On-Demand Ride Hailing
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From Street Hailing to On-Demand Ride Hailing

Street hailing

- lack of information sharing with commuters

On-demand ride hailing

- fast, flexible, convenient
Is On-Demand Ride Hailing More Efficient?

• “The Shanghai city government bans the use of taxi-booking apps by cab drivers during rush hours.”

• “People waiting on Manhattans Fifth Avenue in the middle of rush hour, don’t need an app to tell cabs to come to the area.”

• New York City Taxi and Limousine Commission (T&LC) maintain a certain number of taxis dedicated to street hailing through Street Hail Livery (SHL).
Research Questions

Street hailing v.s. On-demand ride hailing

• Which matching mechanism is more efficient in terms of passengers' average waiting time?
  - Build models to study the street-hailing and on-demand ride hailing systems.
  - Identify the advantage and disadvantage of the two matching mechanisms
  - How to approximate of the two mechanisms using $M/M/k$ queueing systems?

• How to address the inefficiency of on-demand ride hailing mechanism?
Related Literature

Matching
- Allon et al. (2012)
- Cullen and Farronato (2014)
- Anderson et al. (2015)
- Hu and Zhou (2016)

Vehicle routing
- Spivey and Powell (2004)
- Meyer and Wolfe (1961)
- McLeod (1972)
- Bailey and Clark (1992)

Sharing economy
- Benjaafar et al. (2015)
- Fraiberger and Sundararajan (2015)
- Jiang and Tian (2015)

On-demand platform staffing and pricing
- Gurvich et al. (2015)
- Taylor (2016)
- Cachon et al. (2015)
- Fraiberger et al. (2015)
- Riquelme et al. (2015)
- Tang (2016)
Model Setup: Transportation System on a Circular Road

- Passengers arrive according to a Poisson process with rate $\lambda$
- The location of each arrival is uniformly distributed
- The duration of each trip follows an exponential distribution with mean $1/\mu$
- Taxis have a constant speed of one
Matching Mechanisms for Street Hailing and On-Demand Ride Hailing

On-demand ride hailing

- Matched to nearest available taxi

Street hailing

- No matching until a taxi is passing by a passenger.
One Direction No-Call System (Street Hailing)

The average waiting time of the one direction no-call system is increasing in the utilization $\lambda/(k\mu)$.

- Longer waiting time with higher road length $R$.
- Shorter waiting time with more taxis in the system.
One Direction No-Call/Call Systems

One Direction Call System (On-demand Ride Hailing)

The average waiting time of the one direction call system is not always monotone in the utilization $\lambda/(k\mu)$.

The non-monotonicity is more significant with higher road length $R$.

Shorter waiting time with more taxis in the system.
Decompose Passengers’ Waiting Time

Arrival  Dispatch  Pick-up  Drop-off

Response  Enroute  On-trip
Decompose Passengers’ Waiting Time

A passenger’s waiting time consists of two parts:

- **Response time**: Time before a ride request is responded.
- **Enroute time**: Time a taxi spent to approach a passenger.
One Direction Call System: Non-monotonicity

Waiting Time = Response Time + Enroute time

- Enroute time is non-monotone in utilization, and it peaks at medium utilization level.
When Utilization is Low

Medium utilization

Low utilization

Enroute time becomes smaller when a lot of taxis are idle
When Utilization is High

Medium utilization

High utilization

Enroute time becomes smaller when a lot of passengers are waiting
When Utilization is Medium

- Enroute time is the highest when the system is balanced.
- Taxis spend too much time in picking up passengers
- Passengers have to wait for longer time
- The inefficiency is most significant when R is large
Comparison of One Direction Call/No-Call Systems

One direction no-call system leads to smaller average waiting time compared to the call system.
Two Direction No-Call/Call Systems

No-Call System

The average waiting time is increasing in the utilization

Call System

The average waiting time is not always monotone in the utilization
Comparison of Two Direction Call/No-Call Systems

The two direction call system is not always more efficient than the two direction no-call system.

The no-call system is more efficient when the utilization is in the middle range.
Two Dimensional Grid Network

Number of horizontal roads

Number of vertical roads

$m$

$n$
The disadvantage of street hailing is more significant with the increase of the road complexity.
Two Dimensional Grid Network

Increase number of taxis

The disadvantage of on-demand ride hailing is more significant with the increase of number of taxis $k$
Approximation: M/M/k Queue with State Dependent Service Rate

- State: Number of passengers $n$ in the system
- Arrival Rate: $\lambda_n = \lambda$
- Expected Extended Service time:
  \[
  \frac{1}{\mu} + \text{Expected Enroute Time (EET)}
  \]
- State Dependent Service Rate:
  \[
  \mu_n = \begin{cases} 
  \frac{n}{1/\mu + \text{EET}}, & \text{if } n \leq k, \\
  \frac{k}{1/\mu + \text{EET}}, & \text{if } n > k.
  \end{cases}
  \]
On-demand ride hailing

Street hailing

One-Direction

Two-Direction
Disadvantage of On-demand/Street Hailing Systems

On demand ride hailing (call)
• The match may not be efficient enough since
  - the taxi may encounter other incoming passengers before reaching the matched passenger
  - the passenger may be more close to a taxi that becomes available after the matching.

Street hailing (no-call)
• A taxi near a passenger could be driving in the opposite direction.
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How to alleviate disadvantages of both systems?

Street hailing (no-call)
• A taxi near a passenger could be driving in the opposite direction.
How to Alleviate Disadvantages of Both Systems?

Response Cap

If the nearest passenger-vehicle has a distance no larger than a fixed cap $C$, then match them; otherwise, do not match them.

Match if the nearest taxi is within the distance $C$

Do not match if the nearest taxi is out of the distance $C$
How to Alleviate Disadvantages of Both Systems?

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How to Alleviate Disadvantages of Both Systems?

An on-demand ride hailing system with a response cap could outperform both street hailing and on-demand ride hailing without a cap.
Heuris Cap

- The probability that it takes longer than \( x \) for a taxi to encounter a passenger is

\[
P(N = 0) = \exp\left(-\frac{\lambda x^2}{2R}\right)
\]

- The expected distance to drive before encountering a later arrived passenger:

\[
\int_0^\infty \exp\left(-\frac{\lambda x^2}{2R}\right)dx = \sqrt{\frac{\pi R}{2\lambda}}
\]

- Heuristic Cap: \( \min\{R/2, \sqrt{\frac{\pi R}{2\lambda}}\} \)
Performance Difference Compared to the Optimal Capped System

$R=100, k=10$

$R=100, k=20$

$R=100, k=30$
Summary

• On demand ride hailing may result in higher waiting time than street hailing. It is more likely to happen when
  – the road is long,
  – the utilization level is in the middle range.
  – many taxis in the system.
  – roads are not very complex.

• Enroute time is high when the system is balanced.
  – Passengers’ average waiting time in on-demand ride hailing can be non-monotone in system utilization
  – Taxis spend too much time in picking up passengers
  – A driver may miss the chance to serve another incoming passenger who is in a shorter distance in the call system

• A proper distance cap can reduce passengers’ average waiting time.
Thank you!
M/M/k Queueing Approximation

• On-demand Ride Hailing
  -- One-direction
  \[ \mu_n = \begin{cases} 
  \frac{n}{1/\mu + R/(k-n+2)}, & \text{if } n \leq k, \\
  \frac{1}{1/\mu + R/(n-k+1)}, & \text{if } n > k.
  \end{cases} \]

  -- Two-direction
  \[ \mu_n = \begin{cases} 
  \frac{n}{1/\mu + R/2/(k-n+2)}, & \text{if } n \leq k, \\
  \frac{1}{1/\mu + R/2/(n-k+1)}, & \text{if } n > k.
  \end{cases} \]

• Street Hailing: One/Two-direction
  \[ \mu_n = \begin{cases} 
  \frac{n}{1/\mu + \int_0^R (\frac{R-x}{R})^{k-n+1} \exp\left(-\frac{(n-1)\mu x^2}{2R}\right) dx}, & \text{if } n \leq k, \\
  \frac{k}{1/\mu + \int_0^R (\frac{R-x}{R})^{n-k} \exp\left(-\frac{\lambda x^2}{2R}\right) dx}. & \text{if } n > k.
  \end{cases} \]
The average waiting time of approximated one (two)-direction call system satisfies that

1. \( W(\lambda, \mu, k, R) < \infty \) if and only if \( 0 \leq \lambda < k\mu \).

2. For any given \( \mu, k \) and \( R \), \( \frac{\partial W(\lambda, \mu, k, R)}{\partial \lambda} \bigg|_{\lambda=0} \geq 0 \) and \( \lim_{\lambda \to k\mu} \frac{\partial W(\lambda, \mu, k, R)}{\partial \lambda} > 0 \).

3. For any given \( \mu \) and \( k \geq 2 \), there exists a constant \( R^*(\mu, k) \) such that when \( R > R^*(\mu, k) \), there exists \( 0 \leq \lambda(\mu, k, R) < k\mu \) such that \( \frac{\partial W(\lambda, \mu, k, R)}{\partial \lambda} \bigg|_{\lambda=\lambda(\mu, k, R)} < 0 \).
One Direction Approximation

On-demand Ride Hailing

$$\mu_n = \begin{cases} 
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Street Hailing

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Two Direction Approximation

On-demand Ride Hailing

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