October 10, 2024

# 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

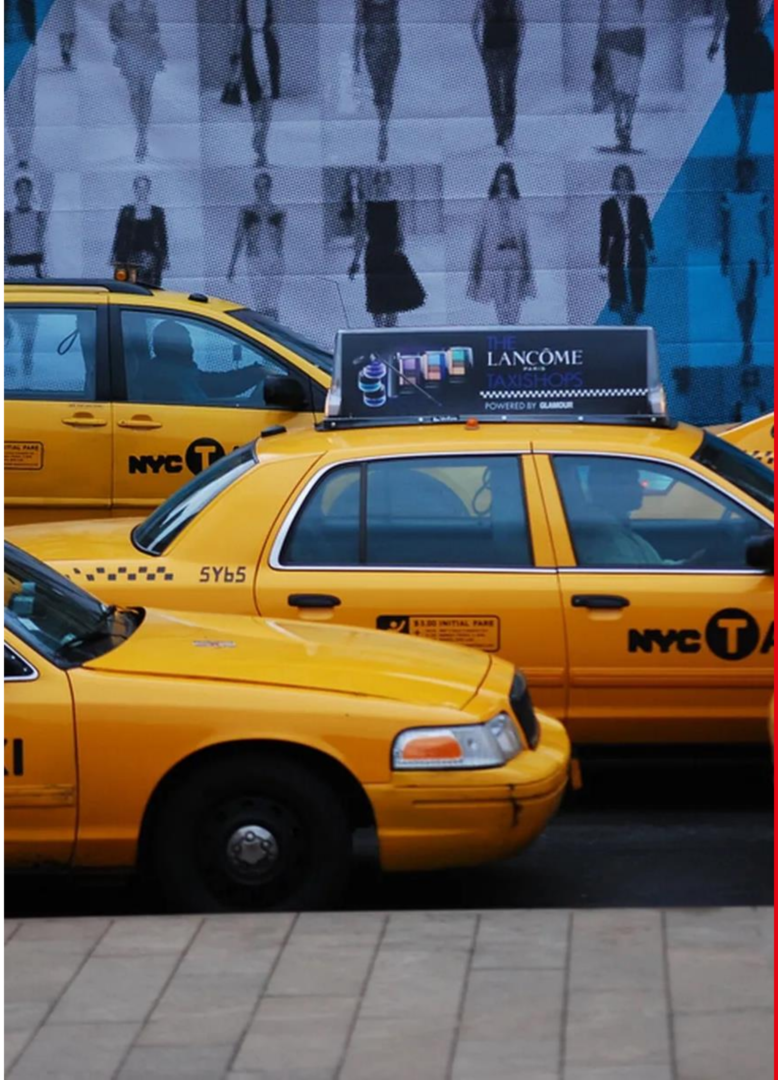
- network modeling
- game theory
- min F(x) optimization
- data-driven & learning

# 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
  - Routing, choice modeling, incentives design, and network analysis
  - Learning and data-driven analyses on travel behaviors
  - Simulation of on-demand mobility and meal-delivery
  - Analysis of carpooling and bikesharing on EPFL campus (with Mobility Office)

HOMES @ EPFL








# Agenda

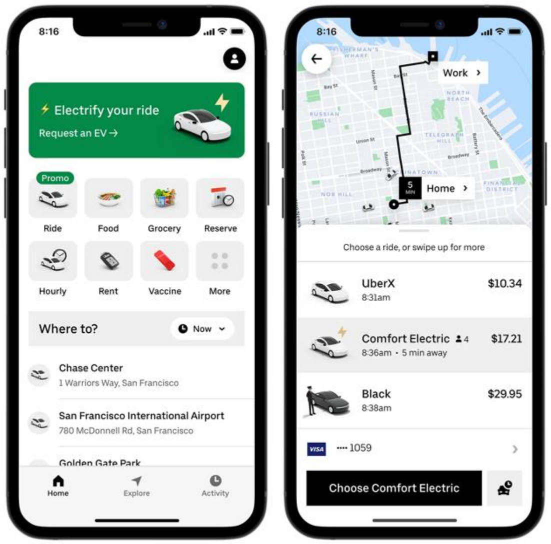
- Basics
- Matching
- Operations
- Regulations

# What is on-demand and shared mobility

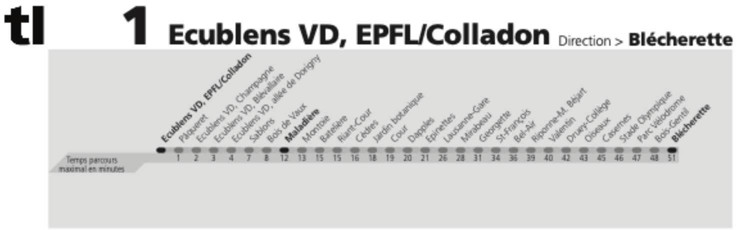


Kenan Zhang

- "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**

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

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| **Ecublens VD, EPFL/Colladon** | 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 51 | 06 58 | 07 04 | 07 10 | 07 16 | 07 22 | 07 29 | 07 36 | 07 42 | 07 48 | 07 55 |
| Sablons | 06 54 | 07 01 | 07 07 | 07 13 | 07 19 | 07 25 | 07 32 | 07 39 | 07 45 | 07 51 | 07 58 |
| **Maladière** | 06 58 | 07 05 | 07 11 | 07 17 | 07 23 | 07 29 | 07 36 | 07 43 | 07 50 | 07 56 | 08 03 |
| Montoie | 06 59 | 07 06 | 07 12 | 07 18 | 07 24 | 07 30 | 07 37 | 07 44 | 07 51 | 07 57 | 08 04 |
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| Casernes | 07 27 | 07 34 | 07 40 | 07 46 | 07 53 | 07 59 | 08 06 | 08 13 | 08 20 | 08 26 | 08 33 |
| **Blécherette** | 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





- "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…

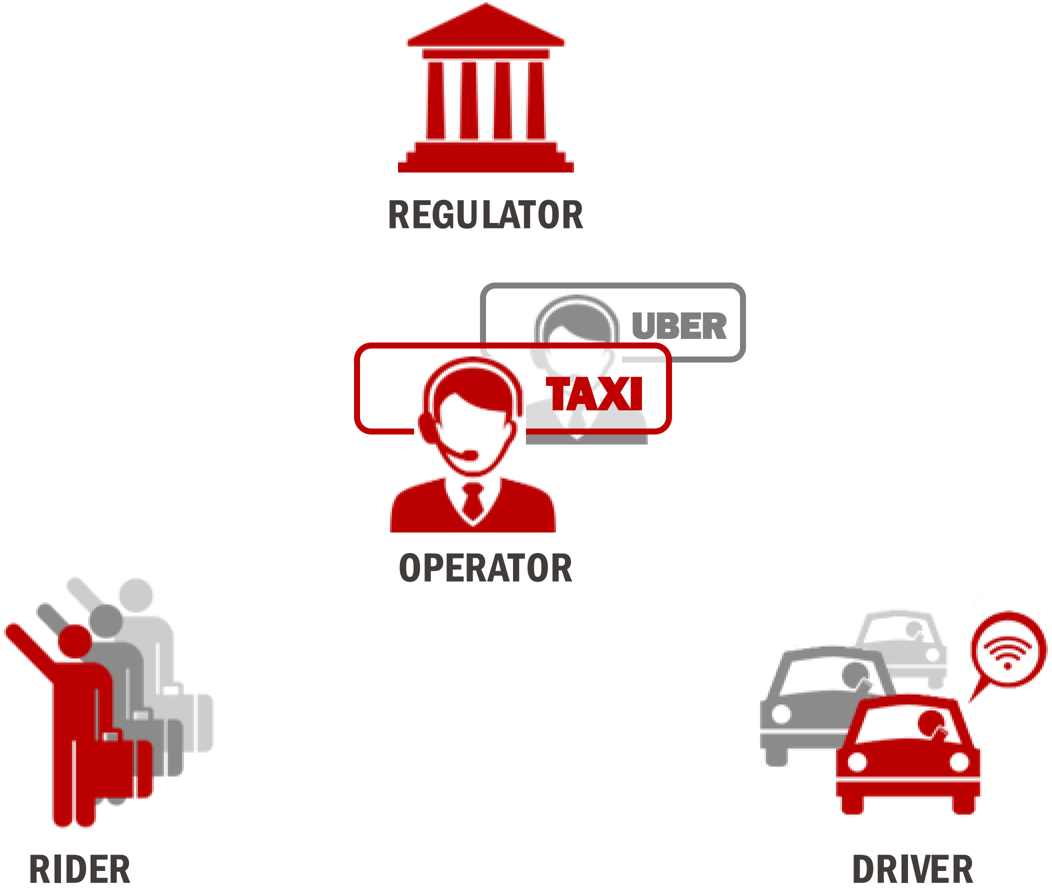
**ride-hailing**
- taxi
- e-hailing
- ride-pooling
- micro-transit

**micromobility**
- bike-sharing
- scooter-sharing

**ride-sharing**
- carpooling


**(on-demand) car-sharing**

# Who are the stakeholders?



# 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

# 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

# Who are the stakeholders?

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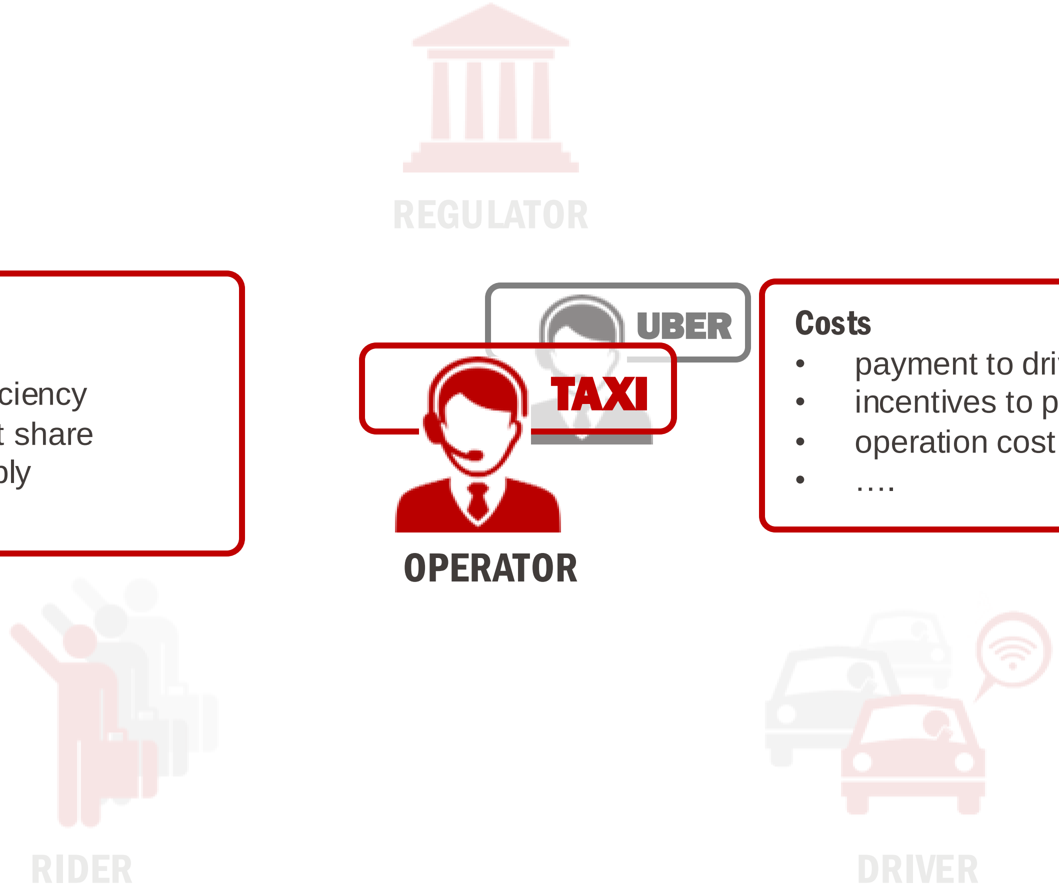



**Pursuits**
- high profit
- dispatch efficiency
- large market share
- reliable supply
- ….

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

Kenan Zhang

# 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

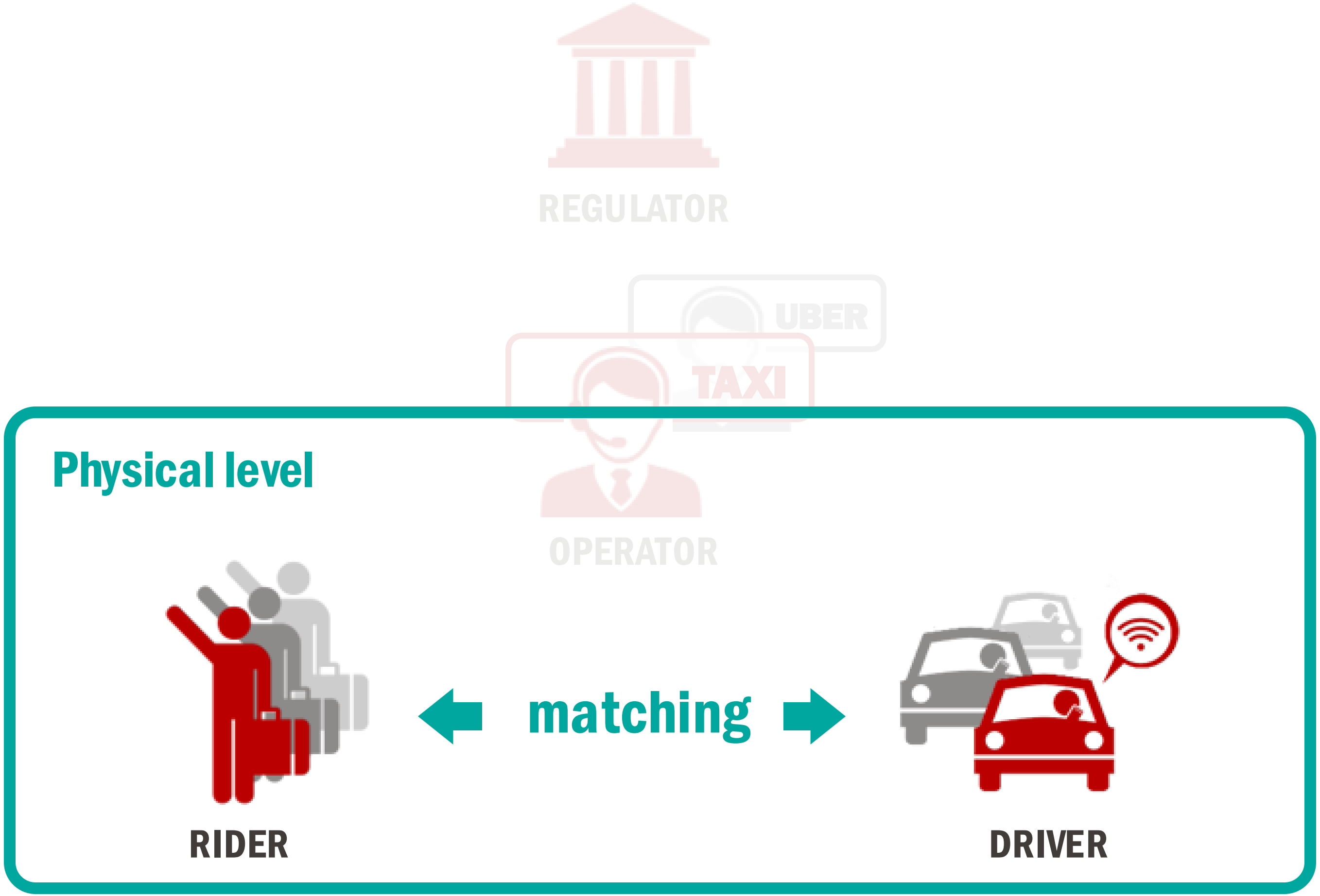


DRIVER

# What problems do we study?



Kenan Zhang



# What problems do we study?





street-hailing

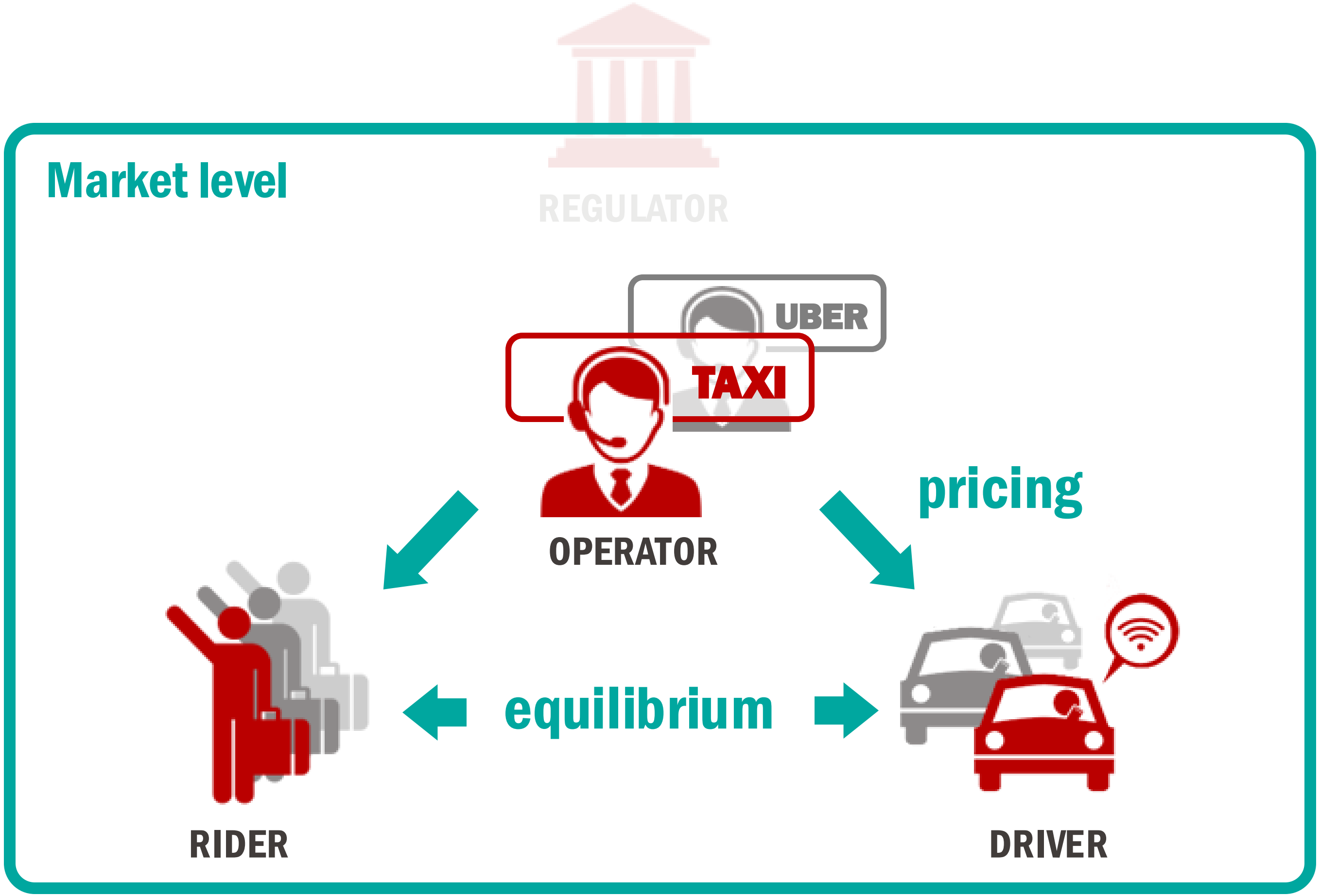

e-hailing


taxi stand


Ride-sharing with meeting point

# What problems do we study?

Kenan Zhang



# What problems do we study?

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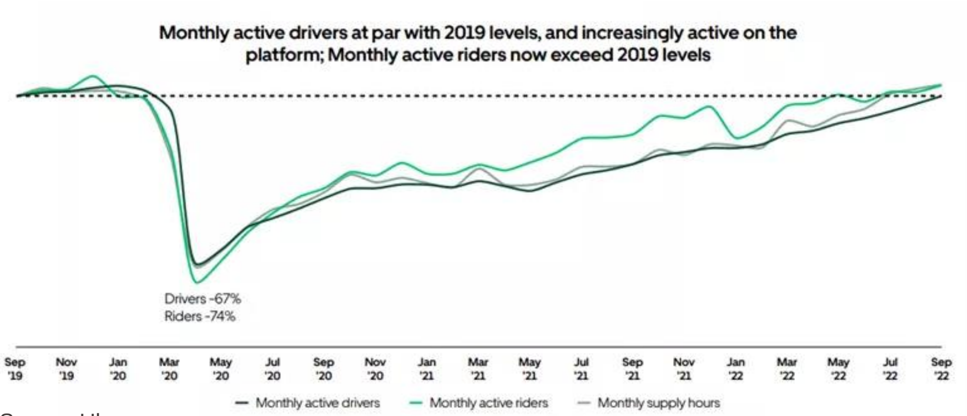
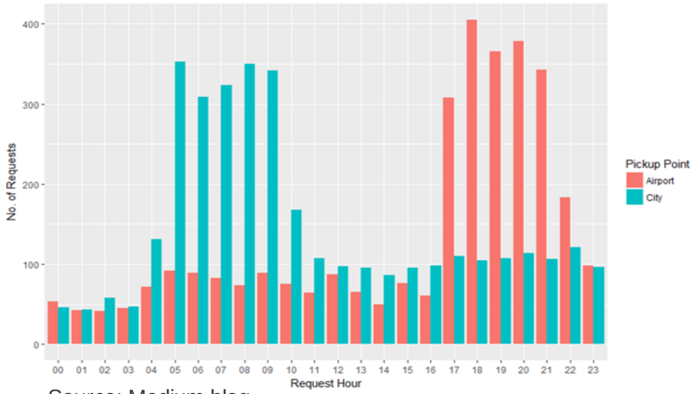
## Active riders and drivers



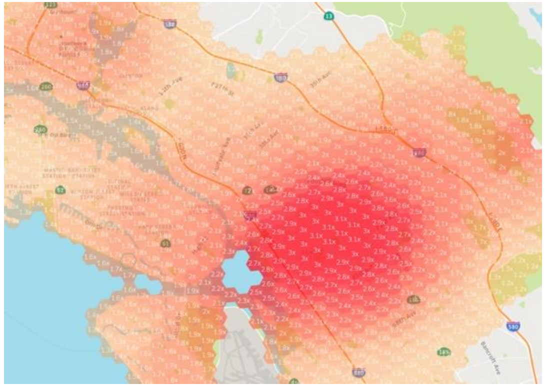

Source: Uber

## Temporal demand pattern



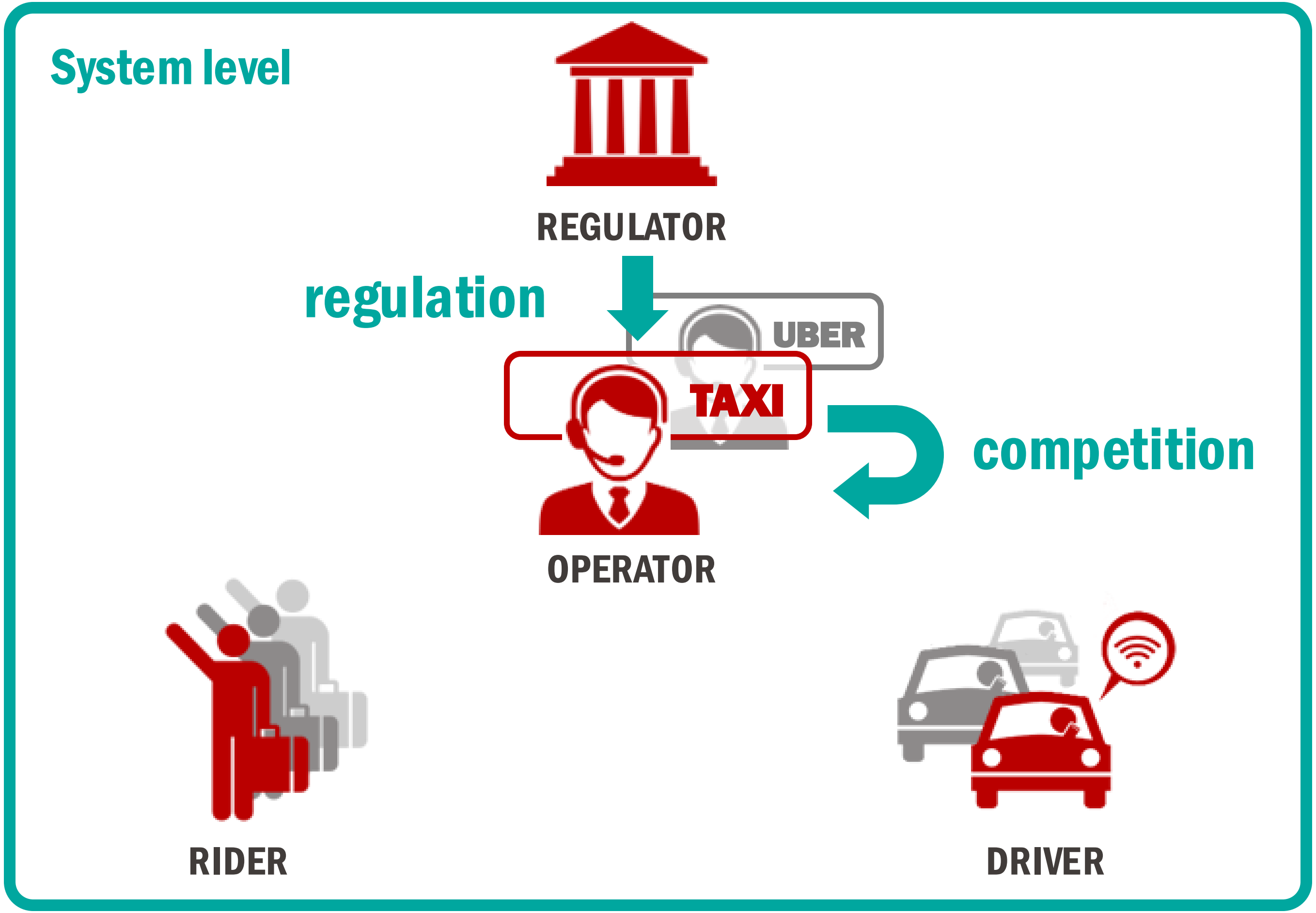

Source: Medium blog

## Peak-hour surge pricing



Source: Uber

# What problems do we study?

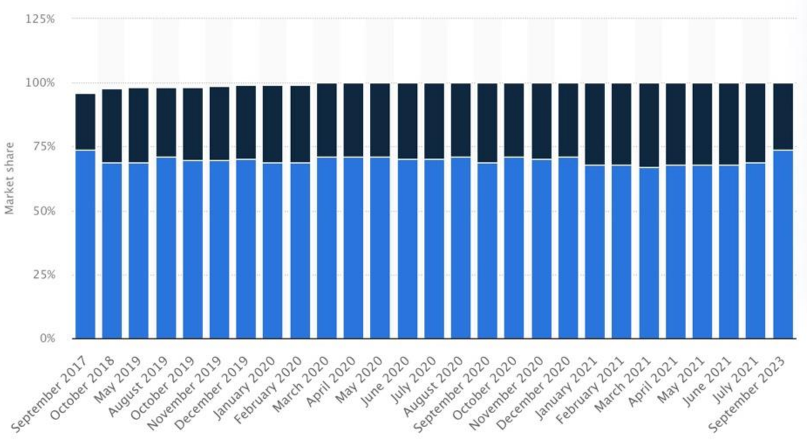



Kenan Zhang

Kenan Zhang

# What problems do we study?


U.S. market share




Source: Statista


Multi-homing drivers


Driver protest for higher payment

# Questions?

Next topic: Matching

# Matching problem

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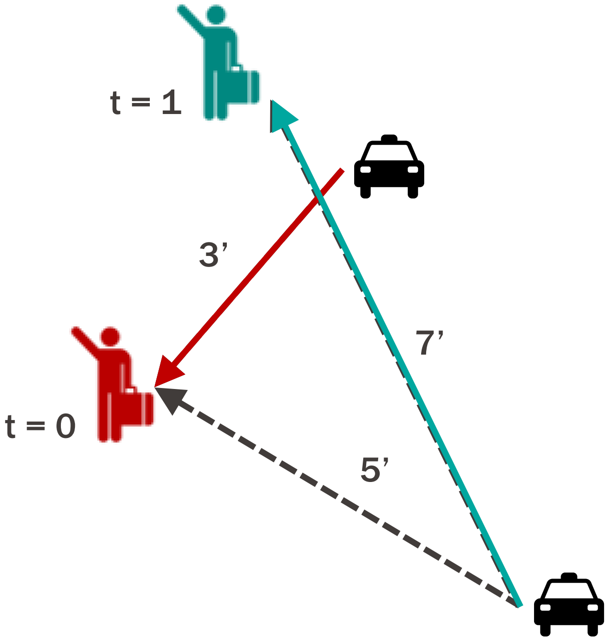
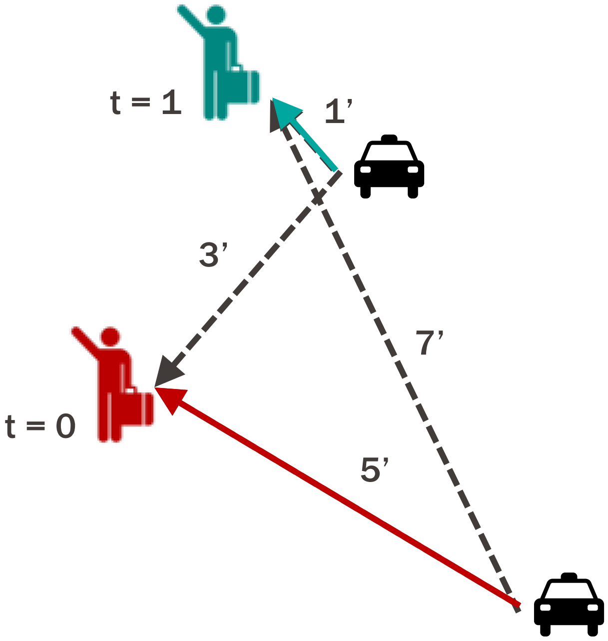
- How to dispatch drivers to picking up riders
  - Policy I: Instant matching
    - riders are first-come-first-served
    - riders are match to the closest driver



# Matching problem

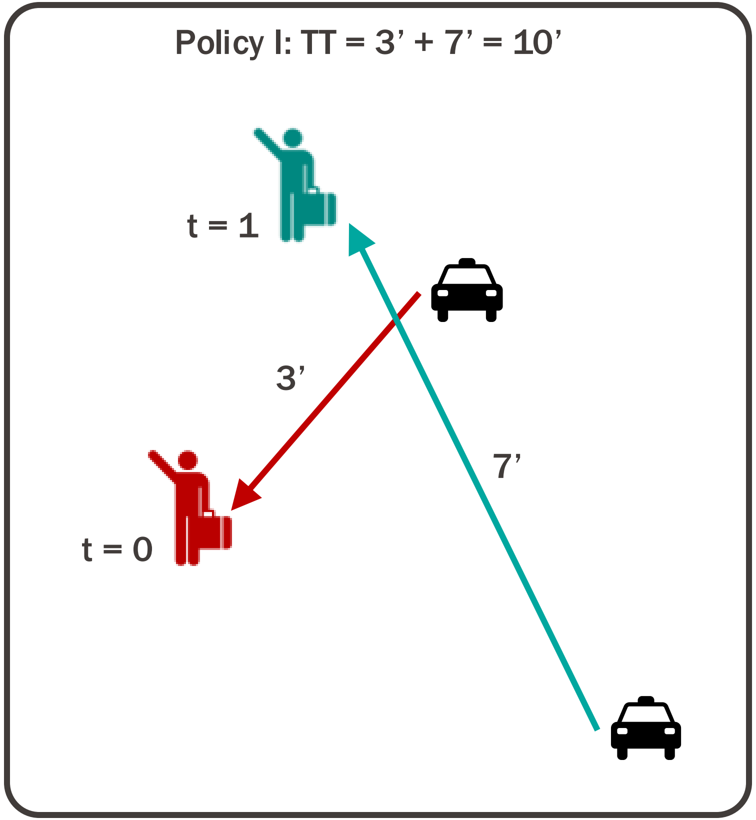


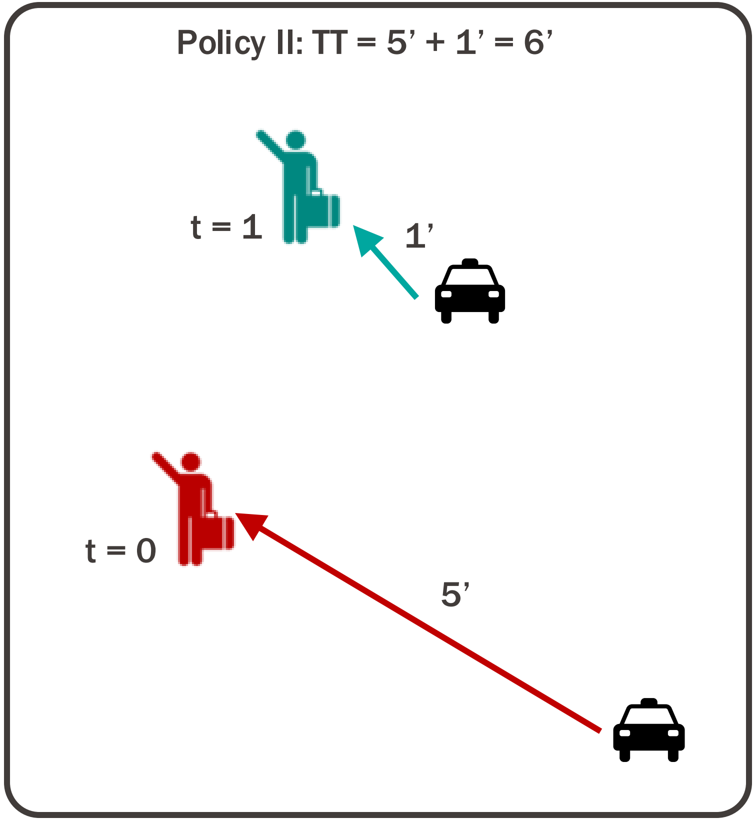
- How to drivers to picking up riders
  - Policy II: Batch matching
    - consolidate requests over a matching interval into a batch
    - match riders and drivers to minimize the total pickup time



# Matching problem

- Advantage of batch matching



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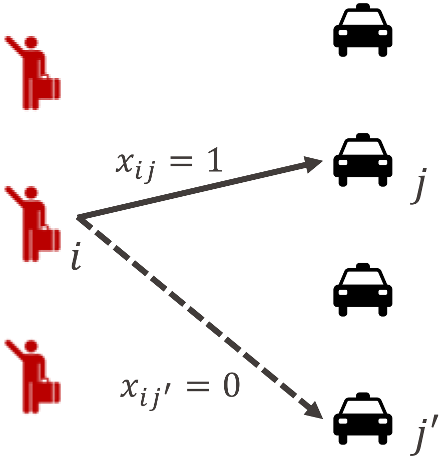
# Matching problem

- 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





- Mathematical formulation of batch matching
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  - Pickup time: $t_{ij} \in R_+, \quad i \in I, j \in J$

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

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

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

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

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

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

**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: $x_{ij} \in \{0,1\}, \quad i \in I, j \in J$
  - Pickup time: $t_{ij} \in R_+, \quad i \in I, j \in J$

$$\begin{aligned} \min_x \quad & \textstyle\sum_{ij} t_{ij} x_{ij} \\ s.t. \quad & \textstyle\sum_j x_{ij} = 1, \\ & \textstyle\sum_i x_{ij} \leq 1, \\ & x_{ij} \in \{0,1\}. \end{aligned}$$

**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!**

# 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

$$\underbrace{w}_{\text{matching outputs}} = f(\underbrace{\Pi, \Lambda}_{\text{matching inputs}})$$

where $w$: average waiting time (s)
$\Pi$: density of waiting riders (#/m$^2$)
$\Lambda$: density of idle drivers(#/m$^2$)

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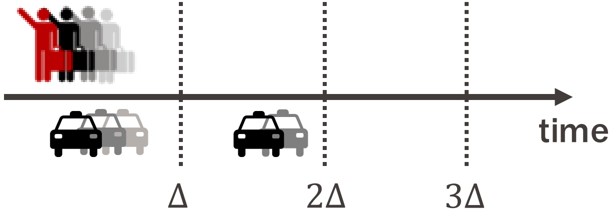
# Matching model

- Model I: Frictionless batch matching
  - Matching interval: $\Delta$ (s)
  - Rider arrival rate: $\lambda$ (#/s/m$^2$)
  - Idle driver arrival rate: $\mu$ (#/s/m$^2$)




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

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

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

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

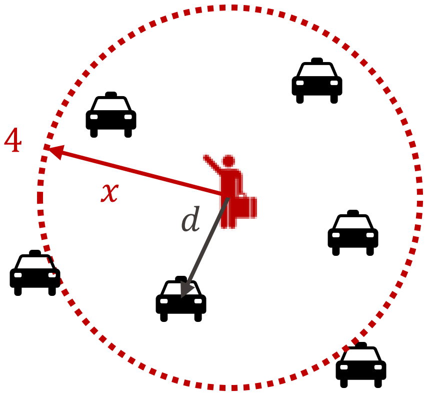
**Looks good, but ...**

# Matching model





- Model II: Non-congested instant matching
  - Matching radius ∞ (m)
  - Vehicle speed $v$ (m/s)




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:

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

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

**Independent of rider demand because…**

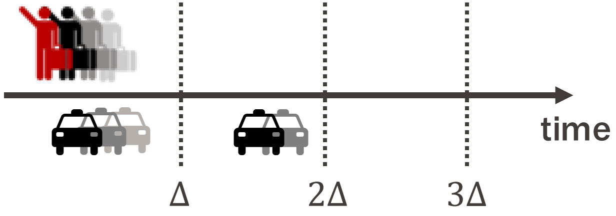
# Matching model

- Both make sense but look so different…

  *** because they each capture one part of total waiting time**

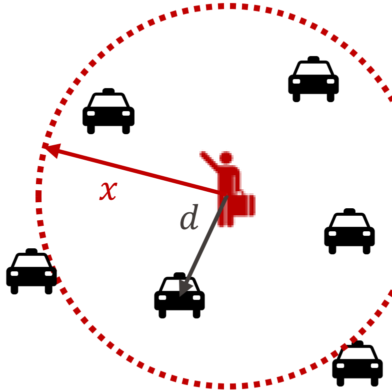
- Model I: $w \approx w_m = \left(\max\left(1, \frac{\Pi}{\Lambda}\right) - \frac{1}{2}\right)\Delta$

  *** pickup time is missing**




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

  *** matching time is missing**




*** The general model capturing both times is beyond the scope of this lecture**

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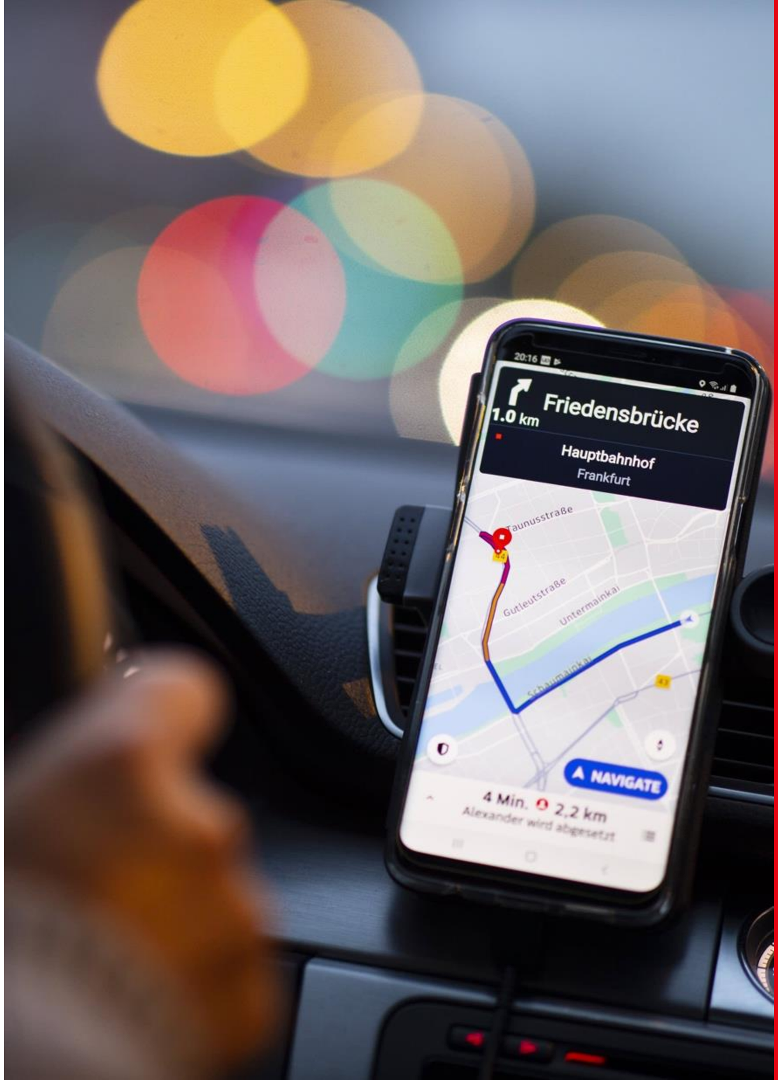
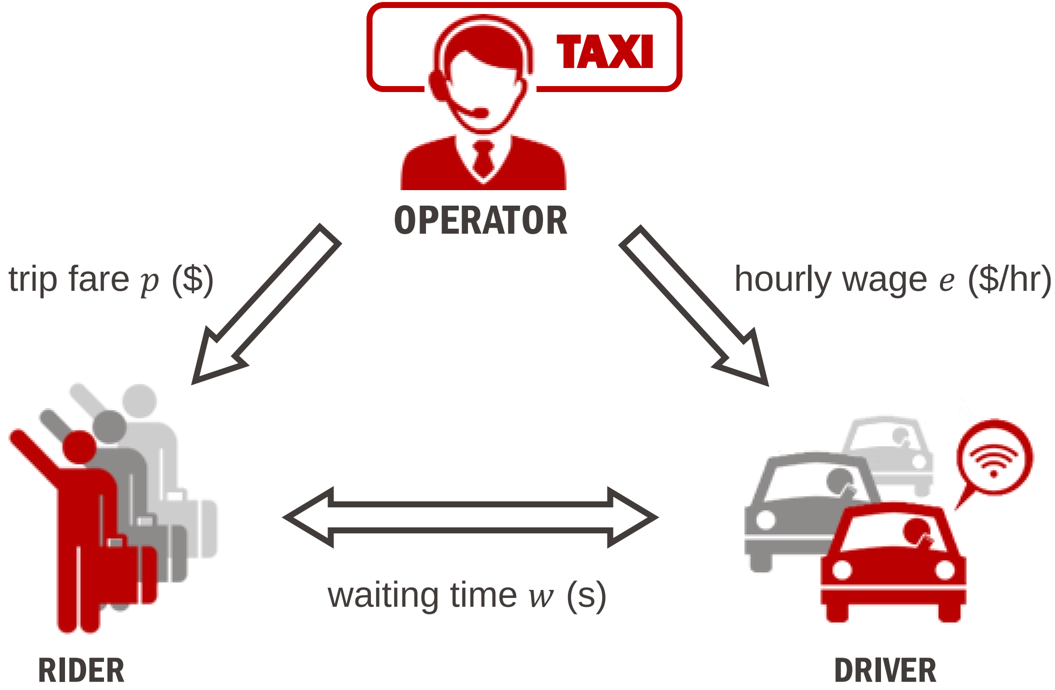



# Questions?

Next topic: Operations

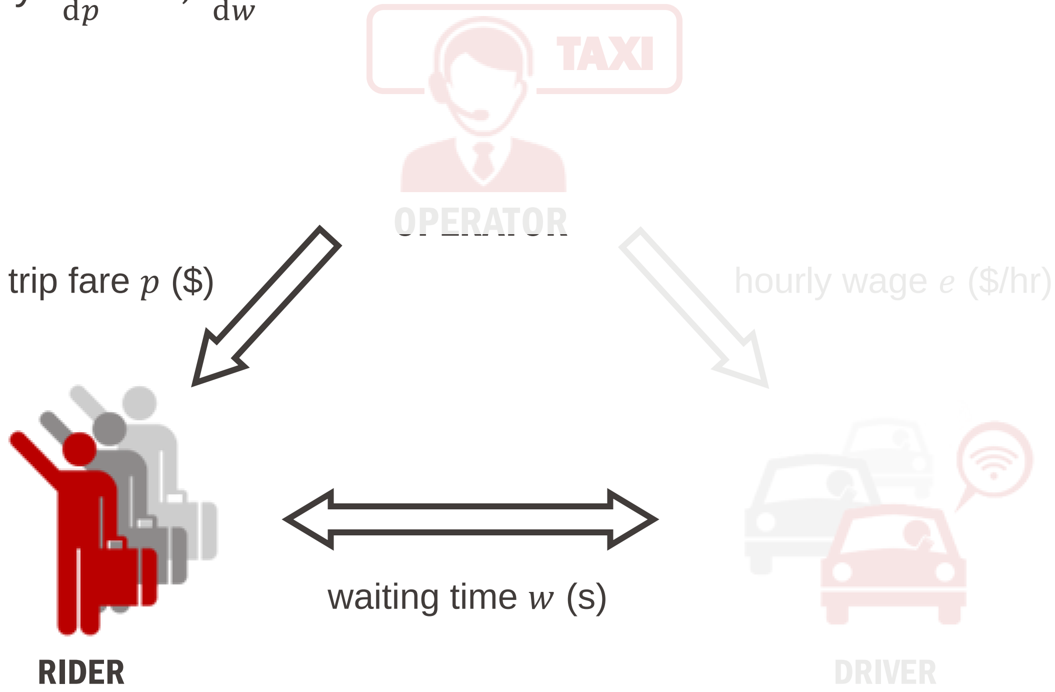
# Monopoly market

- A single dominating operator



# Monopoly market

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



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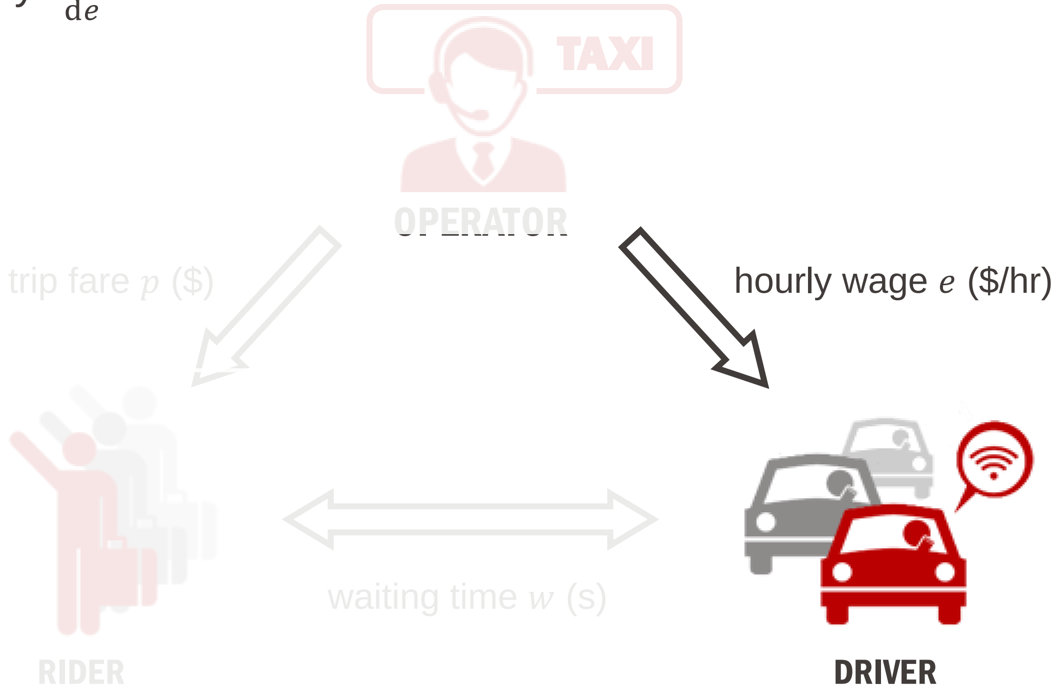
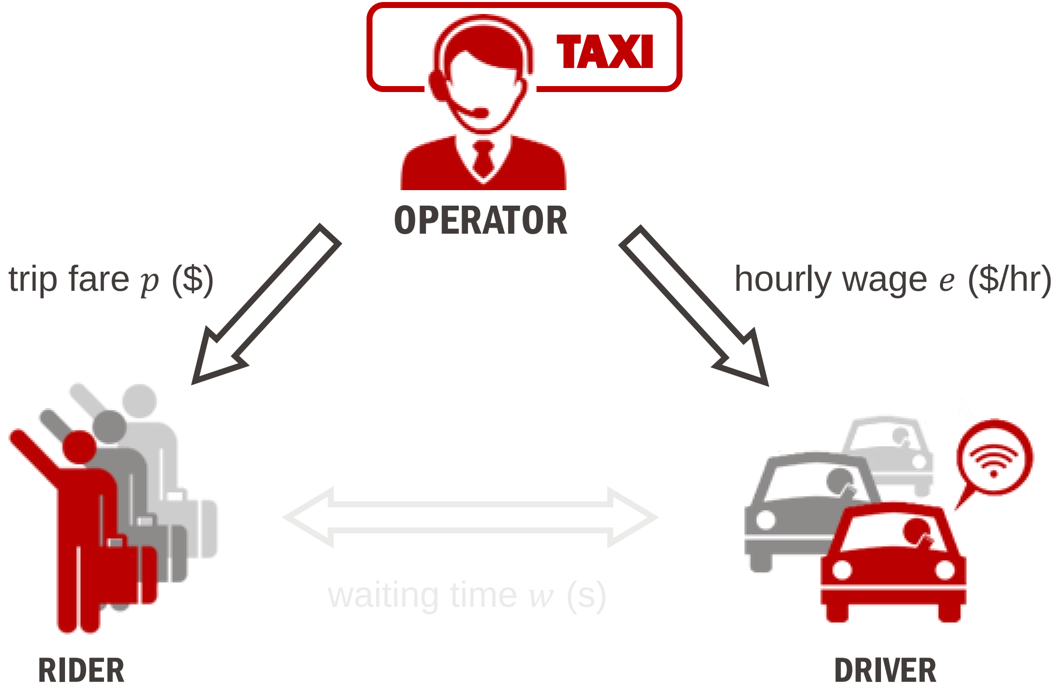
# Monopoly market

- Driver supply $N = S(e)$
  - Sensitivity: $\frac{\mathrm{d}N}{\mathrm{d}e} > 0$



# Monopoly market

- Operator profit $R(p, e) = pQ - eN$



# Monopoly market





- Pricing in a monopoly market
  - Assume trips are uniformly distributed with average in-vehicle time $\tau$ (s)
  - Decide trip fare $p$ (\$) and hourly wage $e$ (\$/hr) to max profit

$$\max_{p,e} \quad R(p,e) = pQ - eN$$

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

Demand function

Supply function

Matching model

Fleet conservation

Unmatched riders

**market equilibrium**

# 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**

# Monopoly market

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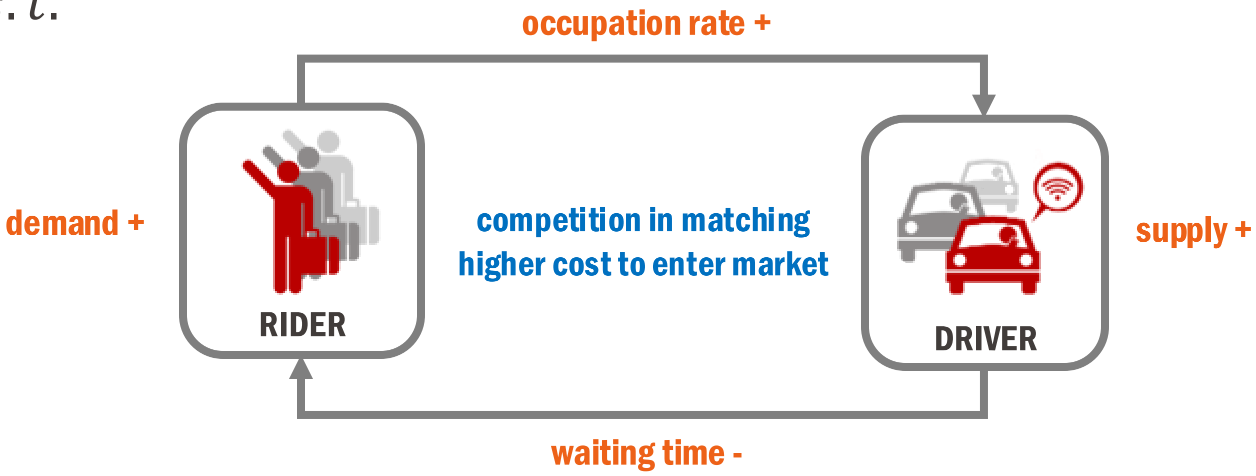
- How to solve the optimal pricing strategy?
  - Option I: throw the entire problem into solver
  - Option II: solve the equilibrium at each feasible price

$$\max_{p,e} \quad R(p,e) = pQ - eN$$

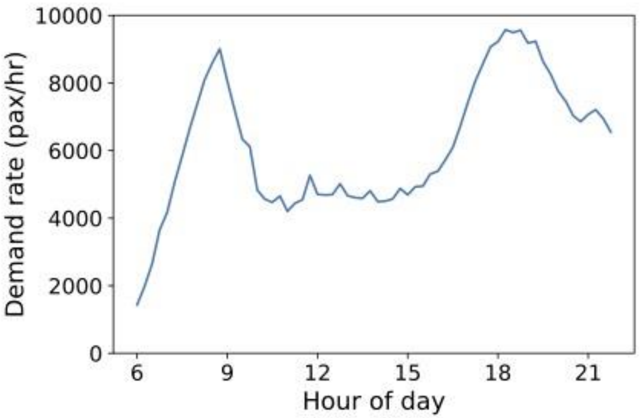
$$s.t.$$



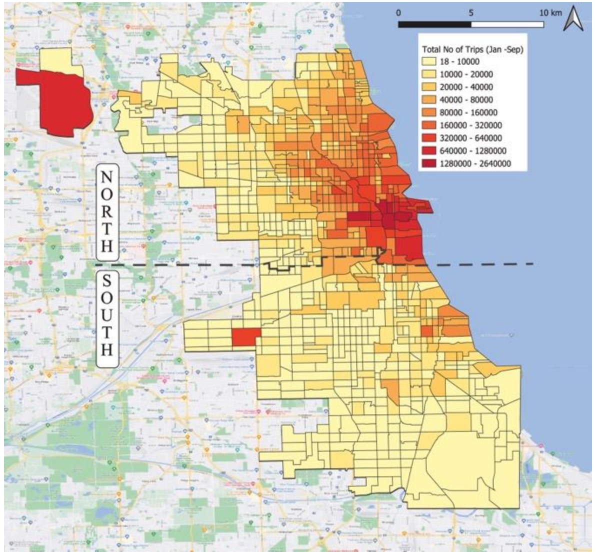
# Monopoly market

- 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



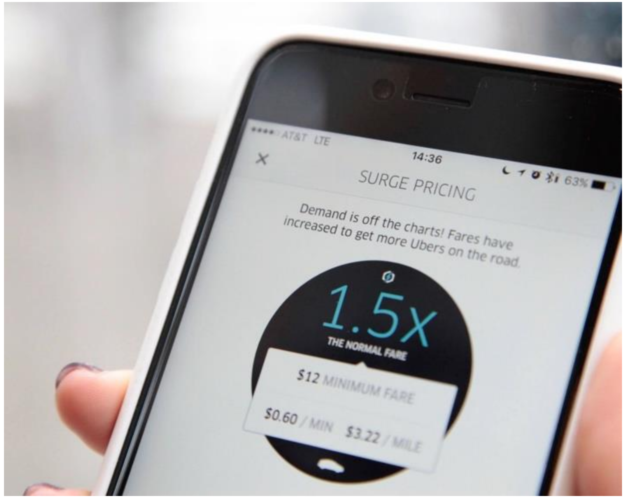

Trip origin distribution



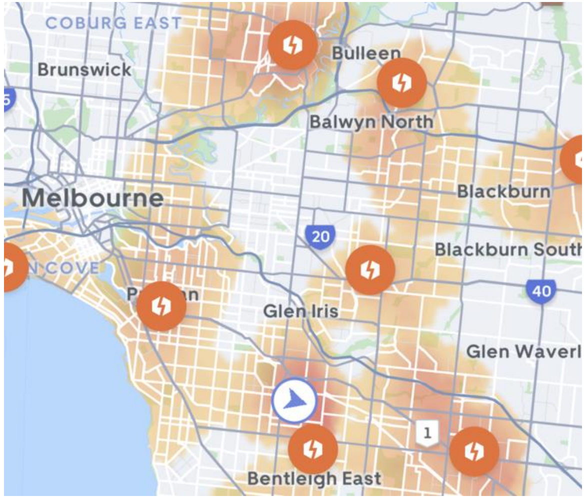
# Monopoly market

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

**Rider side: surge multiplier**




**Driver side: demand heat map**

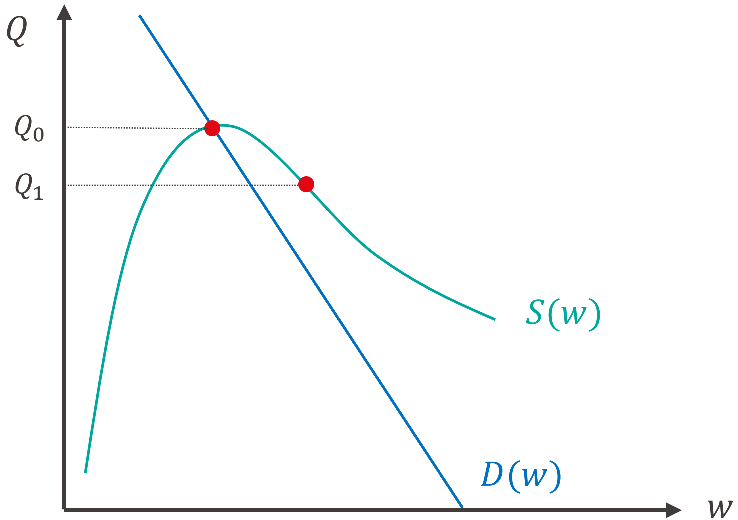


# Monopoly market




- The rational of surge pricing
  - Demand curve: $D(w) = D_0 - p - w$
  - Supply curve: $S(w) = \frac{N - \Lambda(w)}{w+\tau}$

Notations:
- $D_0$: potential demand
- $p$: trip fare
- $w$: waiting time
- $N$: fleet size
- $\Lambda$: idle driver density
- $\tau$: trip duration
- $Q$: trip throughput

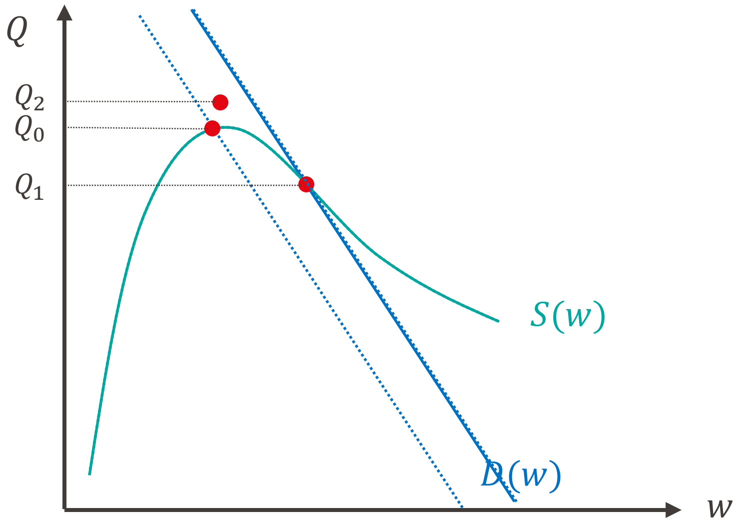



During a demand peak,
- $D_0$ increase while $N$ remain the same
- Market moves to an inefficient state $Q_0 \rightarrow Q_1$

# Monopoly market

- The rational of surge pricing
  - Demand curve: $D(w) = D_0 - p - w$
  - Supply curve: $S(w) = \frac{N-\Lambda(w)}{w+\tau}$

Notations:
- $D_0$: potential demand
- $p$: trip fare
- $w$: waiting time
- $N$: fleet size
- $\Lambda$: idle driver density
- $\tau$: trip duration
- $Q$: trip throughput

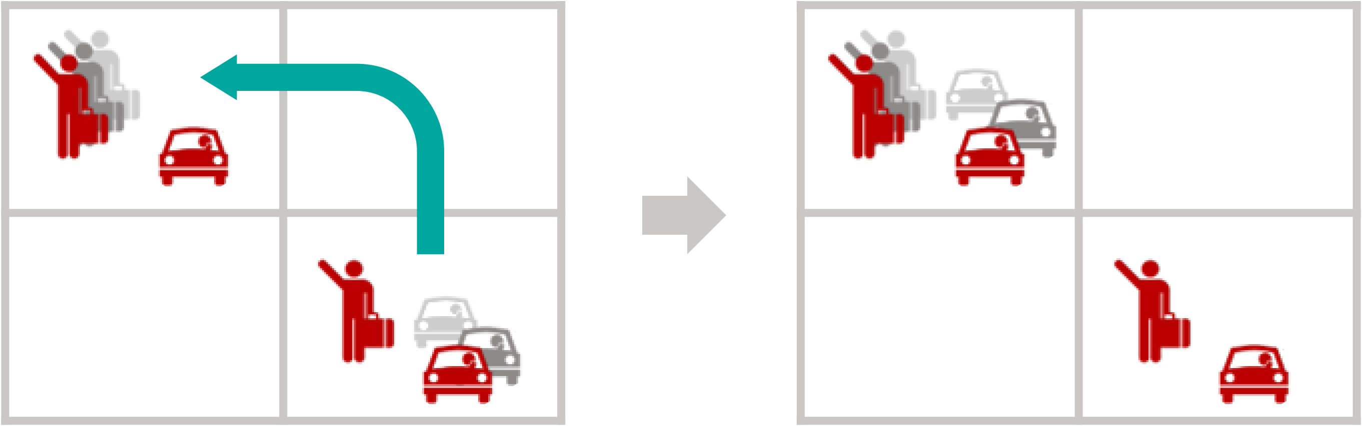



During a demand peak,
- $D_0$ increase while $N$ remain the same
- Market moves to an inefficient state $Q_0 \rightarrow Q_1$
- A surge price pushes demand curve back and induce a larger supply $Q_1 \rightarrow Q_2$

Kenan Zhang

# Monopoly market

- Motivations of vehicle relocation
  - 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



# Monopoly market

- A static model of vehicle relocation

Notations:
- $p_{ij}$: trip fare
- $c_{ij}$: relocation cost
- $x_{ij}$: trip flow
- $x_{ij}^0$: relocation flow
- $\lambda_i$: rider arrival rate
- $\mu_i$: driver arrival rate
- $\alpha_{ij}$: OD distribution
- $\tau_{ij}$: 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**

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

Kenan Zhang

# Beyond monopoly market

- 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.

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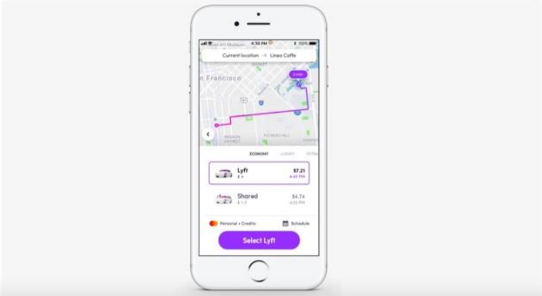
Source: New York Times

## Lyft's new app to integrate directly with public transit

Published June 8, 2018

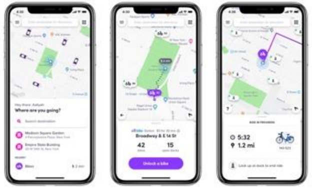
Kristin Musulin
Senior Editor




Source: Smart Cities Dive

## Citi Bike: Now available in the Lyft app

Update your Lyft app to get riding!



Source: Citi Bike

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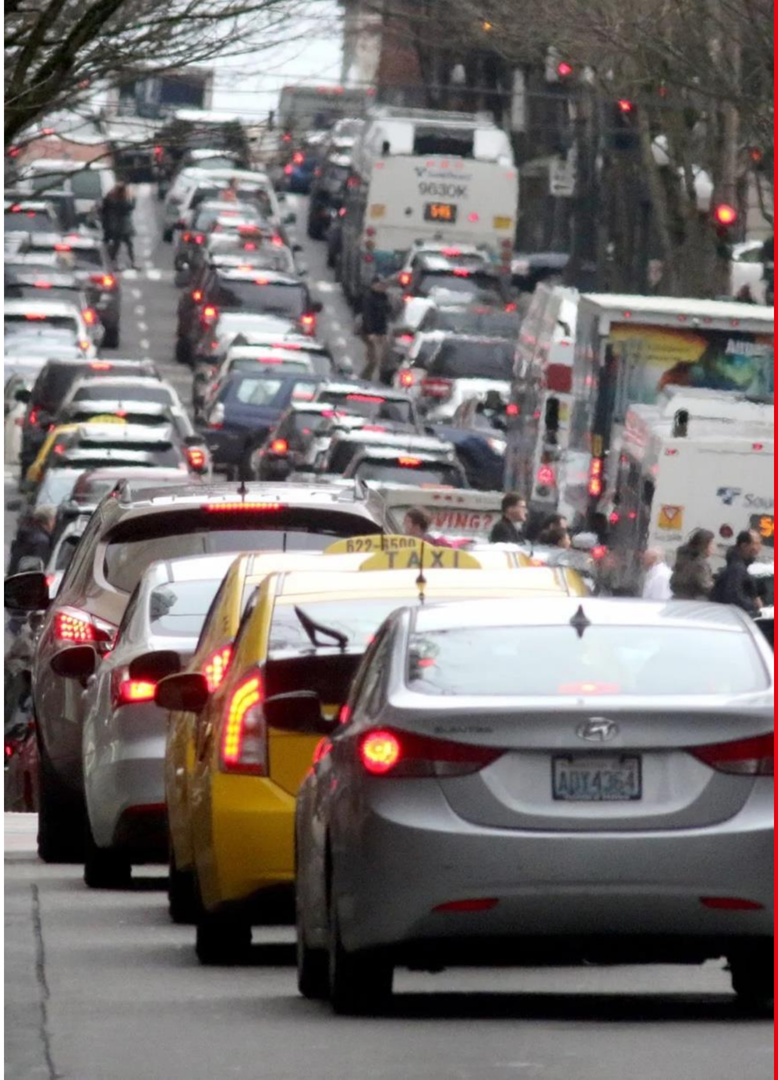


# Questions?

Next topic: Regulations

# 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**

EPFL

# Regulations in practice



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## 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

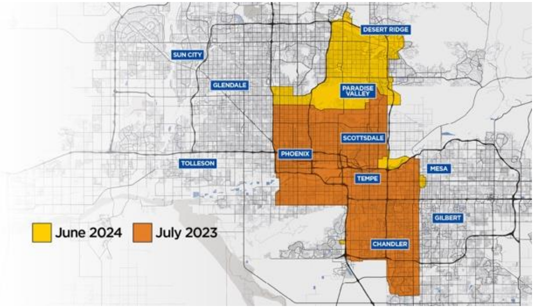

**Chicago congestion tax on rideshare trips takes effect**

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 $\bar{N}$ and min wage rage $\underline{e}$

$$\max_{p,e} \quad R(p,e) = pQ - eN$$

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

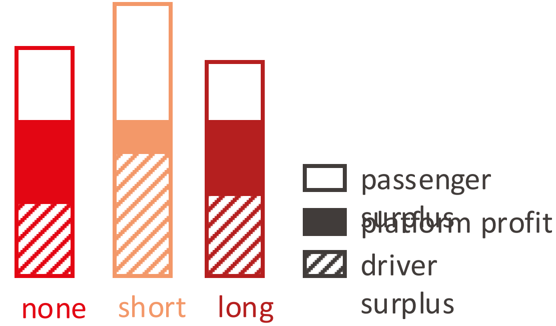
market equilibrium

$$\boxed{N \le \bar{N}, e \ge \underline{e},}$$

regulatory constraints

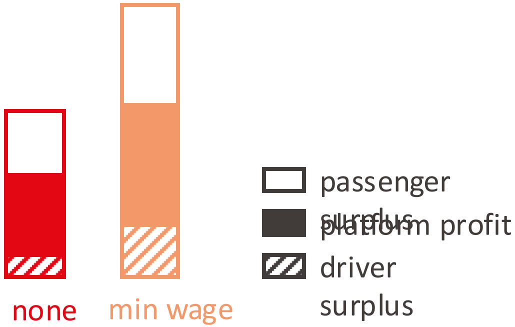
# How to analyze a policy

- 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
  - ….


# Thanks!
# Q & A

HOMES @ EPFL