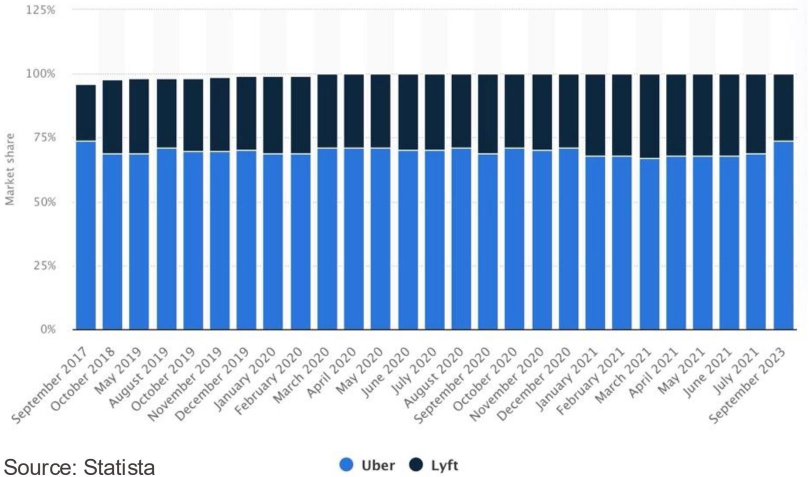
What problems do we study?

U.S. market share



Source: Statista

Multi-homing drivers

Driver protest for higher payment

Questions?

Next topic: Matching

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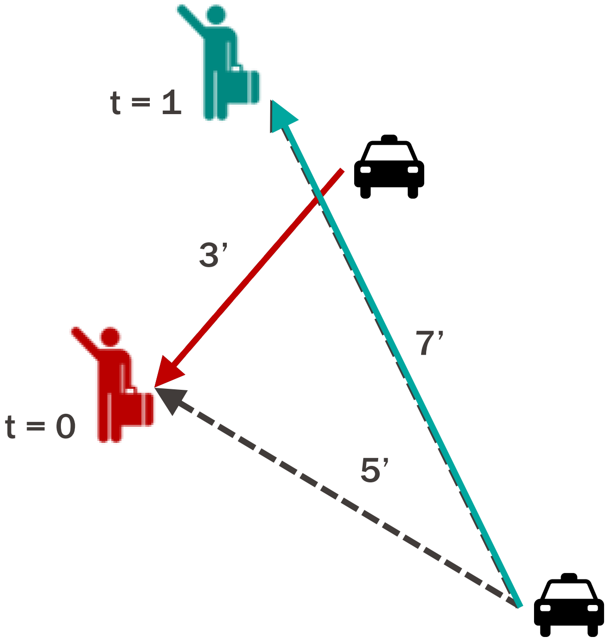
Matching problem

- How to dispatch drivers to pick up riders
  - Policy I: Instant matching
    - riders are first-come-first-served and matched to the closest driver



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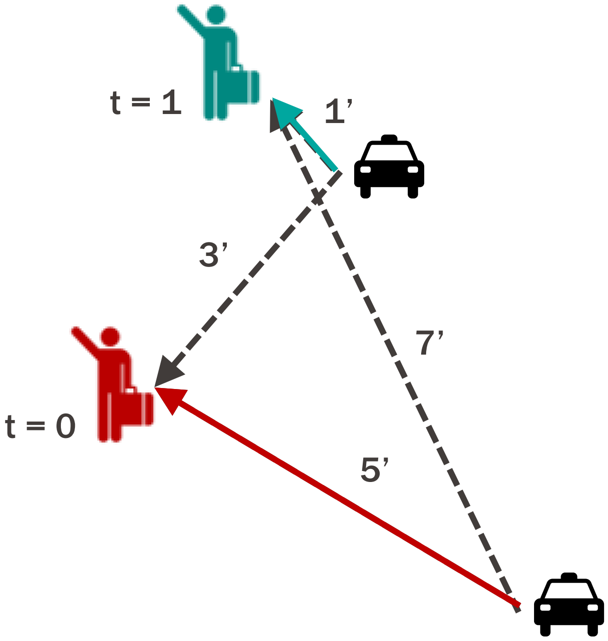
Matching problem

- How to dispatch drivers to pick up riders
  - Policy II: Batch matching
    - consolidate requests over a matching interval into a batch
    - match riders and drivers to minimize the total pickup time



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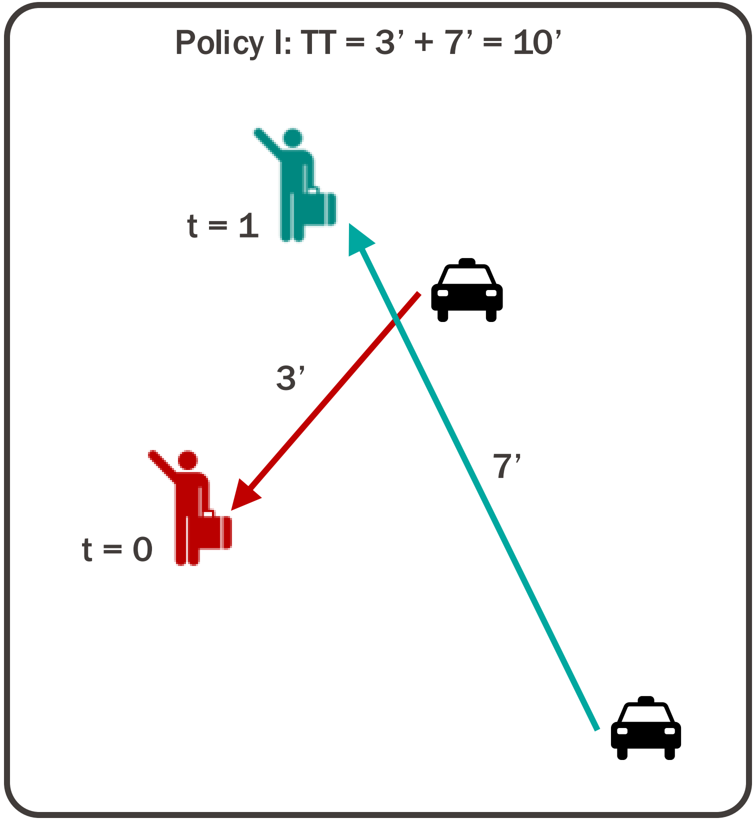
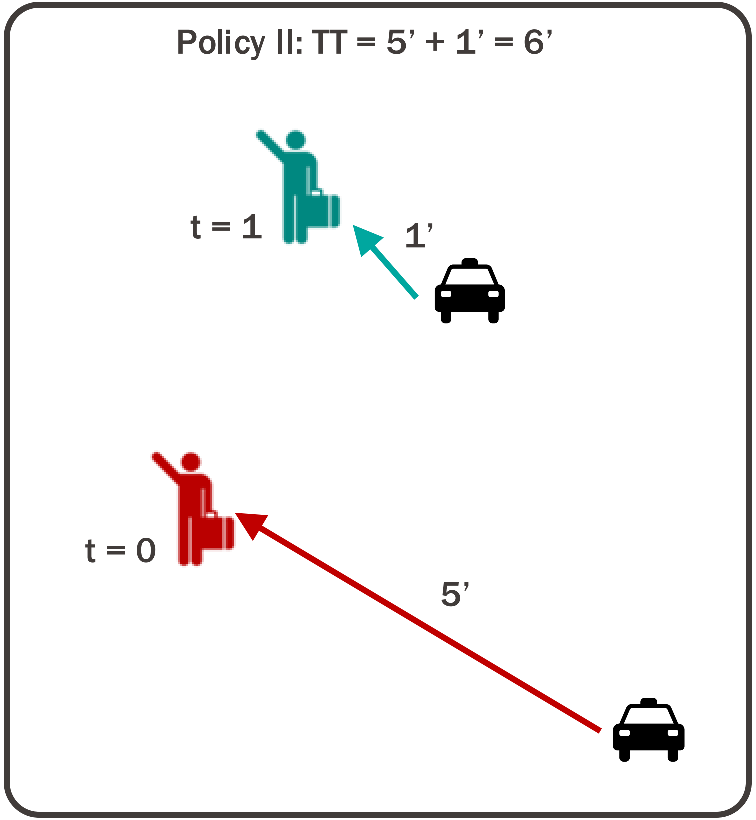
Matching problem

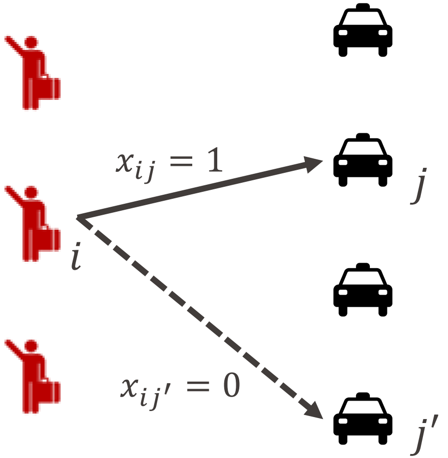
- Advantage of batch matching





Matching problem

- Mathematical formulation of batch matching
  - Set of riders: $I = \{1, \ldots, N\}$
  - Set of drivers: $J = \{1, \ldots, M\}, \quad M \geq N$
  - Matching indicator: $x_{ij} \in \{0,1\}, \quad i \in I, j \in J$
  - Pickup time: $t_{ij} \in R_+, \quad i \in I, j \in J$



Matching problem

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$$\min_x \quad \sum_{ij} t_{ij} x_{ij}$$

Objective: min total pickup time

$$s.t. \quad \sum_j x_{ij} = 1,$$

Constraint: all riders are matched

$$\sum_i x_{ij} \leq 1,$$

Constraint: each driver at most serves one rider

$$x_{ij} \in \{0,1\}.$$

Feasibility: binary matching decision

Matching problem

- Mathematical formulation of batch matching
  - Set of riders: $I = \{1, \dots, N\}$
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$$\begin{aligned} \min_x \quad & \textstyle\sum_{ij} t_{ij} x_{ij} \\ s.t. \quad & \textstyle\sum_j x_{ij} = 1, \\ & \textstyle\sum_i x_{ij} \leq 1, \\ & x_{ij} \in \{0,1\}. \end{aligned}$$

linear assignment problem

- **a fundamental combinatorial optimization problem**
- **small instances are easily solved by linear program**
- **other algorithms have been developed for large instances**

Matching problem

- Mathematical formulation of batch matching
  - Set of riders: $I = \{1, \dots, N\}$
  - Set of drivers: $J = \{1, \dots, M\}, \quad M \geq N$
  - Matching indicator: $x_{ij} \in \{0,1\}, \quad i \in I, j \in J$
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Extensions

- **hold some riders for future match**
- **ride-pooling, i.e., match one driver to multiple riders**
- **ensure fairness among drivers in a long term**

*** Research questions!**

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Matching model

- Solving the matching problem is good, but …
  - We need a model to capture the main trade-off in matching

    e.g., when # riders remains the same, increasing # drivers can reduce total pickup time

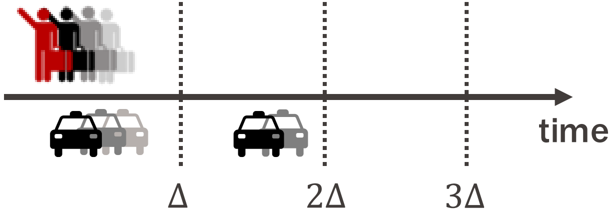
$$w = f(\Pi, \Lambda)$$

matching outputs **matching inputs**

where w: average waiting time (s)
Π: density of waiting riders (#/km^2)
Λ: density of idle drivers(#/km^2)

Matching model

- Model I: Frictionless batch matching
  - Matching interval: Δ (s)
  - Rider arrival rate: λ (#/s/km^2)
  - Idle driver arrival rate: μ (#/s/km^2)



Matching probability: $p = \min(1, \mu/\lambda)$

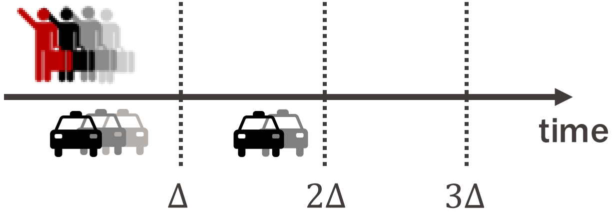
Expected num of matches: $n = 1/p$

Expected waiting time: $w = (n - 1/2)\Delta$

How is each equation derived?

Matching model

- Model I: Frictionless batch matching
  - Matching interval: Δ (s)
  - Rider arrival rate: λ (#/s/km^2)
  - Idle driver arrival rate: μ (#/s/km^2)



Matching probability: $p = \min(1, \mu/\lambda)$

Expected num of matches: $n = 1/p$

Expected waiting time: $w = (n - 1/2)\Delta$

How is this related to the general model $w = f(\Pi, \Lambda)$?

- Π: density of waiting riders (#/km^2)
- Λ: density of idle drivers(#/km^2)

Matching model

- Model I: Frictionless batch matching
  - Matching interval: Δ (s)
  - Rider arrival rate: λ (#/s/km^2)
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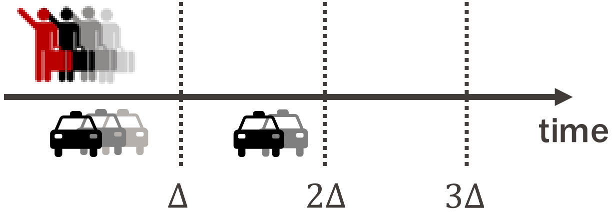

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How is this related to the general model $w = f(\Pi, \Lambda)$?

- Π: density of waiting riders (#/km^2) $\Pi = \lambda\Delta$
- Λ: density of idle drivers(#/km^2) $\Lambda = \mu\Delta$

Matching model

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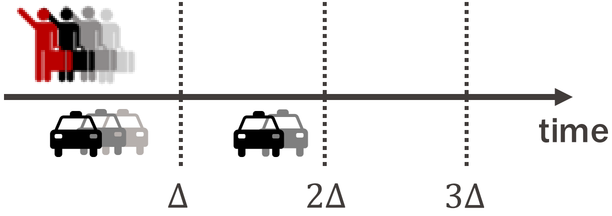
- Model I: Frictionless batch matching
  - Matching interval: Δ (s)
  - Rider arrival rate: λ (#/s/km²)
  - Idle driver arrival rate: μ (#/s/km²)



Matching probability: $p = \min(1, \mu/\lambda)$

Expected num of matches: $n = 1/p$

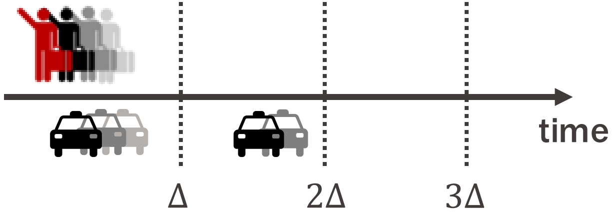
Expected waiting time: $w = (n - 1/2)\Delta$

$$w = \left(n - \frac{1}{2}\right)\Delta = \left(\frac{1}{\mathrm{p}} - \frac{1}{2}\right)\Delta = \left[\frac{1}{\min\left(1, \frac{\mu}{\lambda}\right)} - \frac{1}{2}\right]\Delta$$

$$= \left[\max\left(1, \frac{\lambda}{\mu}\right) - \frac{1}{2}\right]\Delta = \left[\max\left(1, \frac{\Pi/\Delta}{\Lambda/\Delta}\right) - \frac{1}{2}\right]\Delta$$

Matching model

- Model I: Frictionless batch matching
  - Matching interval: Δ (s)
  - Rider arrival rate: λ (#/s/km^2)
  - Idle driver arrival rate: μ (#/s/km^2)



Matching probability: $p = \min(1, \mu/\lambda)$

Expected num of matches: $n = 1/p$

Expected waiting time: $w = (n - 1/2)\Delta$

$$w = f(\Pi, \Lambda) = \left[\max\left(1, \frac{\Pi}{\Lambda}\right) - \frac{1}{2}\right]\Delta$$

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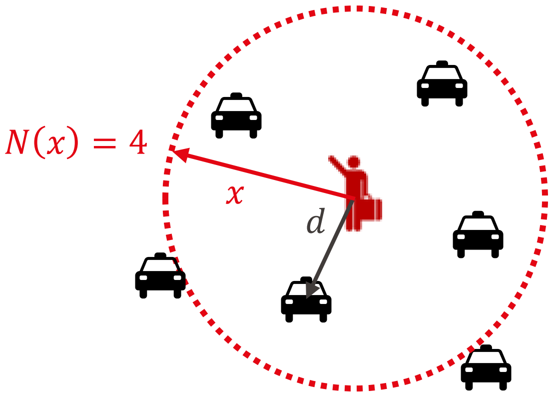
Matching model

- Model II: Non-congested instant matching
  - Matching radius ∞
  - Vehicle speed v (km/hr)
  - Density of idle drivers Λ (#/km²)



$$w = f(\Pi, \Lambda) = \frac{1}{2v\sqrt{\Lambda}}$$

Num of idle drivers within a distance x:

$$N(x) \sim \text{SpatialPP}(\Lambda)$$

Prob of at least one driver within a distance x:

$$1 - \Pr(N(x) = 0) = 1 - \exp(-\pi\Lambda x^2)$$

- equal to prob that the closest driver is within x
- equal to prob that the pickup distance $d \leq x$

Expected waiting time:

$$w = \frac{\mathbb{E}[d]}{v} = \frac{1}{2v\sqrt{\Lambda}}$$

Matching model

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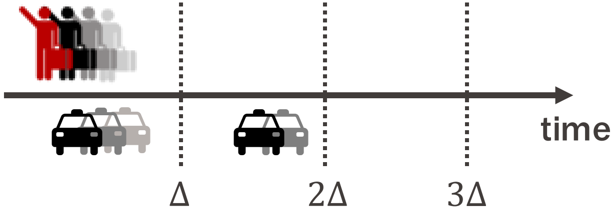
- Both make sense but look so different…

  * Because they each capture one part of total waiting time

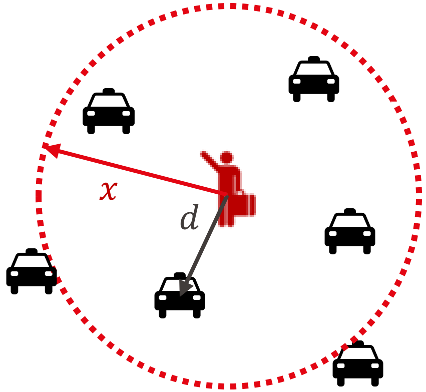
- Model I: $w \approx w_m = \left(\max\left(1, \frac{\Pi}{\Lambda}\right) - \frac{1}{2}\right)\Delta$

  * Pickup time is missing



- Model II: $w \approx w_p = \frac{1}{2v\sqrt{\Lambda}}$

  * Matching time is missing



* A general should model consider both pickup and matching

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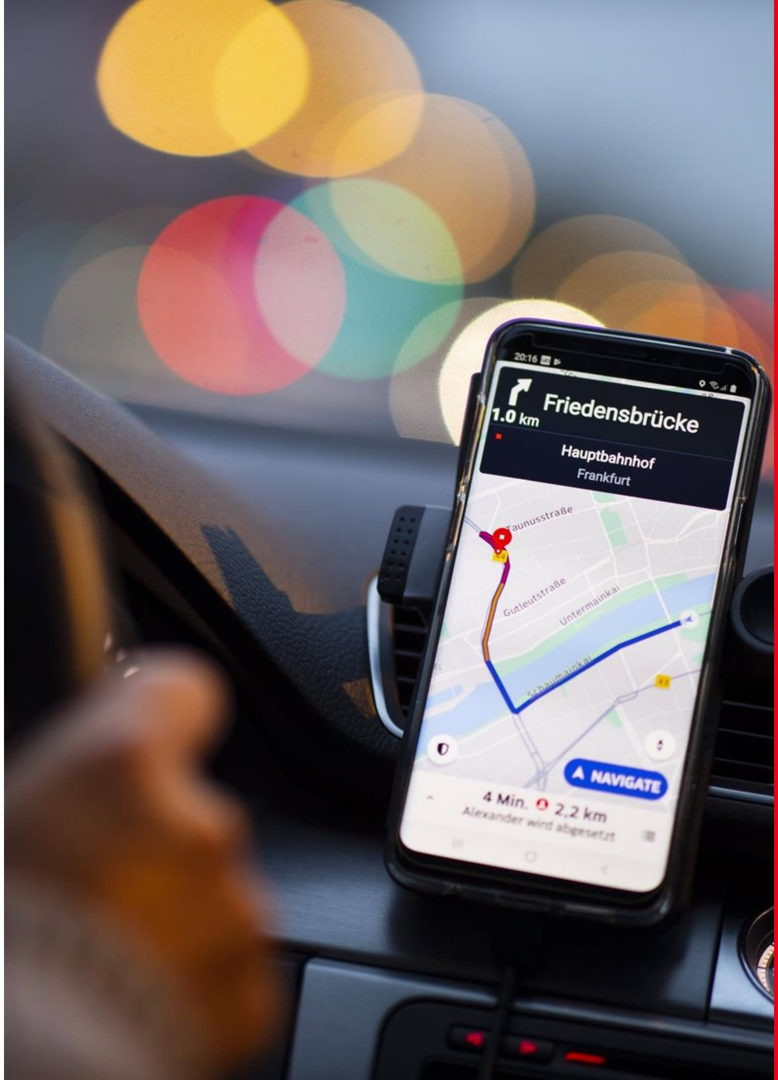
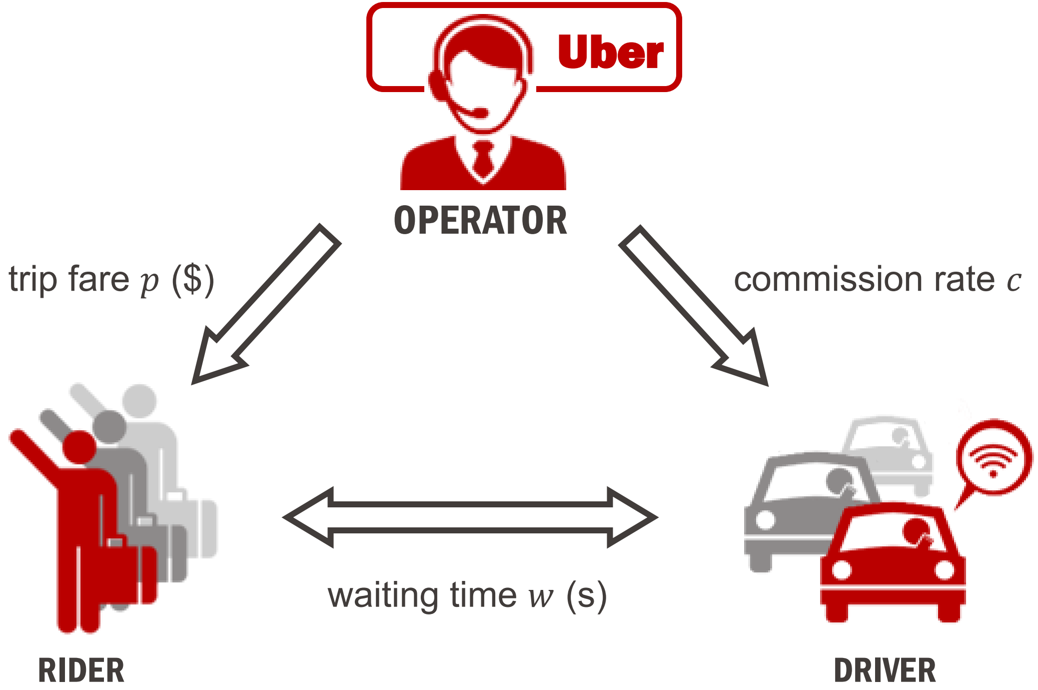


Questions?

Next topic: Operations

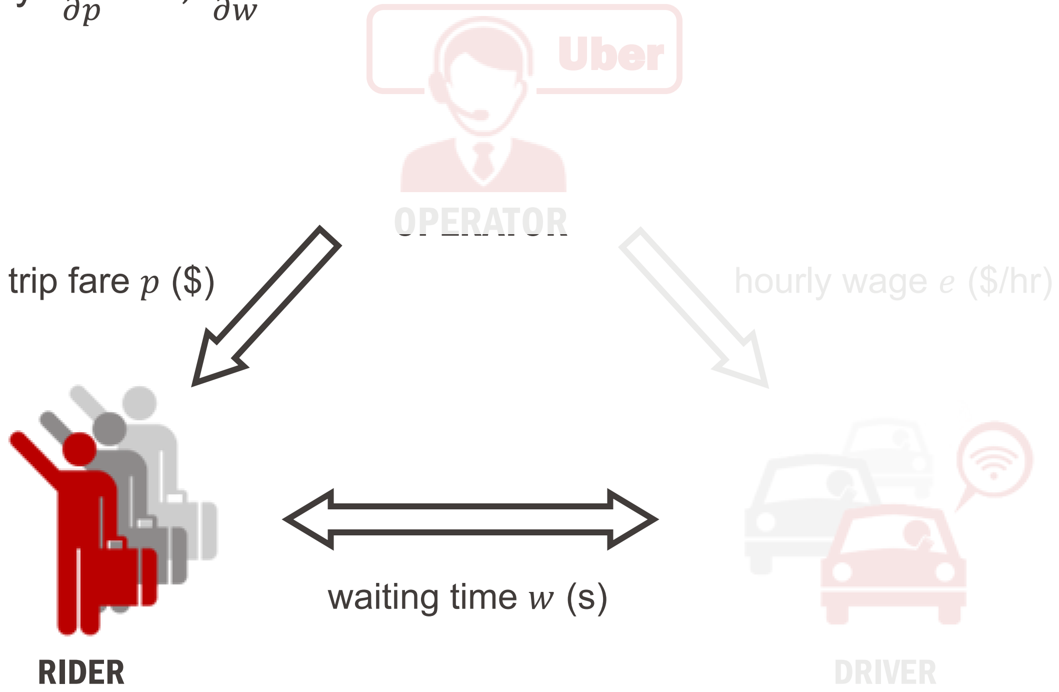
Monopoly market

- A single dominating operator



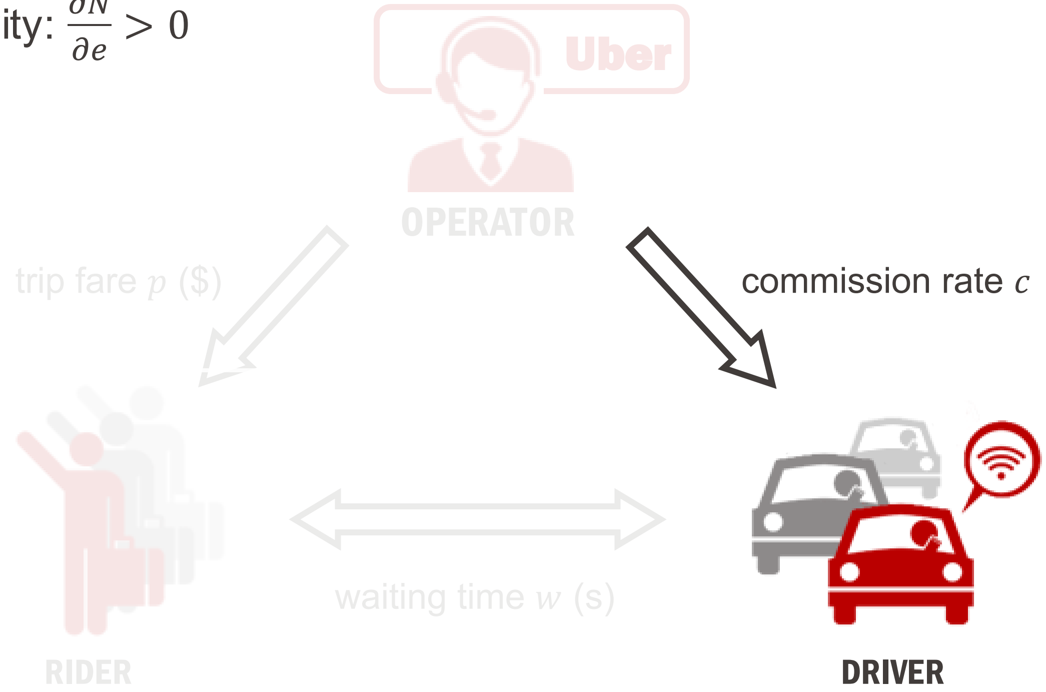
Monopoly market

- Rider demand $Q = D(p, w)$
  - Sensitivity: $\frac{\partial Q}{\partial p} < 0$, $\frac{\partial Q}{\partial w} < 0$



Monopoly market

- Driver supply $N = S(e)$
  - Hourly wage $e = (1 - c)pQ/N$
  - Sensitivity: $\frac{\partial N}{\partial e} > 0$



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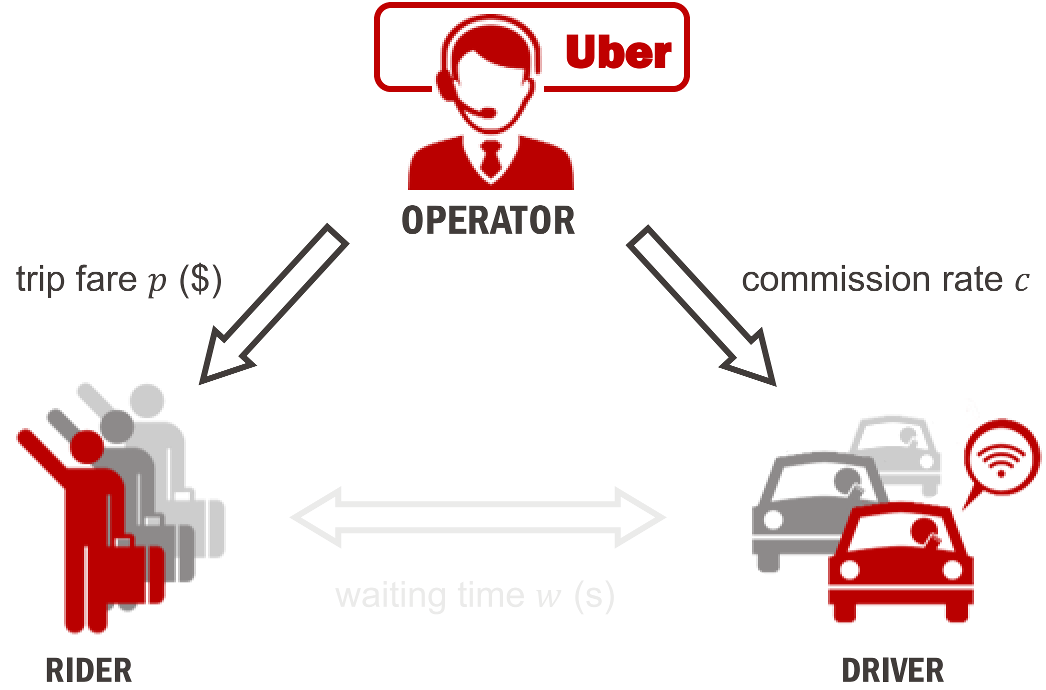
Monopoly market

- Operator profit $R(p, c) = cQ$



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Monopoly market

- Pricing in a monopoly market
  - Assume trips are uniformly distributed with average in-vehicle time τ (s)
  - Decide trip fare p ($) and commission rate c to max profit

$$\max_{p,c} \quad R(p,c) = cQ$$

$$s.t.$$

$$Q = D(p,w), \qquad \text{Demand function}$$

$$N = S(e(p,c,Q)), \qquad \text{Supply function}$$

$$w = f(\Pi,\Lambda), \qquad \text{Matching model}$$

$$N = \Lambda + Q(w+\tau), \qquad \text{Fleet conservation}$$

$$\Pi = Qw. \qquad \text{Unmatched riders}$$

Market equilibrium constraints

Monopoly market

- How to solve the optimal pricing strategy?
  - Option I: throw the entire problem into solver

    *** Infeasible when model is highly nonlinear and complicated**

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Monopoly market

- How to solve the optimal pricing strategy?
  - Option I: throw the entire problem into solver
  - Option II: solve the equilibrium at each feasible price

$$\max_{p,c} \quad R(p,c) = cQ$$

$$s.t. \quad Q = D(p,w),$$

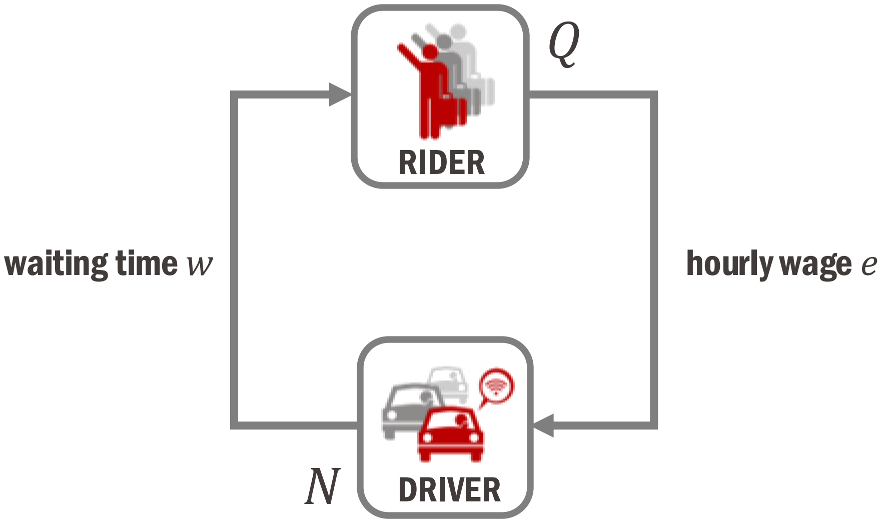
$$N = S(e(p,c,Q)),$$

$$w = f(\Pi, \Lambda),$$

$$N = \Lambda + Q(w+\tau),$$

$$\Pi = Qw.$$

Given price p & commission c

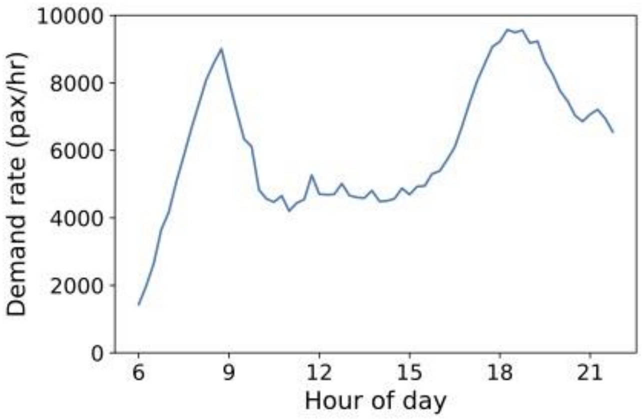


*** We will learn how to solve this in CIVIL 324**

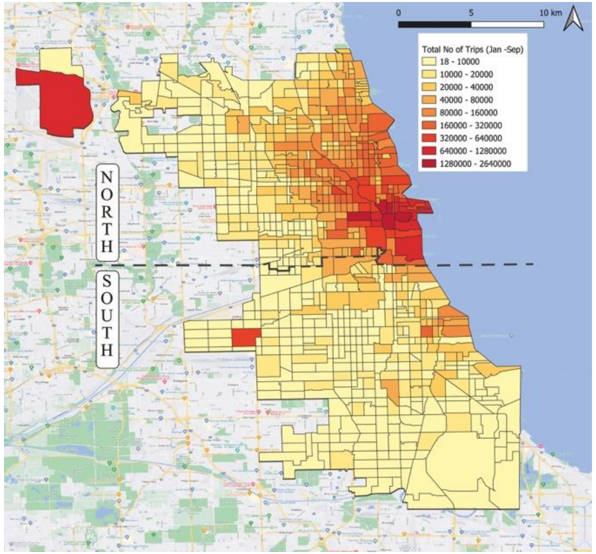
Monopoly market

- So far, we consider a uniform market
  - Demand and supply are evenly distributed over time and space
  - Clearly not the case in reality
    - e.g., Chicago ride-hailing trips

Daily demand pattern



Trip origin distribution



Monopoly market

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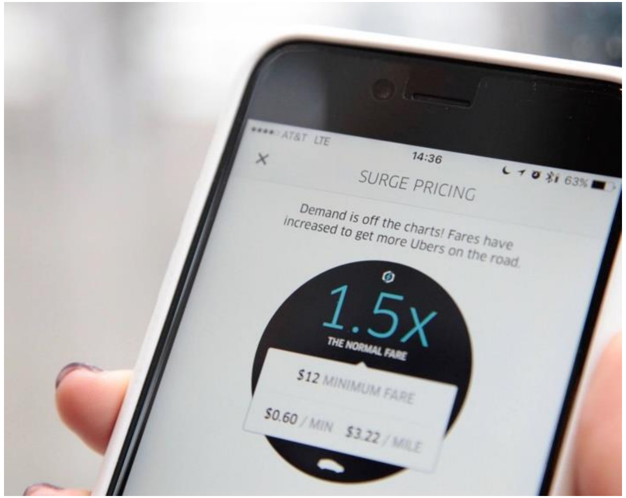
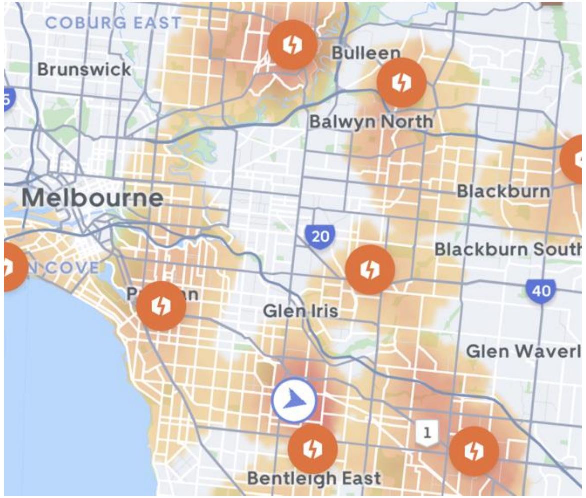
- Common solutions to address demand-supply imbalance
  - Surge pricing
  - Vehicle rebalancing

Rider side: surge multiplier



Driver side: demand heat map



Surge pricing

- Assumption of short-term market
  - Demand curve: $Q = D(p, w) = D_0 - p - w$
    - Potential demand D_0 increase during a demand peak
  - Supply curve: $Q = S(w) = \frac{N - \Lambda(w)}{w + \tau}$
    - Fleet size N remains the same
    - Density of idle drivers $\Lambda(w)$ as a function of waiting time w

$$w = \frac{1}{2v\sqrt{\Lambda}} \Rightarrow \Lambda = \frac{1}{4v^2 w}$$

    - Trip supply $S(w)$ is derived from flow conservation

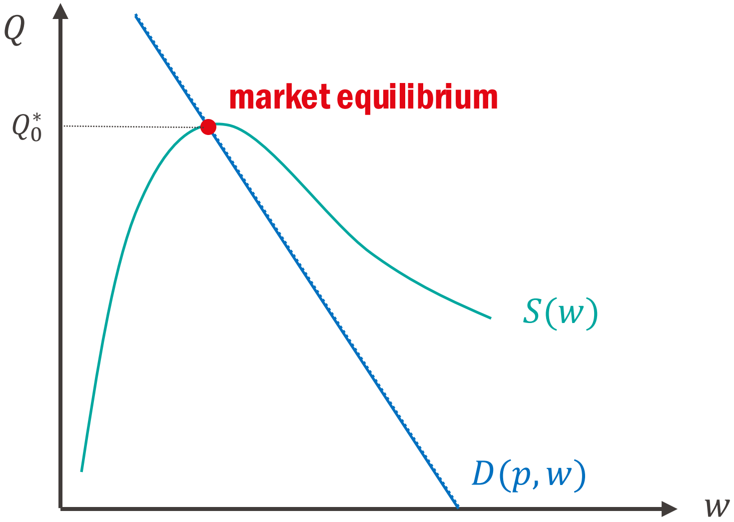
$$N = \Lambda + Q(w + \tau),$$

$$\Rightarrow N = \Lambda(w) + S(w)(w + \tau),$$

Surge pricing

Kenan Zhang

- Assumption of short-term market
  - Demand curve: $Q = D(p, w) = D_0 - p - w$
  - Supply curve: $Q = S(w) = \frac{N - \Lambda(w)}{w + \tau}$



Surge pricing

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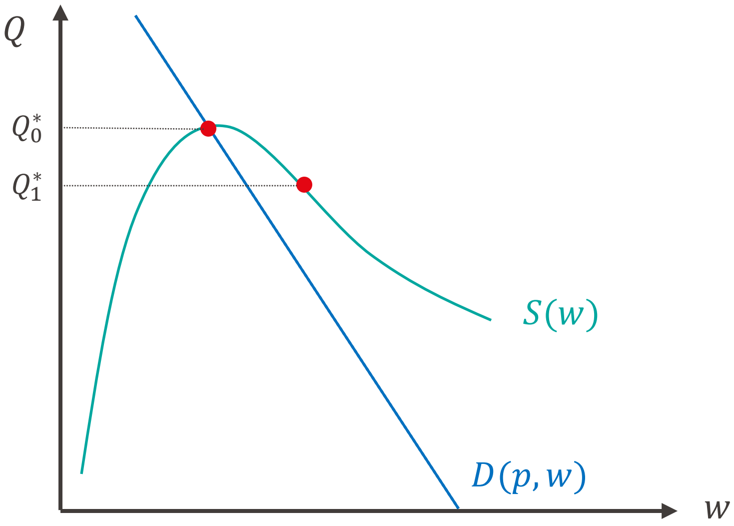

During a demand peak,

- D_0 increase while N remain the same
- Market moves to an inefficient state $Q_0^* \rightarrow Q_1^*$ with fewer served trips

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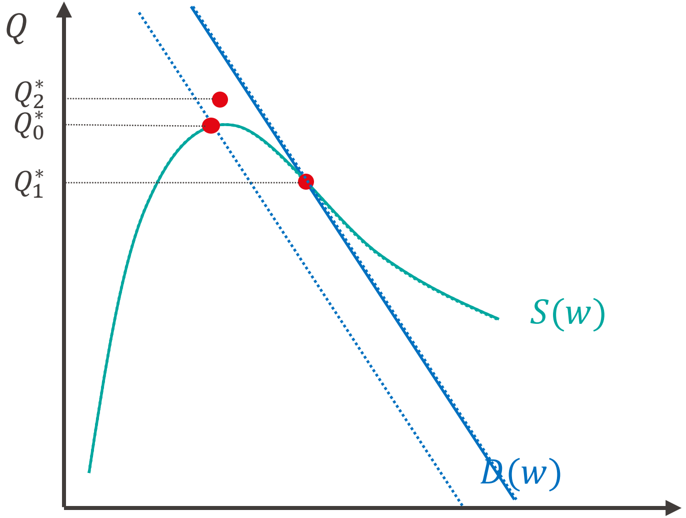
Surge pricing

- Assumption of short-term market
  - Demand curve: $Q = D(p, w) = D_0 - p - w$
  - Supply curve: $Q = S(w) = \frac{N - \Lambda(w)}{w + \tau}$

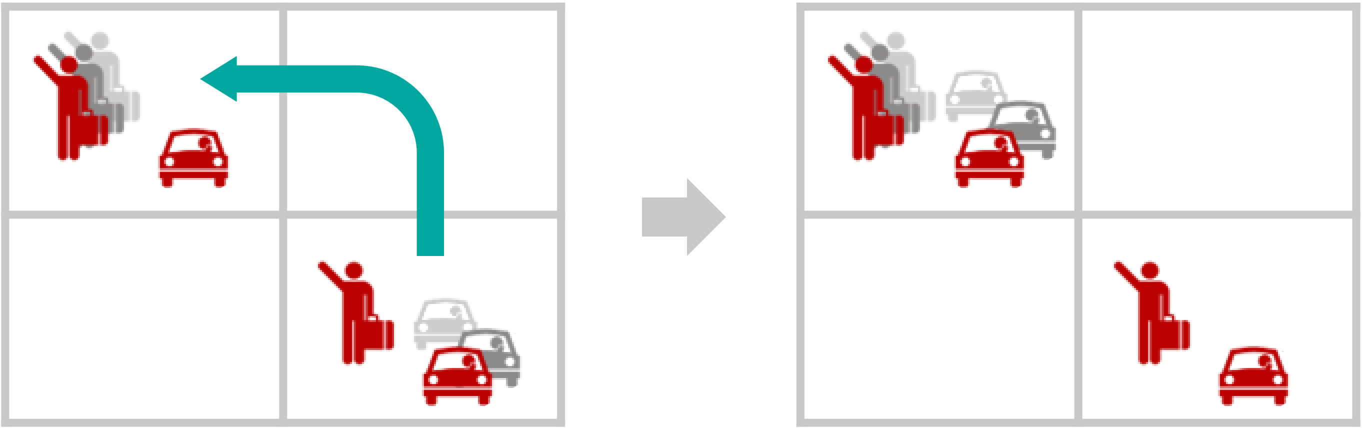


During a demand peak,

- D_0 increase while N remain the same
- Market moves to an inefficient state $Q_0^* \rightarrow Q_1^*$ with fewer served trips
- A surge price pushes demand curve back and possibly induce a larger N
- Market returns to an efficient state $Q_1^* \rightarrow Q_2^*$

Vehicle rebalancing

- Motivations
  - Trips are not evenly distributed over space
  - Drivers' spontaneous search may not be efficient
    - lack of real-time information
    - selfish decisions do not ensure system optimum
  - Some centralized control and intervention are beneficial to all



Vehicle rebalancing

- A static model

Notations:

- p_{ij}: trip fare
- c_{ij}: relocation cost
- x_{ij}: trip flow
- x_{ij}^0: relocation flow
- λ_i: rider arrival rate
- μ_i: driver arrival rate
- α_{ij}: OD distribution
- τ_{ij}: trip duration
- N: fleet size

$$\max_{x,x^0} \quad \sum_{ij} p_{ij}x_{ij} - c_{ij}x_{ij}^0$$

Objective: max total revenue

$$s.t. \quad x_{ij} = \alpha_{ij} g(\lambda_i, \mu_i)\,,$$

Trip flow between every two zones

$$\mu_i = \sum_k (x_{ki} + x_{ki}^0)\,,$$

Driver supply in each zone

$$\sum_k (x_{ki} + x_{ki}^0) = \sum_j (x_{ij} + x_{ij}^0)\,,$$

Inflow equals outflow for each zone

$$\sum_{ij} (x_{ij} + x_{ij}^0)\tau_{ij} = N,$$

Fleet conservation

$$x_{ij}, x_{ij}^0 \geq 0.$$

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Beyond monopoly market

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- Cities are rarely dominated by a single operator
- Competition and cooperation often co-exist
  - Uber vs Lyft
  - Uber + taxis
  - Lyft + Metro/Citi Bike

Uber Rewards

Source: Uber

Uber Partners With Yellow Taxi Companies in N.Y.C.

The ride-hailing giant is teaming up with two taxi technology companies in an unlikely alliance.

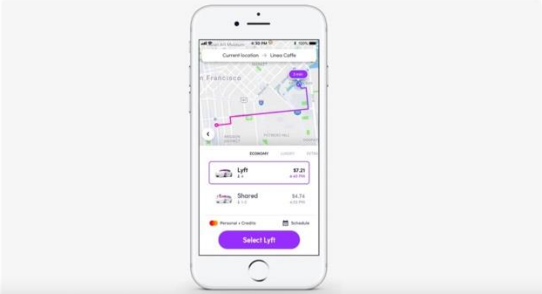
Share full article 160

Source: New York Times

Lyft's new app to integrate directly with public transit

Published June 8, 2018

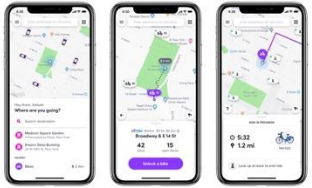
Kristin Musulin
Senior Editor



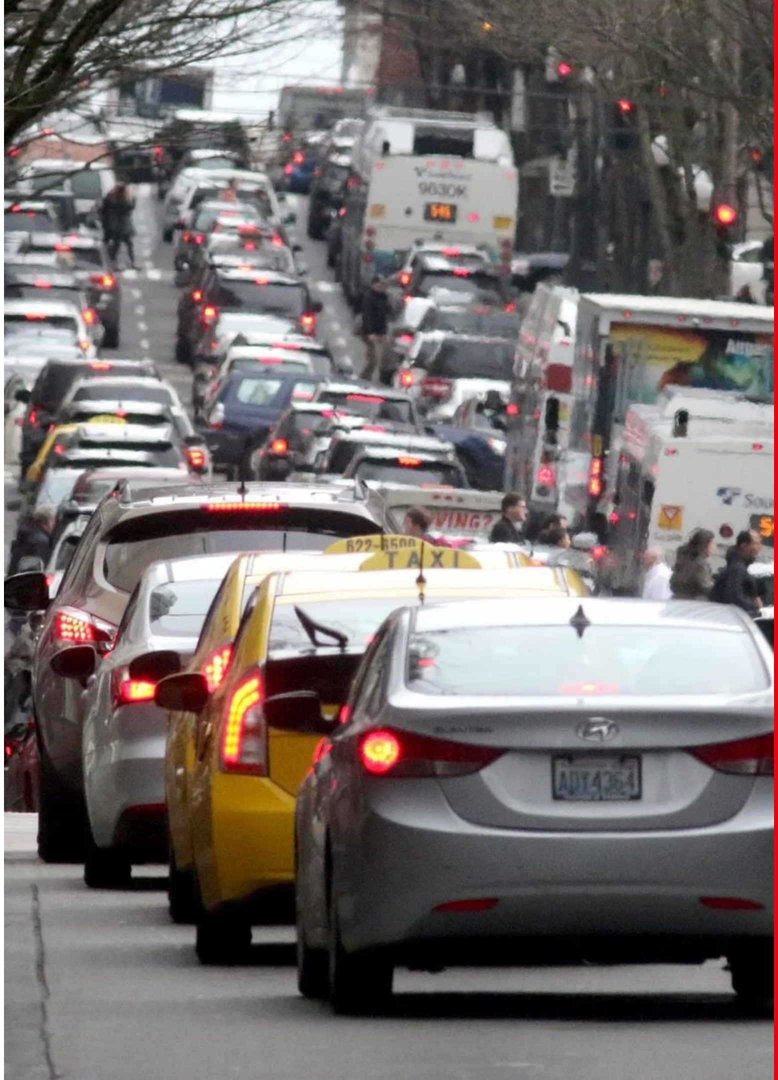
Source: Smart Cities Dive

Citi Bike: Now available in the Lyft app

Update your Lyft app to get riding!



Source: Citi Bike



Questions?

Next topic: Regulations

EPFL

Why regulation is needed

- Incompatible objectives

- Operator:
  - max profit, market share, …

- Regulator:
  - max social welfare
    = travel utility of riders
    + profit of operator
    + earning of drivers
    + …
  - min congestion and emission
  - ensure mobility accessiblity

Ride-hailing vehicles cause more congestion in San Francisco Erhardt et al. (2019)

Oversupply of shared bikes in China

Kenan Zhang

Regulations in practice

Kenan Zhang

Supply side
- min wage rate
- fleet cap
- contractor vs employee
- ….

Demand side
- congestion charge
- mobility credits
- ….

Operations
- dedicated service region
- data sharing
- ….

Uber, Lyft must continue to limit size of fleets in New York City

To fight congestion, the city council votes to indefinitely extend a cap on the number of ride-hailing vehicles on New York streets.

Corinne Reichert
June 12, 2019 2:32 p.m. PT
3 min read

CAPITOL ALERT
Capitol Alert

California sued over gig economy law. What Uber and Postmates say about AB 5

BY DALE KASLER
UPDATED DECEMBER 30, 2019 5:40 PM

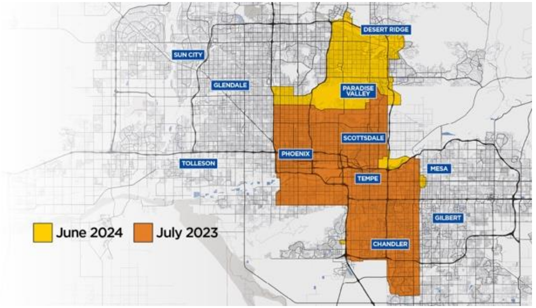
Chicago congestion tax on rideshare trips takes effect

By Jessica D'Onofrio and Sarah Schulte
Tuesday, January 7, 2020

Waymo expands into metro Phoenix, downtown Mesa, Talking Stick

By Lauren Kobley
Published: Jun. 6, 2024 at 1:08 AM CEST | Updated: Jun. 6, 2024 at 3:39 AM CEST

PHOENIX (AZFamily)—Waymo, the autonomous rideshare program, is expanding its reach in the Valley to include parts of north Scottsdale, north Phoenix, Mesa, and Ahwatukee.



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How to analyze a policy

- Additional constraints in the operator's problem
  - e.g., max fleet size $\overline{N}$ and min wage rage $\underline{e}$

$$\max_{p,c} \quad R(p,c) = cQ$$

$$\begin{aligned} s.t. \quad & Q = D(p,w), \\ & N = S(e(p,c,Q)), \\ & w = f(\Pi, \Lambda), \\ & N = \Lambda + Q(w+\tau), \\ & \Pi = Qw. \end{aligned}$$

market equilibrium

$$N \leq \overline{N}, e \geq \underline{e},$$

regulatory constraints

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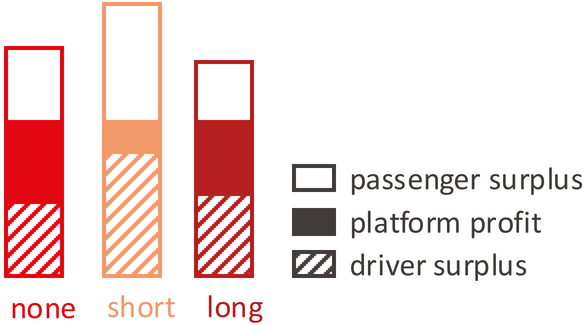
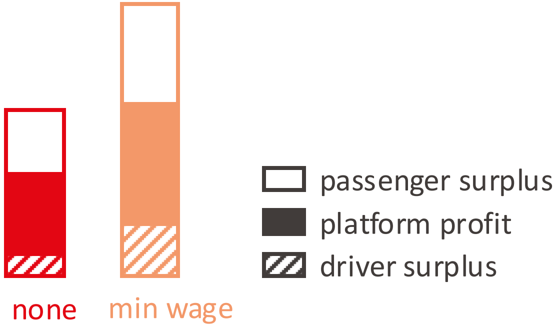
How to analyze a policy

- Be careful of potential "pitfalls"
  - Short-term vs long-term



- min wage helps improve social welfare in short-term by sacrificing platform profit
- in a long run, it could even be harmful to social welfare

  - Market structure



- min wage does benefit a duopoly market with multi-homing by maintaining a sufficient supply

Summary

- What we've discussed today
  - Matching in a solo ride-hailing trip
  - Pricing strategy of a monopoly operator
  - Surge pricing and vehicle relocation
  - Overview of regulations

- What are other interesting topics
  - Matching in micromobility and pooling trips
  - Competition and cooperation among operators
  - Introduction of autonomous vehicles
  - Integration of mobility-on-demand into transit system
  - Issue of equity and fairness
  - ….

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Thanks!
Q & A

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