Online public transportation networks:

Evidence from the world's largest bus rapid transit system in Jakarta

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April 11, 2025

Motivation: The challenges of public transport network design

- Massive increase in private vehicles in LMICs.
  - 10% growth in private vehicles in India 2010-2019.
  - Motorcycle ownership jumped from 37% to 75.8% in Jakarta 2002-2010.
- Large public transport investments and trend toward centralized operations.
  - 100 LMIC cities with Bus Rapid Transit (BRT) in 2020, up from 14 in 2000.
- This paper focus on bus systems, which are important and flexible.
  - India: 73% urban public transport by bus (2011).
  - Light infrastructure with low fixed cost of routes (unlike rail) $\Rightarrow$ Large design space.

This paper...

There are trade-offs in public transport network design. Based on how customers respond to changes in the design, we can estimate travel demand parameters relevant for optimal network design.

Transport network design	Demand parameter
Many lines vs. high frequency	Value of wait time
Direct lines vs. hub and spoke network	Cost of transfers
Dense converage vs. fast service	Value of bus travel time

This paper: Estimates these micro travel demand parameters relevant for optimal network design and show its implications on optimal network design.

Paper outline: Three steps

1. Estimate the impact of Transjakarta's network expansion in 2016-2020 on ridership.
2. use impact estimates and a demand model to infer how commuters value different dimensions of service quality: wait time, transfers, and bus travel time.
3. Use estimates of the preference parameters to describe the shape of the optimal network.

Warning: Due to time constraint, some of the parts about the model will have to be more results-oriented.

Institutional background

The TransJakarta bus network

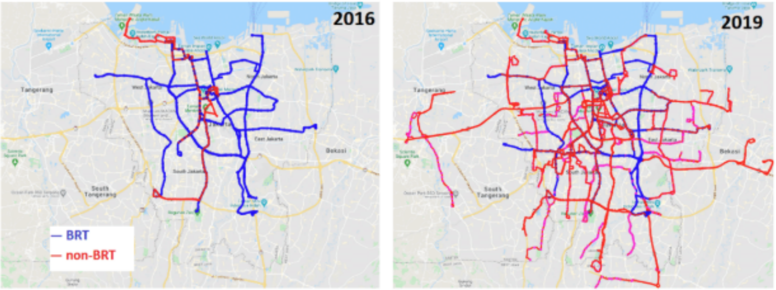
- Integrated bus system serving the central urban districts in Greater Jakarta (Daily ridership: 1 million in 2020).
- Over 139 bus route (BRT + Non-BRT), network length of more than 120 miles of BRT corridors.
- Primary public rapid transit system in the city (rimary alternative: private transport).

TransJakarta bus network expansion

- New 93 BRT and non-BRT routes (Jan 2016 - Feb 2020).
- # of buses more than doubled (700 to 1600).

Expansion: Visualization

(a) Expansion of TransJakarta Route Network



Data

Geography: Central urban districts divided into identical grid cells and aggregate stations at the grid cells level, and trips at the grid cell pair level.

Ridership data

- Highly granular TransJakarta origin-destination ridership matrix at each point in time since 2016.
- Use algorithm to proxy rider's destination station.

Aggregate trip flows

- Smartphone data to construct aggregate trip flows (35 million trips, 2018 - 2020).

Bus location and expansions

- GPS location of buses and their routes to construct travel time, wait time, etc.

Reduced-form: Impacts of expansion on ridership and on all trips

3 variations induced by new route launch

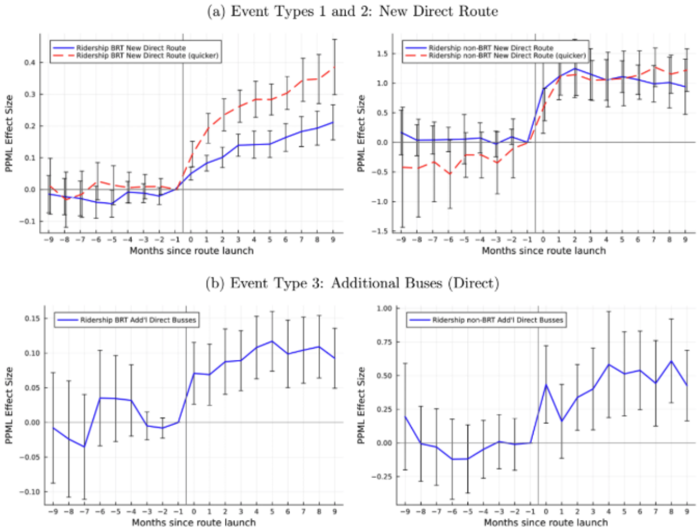
- *First direct route connection* that is not faster than existing transfer (Event 1).
- *First direct route connection* that is faster (Event 2).
- *New route* between two already connected: Arrival rate $\Uparrow$, wait time $\Downarrow$ (Event 3).

Reduced-from specification (for each events)

$$\mathbb{E} Y_{odt} = \exp\left(\alpha Post_{odt} + \alpha_{-10} L_{\leq -10,odt} + \alpha_{10} L_{\geq 10,odt} + \mu_{od} + \nu_{ot} + \xi_{dt} + \varepsilon_{odt}\right)$$

- $Post_{odt}$: Indicator variable for the event having taken place on the (o, d) route in the previous 10 months.
- $L_{\leq -10,odt}, L_{\geq 10,odt}$: Indicators for whether an event between o and d takes place 10 or more months in the future, and in the past, respectively.

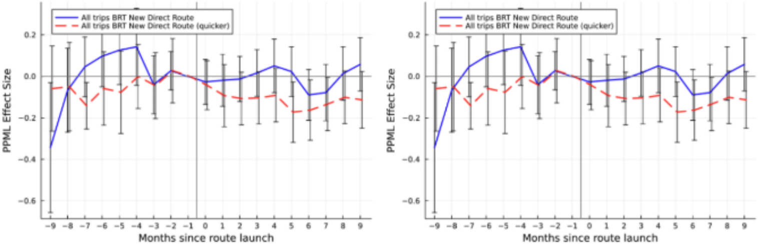
Results: Impacts on ridership



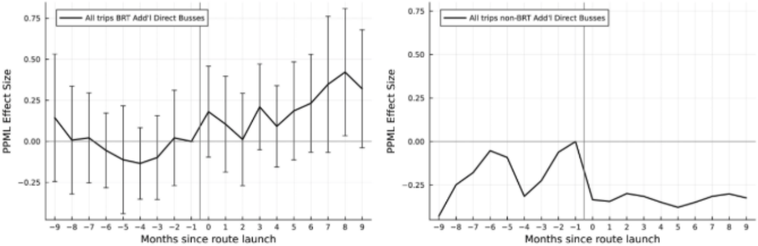
- **Event 1**: ~ 15.9% (BRT) ridership increase.
- **Event 2**: ~ 20.7% (BRT) ridership increase.
- **Event 3**: ~ 9.6% (BRT) ~ 56.8% (non-BRT) ridership increase.

Results: Impacts on aggregate trip volume

(a) Event Types 1 and 2: New Direct Route



(b) Event Type 3: Additional Buses (direct)



Model

Modeling travel demand

- Develop a travel demand model and estimate the set of riders' preferences parameters that best match the reduced-form estimates.
- Nested travel demand model:
  1. **Outer nest**: Commuter chooses between bus vs. outside private mode.
  2. **Inner nest**: Then commuter chooses preferred bus route within the TransJakarta network.
- In the model, a commuter's utility is given by:
  - travel time on the bus.
  - bus transfer cost.
  - bus wait time.
  - esimated with $o - d$ fixed effects and an inattention parameter.

Model setup: Bus route choice model (brief)

Basic setup: Static discrete choice model (over bus options) with idiosyncratic heterogeneity from exponentially distributed random wait times.

- Commuter i chooses travel option that maximize his utility of going from o to d.

- Random utility component comes from wait time (Poisson process).

  $u_k = \underbrace{-\alpha_{time} T_k^{time}}_{v_k} - \alpha_{wait}\omega_k$, ω_k (wait time) is drawn from exponential distribution.

- If commuters choose transfer option:
  $u_k = \alpha_{time} T_{k1}^{time} + \mathbb{E} \max_{k2} \left[-\alpha_{time} T_{k2}^{time} - \alpha_{wait} T_{k2}^{wait} \right] + \mu_{transfer} - \alpha_{wait} T_{k1}^{wait}$.

- In higher decision nest: Commuter decide whether to use TransJarkarta network or alternative (u_{it}^{bus} vs. $u_{it}^{private}$).

Model estimation (brief)

Parameters to estimate: $\theta = \left(\sigma, \alpha^{BRT}_{wait}, \mu^{BRT}_{transfer}, \eta^{BRT}, \alpha^{non-BRT}_{wait}, \mu^{non-BRT}_{transfer}, \eta^{non-BTR}\right)$

Esimation approach (very brief)

- Match reduced-form event study coefficients with the model.
- Apply classical minimum distance estimation to retrieve parameters:

$$\min_\theta (\underbrace{m(\theta)}_{\text{model moments}} - \overbrace{\widehat{m}}^{\text{empirical estimates}})' \widehat{W} (m(\theta) - \widehat{m})$$

Esimation results

Table 4: Estimated Demand Model Parameters

	(1) BRT	(2) BRT	(2) non-BRT
Wait time $\alpha_{\text{wait}}/\alpha_{\text{time}}$	2.1	2.1	3.4
	[1.5, 3.6]	[1.5, 3.5]	[2.7, 5.1]
Travel time α_{time}	1.0	1.0	1.0
	[1.0, 1.0]	[1.0, 1.0]	[1.0, 1.0]
Transfer shifter μ/α_{wait} (minutes)	4.8	4.8	2.2
	[0.1, 7.7]	[0.5, 7.4]	[-1.9, 4.2]
Attention cutoff η	1.36	1.36	1.43
	[1.25, 1.47]	[1.25, 1.47]	[1.42, 1.44]
Logit parameter σ	0.13	0.13	
	[0.04, 0.32]	[0.04, 0.30]	
Moments:			
BRT events (1-3)	Yes	Yes	
BRT event 2 trip duration	Yes	Yes	
non-BRT events (1-3)		Yes	

- Travelers dislike wait time 2.1x (BRT) and 3.4x (non-BRT) more than travel time on the bus.
- Close to zero transfer penalty: Dislike of bus transfer is lower?
- Travelers tend to not consider bus options with travel time 36% (BRT) and 43% (non-BRT) slower than quickest option.

Intuitions for network design

Geography

- 418 2×2 km square grid cells, leading to 1,536 adjacency links (potential bus route path).
- Bus travel time calculated for each grid edge.

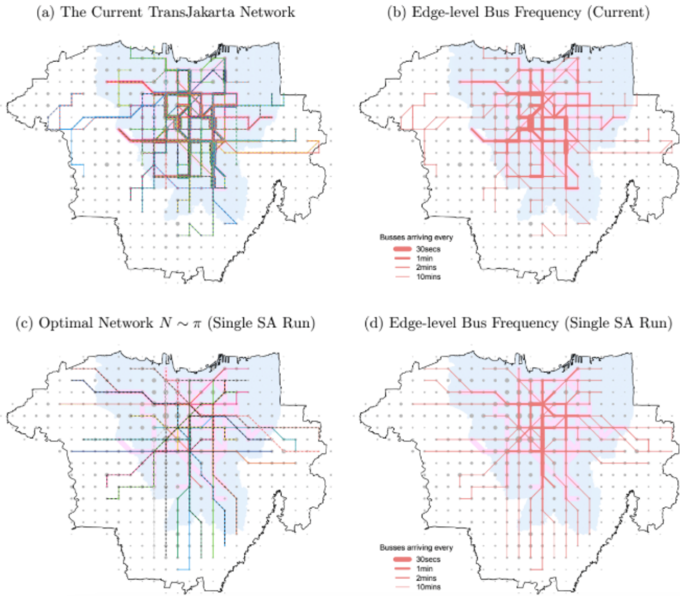
Environment

- Network N: Set of routes with bus allocations (1,500 buses in total).
- Model welfare $W(N, \theta)$.
- Estimated preferences parameter θ.

Objective

Optimal network N^* that maximizes welfare.

Current vs. optimal network design



- **Current**: Buses concentrated in the city center (short wait time in center, long wait time in outer part).
- **Optimal**: A more expansive network (spread out).
- Caveat: Not considering constraints preventing the expansion.

Conclusion

- Additional direct route option leads to increase in ridership.
- Commuter are responsive to public transport (non-price) service improvements (wait-time, travel-time, etc).
- Optimal network suggests that more expansive network could increase commuters' welfare and ridership.
- Kudos to them for conditional accept at AER!