Queueing versus Surge Pricing Mechanism: Efficiency, Equity, and Consumer Welfare

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Background

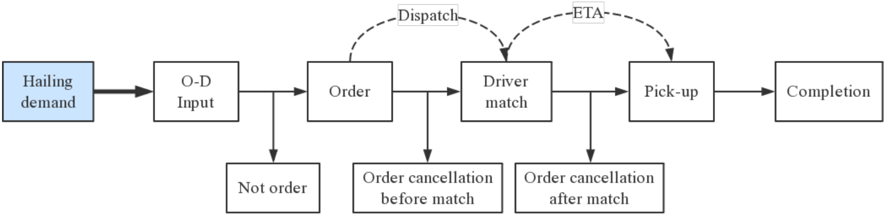


Figure: DiDi ride hailing process

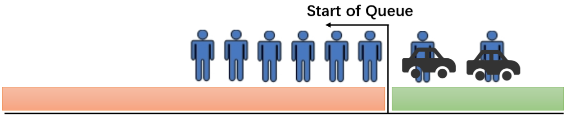
Background: Surge Pricing Mechanism

- Surging price to suppress demand and stimulate supply.
- Surge cap (DiDi Express): surge amount $\leq$ ¥29, surge multiplier$\leq$1.5.

Problem: undisclosed surge pricing algorithm raises concerns about **demographic disparity** and **social bias**.

Background: Virtual Queueing Mechanism

- No surge pricing
- One queue in each region
- Each queue has infinite capacity
- Announce queue length and estimated waiting time in real time.



Research Questions

To compare the surge pricing mechanism and the virtual queueing mechanism in terms of

- (i) operational performance and consumer welfare;
- (ii) fairness.

Research Questions

Performance metrics	Definition
Response rate	Percentage of orders matched
Demand satisfaction rate	Percentage of demand satisfied
Unit-time GMV	Ride price × Number of orders over a unit time period
Consumer surplus per capita	Average (Service valuation – ride price – waiting cost)
Equity	Distribution of welfare among customers

Literature Review

- Dynamic pricing in queueing systems
  Naor (1969); Knudsen (1972); Yechiali (1971); Chen et al. (2015); Cachon et al. (2017); Kim and Randhawa (2017); Bai et al. (2018); Taylor (2018); Hu and Zhou (2019); Fang et al. (2019); Hu et al. (2019) ...
- Queueing systems with impatient riders
  Haight (1959); Ancker Jr and Gafarian (1963); Ward and Glynn (2003); Kumar (2013); Jouini et al. (2011) ...
- Observable queues with delay announcements (analytical)
  Hassin (1986); Whitt (1999); Armony and Maglaras (2004); Guo and Zipkin (2007); Jouini et al. (2009); Hu et al. (2018) ...

1. Data-Driven Model Formulation
2. Mechanism Analysis
   - Virtual Queueing Mechanism
   - Surge Pricing Mechanism
3. Mechanism Comparison
4. Equity Analysis

Dataset

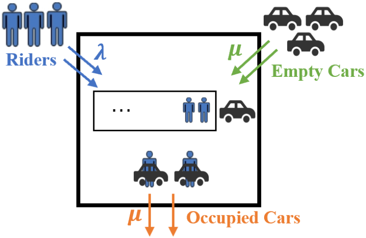
- A sample of DiDi Express within 6 randomly selected regions of Beijing, in the morning and afternoon rush hours with heavy congestion, in November 2017.

Dataset

- A sample of DiDi Express within 6 randomly selected regions of Beijing, in the morning and afternoon rush hours with heavy congestion, in November 2017.
- Data description
  - Order-related (ride price, waiting time, request timestamp, response timestamp, cancellation timestamp, completion timestamp)
  - Queue-related (queue length, queue speed)
  - Number of drivers

Data Evidence

1. Occurrence of rider orders: Pois(λ)
2. Occurrence of empty cars: Pois(μ)
3. Riders' willingness-to-wait before reneging: Exp(γ)
4. Total number of cars: constant s



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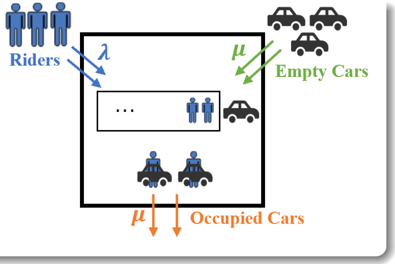


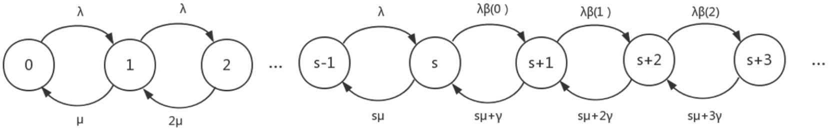
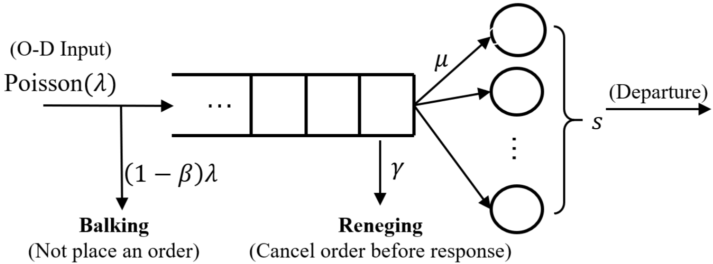
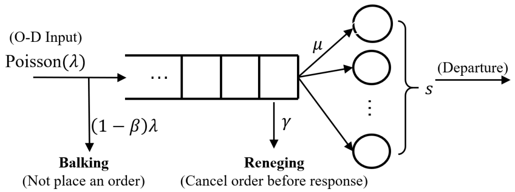


Figure: Empirical birth-and-death process for one region

Model: M/M/s+M Queue



Model: Virtual Queueing Mechanism



- Rider's utility function (when queue length is n)

$$Utility_1 = \overbrace{r}^{\boxed{\text{Uniform}(R_1,R_2)\text{ valuation}}} - \underbrace{p_1}_{\boxed{\text{price}}} - \overbrace{a}^{\boxed{\text{Uniform}(A_1,A_2)\text{ unit waiting cost}}} \cdot \underbrace{d_n}_{\boxed{\text{Conditional expected wait time}}} \qquad (1)$$

- Order probability:

$$\beta(n) = Prob\{Utility_1 \geq 0\}$$

Model: Virtual Queueing Mechanism

- Balance equation $\Longrightarrow$ Stationary distribution P_i

$$P_i = \frac{\lambda^i}{i!\mu^i} P_0, \qquad 0 \le i \le s,$$

$$P_i = \frac{\lambda^i}{s!\mu^s} \left(\prod_{j=1}^{i-s} \frac{\beta(j-1)}{s\mu + j\gamma} \right) P_0, \qquad i > s,$$

$$\text{where } P_0 = \left[\sum_{i=0}^{s} \frac{\lambda^i}{i!\mu^i} + \sum_{i=s+1}^{\infty} \frac{\lambda^i}{s!\mu^s} \left(\prod_{j=1}^{i-s} \frac{\beta(j-1)}{s\mu + j\gamma} \right) \right]^{-1}.$$

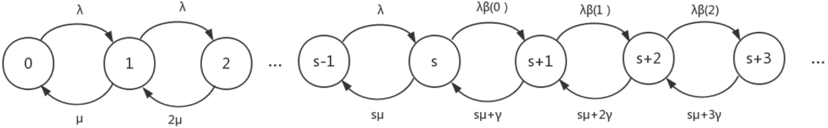


Figure: Birth and death process

Model: Surge Pricing Mechanism

- Rider's utility function

$$\mathit{Utility}_2 = \underbrace{r}_{\text{Uniform}(R_1, R_2)\text{ valuation}} - \underbrace{p_2}_{\text{Surge price}} \quad (3)$$

- Surge price: matching supply and demand

$$\lambda \cdot \beta(p_2) = \left[s \cdot \left(1 + \underbrace{\theta}_{\text{Driver's sensitivity to surging price}}(p_2 - p_1)\right)\right] \cdot \mu \cdot \underbrace{\eta}_{\text{Balancedness coefficient}} \quad (3)$$

- Surge cap

$$p_2 - p_1 \leq \min\{\overline{p}, \overline{m}p_1\}.$$

- Order probability

$$\beta(p_2) = \mathit{Prob}\{\mathit{Utility}_2 \geq 0\}$$

Model: Surge Pricing Mechanism

- Balance equation $\Longrightarrow$ stationary distribution P_i

$$P_i = \frac{\lambda^i}{i!\mu^i} P_0, \qquad 0 \le i \le s,$$

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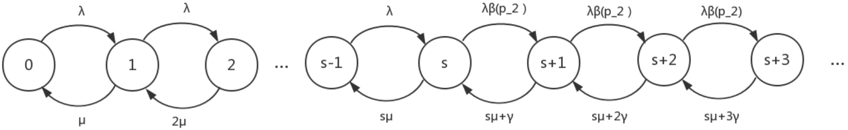

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Mechanism Comparison

- Which mechanism performs better in four metrics?

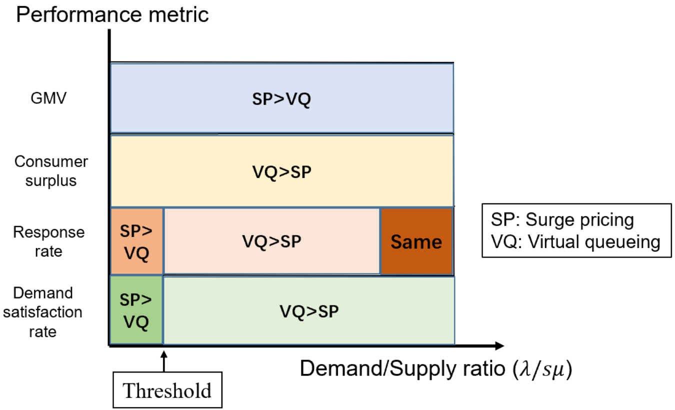


Figure: Comparison of two mechanisms in four metrics

Mechanism Comparison: Thresholds

- What is the property of threshold?

Parameter	Interpretation	Metric	Threshold	Example
$\lambda \uparrow$	larger demand size	RR/DSR	$\uparrow$	big cities
$\gamma \uparrow$	more outside options	RR/DSR	$\uparrow$	competition
$A_2 \uparrow$	higher waiting cost	RR(DSR)	$\downarrow (\uparrow)$	work, flight
$R_2 \uparrow$	higher willingness to pay	RR/DSR	$\downarrow$	rich areas

RR: response rate; DSR: demand satisfaction rate

Mechanism Comparison: Case Study

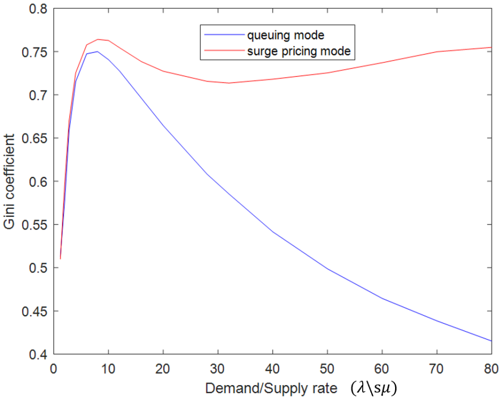
- Case study: November 2017, Beijing

Table 3 Performance metrics under both mechanisms in part of the case study

	Queue A		Queue a		Queue b	
	Queue	Surge	Queue	Surge	Queue	Surge
Response rate	0.6598	0.8842	0.95296	0.95943	0.06832	0.0303
Demand satis. rate	0.1479	0.1295	0.58535	0.5879	0.01377	0.01325
Consumer surplus	1.1263	0.3636	14.8058	14.4192	0.27959	-1.4977
GMV	8102.10	9082.39	15784.1	16172.9	3715.3	5362.18
p_2	-	38.3916	-	30.5882	-	45.0000
Demand/supply	9.6667		1.6667		100.0000	

Equity Analysis

1. Gini coefficient
   - A greater coefficient implies a higher degree of inequality.
   - Virtual queueing is more equitable than surge pricing mechanism.



Equity Analysis

2. Distribution of welfare across various types of riders
   - Demand satisfaction rate, consumer surplus
   - Rider type: (1) low-WTP vs. high-WTP; (2) Patient vs. impatient.
   - Under both mechanisms: high-WTP or patient riders enjoy higher welfare.
   - The imbalance is smaller under virtual queueing.

Takeaway: Both mechanisms are inequitable, but queueing mechanism is relatively more equitable.

Sensitivity Analysis

- More generalized supply functions

$$s' = s \cdot (1 + F(p_2 - p_1)), \text{ where}$$

  $F(x)$ can be any concave or convex increasing function.
- Distribution assumptions: Gaussian distribution, Uniform distribution, Two-point distribution.
- Independence assumption: when WTP and WTW are correlated.

Conclusions

The advantages of a queueing mechanism over the widely used surge pricing mechanism in heavily loaded ridesharing systems.

- Queueing outperforms pricing mechanism in **consumer surplus**.
- Surge pricing mechanism dominates virtual queuing in **GMV**.
- As congestion increases, queueing is more beneficial for higher **response rate** or higher **demand satisfaction rate**.
- Queueuing is more **equitable** than surge pricing mechanism.

Q&A