Analyzing Location-Based Advertising for Vehicle Service Providers Using Effective Resistances

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Background

- Vehicle service providers have recently shown ads in vehicles.
- This talk: Understand how in-vehicle ads impacts service prices.

In-Vehicle Advertising: Example

Example 1 (Taxis): Curb Inc. installs tablets in taxis in 10 major cities in the U.S.

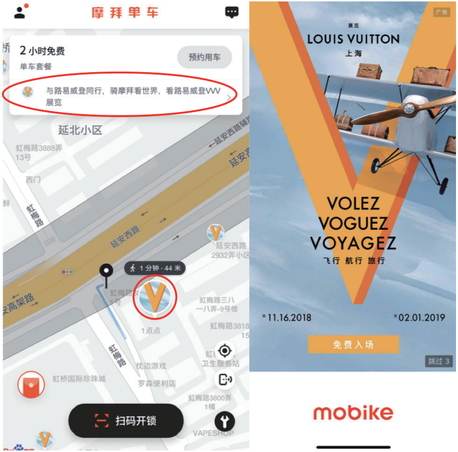
- Passengers can watch TV programs.
- Taxi companies can generate extra revenue by displaying ads.

In-Vehicle Advertising

Example 2 (Ride-Sharing Systems): VUGO Inc. installs tablets for Uber & Lyft drivers, displays ads based on origins & destinations, and shares ad revenue with drivers.

In-Vehicle Advertising

Example 3 (Bike-Sharing Systems): Mobike Inc. recently tested location-based advertising in Shanghai.



Problem

- First, we describe basic settings (e.g., traffic graph and prices).
- Second, we raise one key question about in-vehicle advertising.

Problem Description (Traffic Graph and Prices)

- We focus on a vehicle service provider who owns vehicles.
- Traffic graph (node: location, link: traffic demand)

- Provider sets different vehicle service prices for different links. Let p_{ij} be the price for link (i, j) (i: origin; j: destination).
  - e.g., $p_{13} = \$1/\text{minute}$.
    - Can be converted to $/mile based on vehicle velocity.

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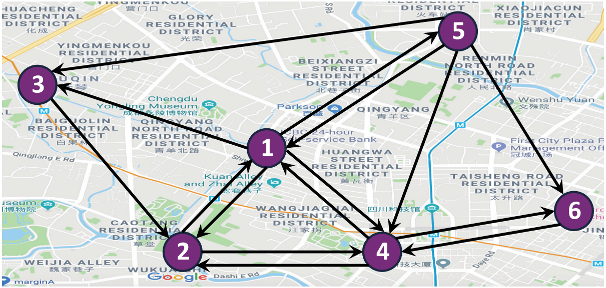

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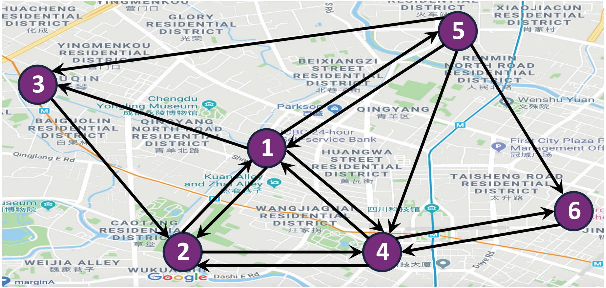

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Q: How Does Advertising Impact Prices in Network?

- Example: Provider collaborates with an advertiser (shopping mall) and gets ad revenues by displaying ads to riders on (2, 1).

- How should the provider change its service prices?
  - Reduce p_{21} to increase the number of riders on (2, 1)?
  - Increase p_{24} to save vehicles on (2, 4)?
  - How about p_{56}? Non-negligible impact?
- This talk: (i) Derive expressions of prices (e.g., p_{21}, p_{24}, p_{56});
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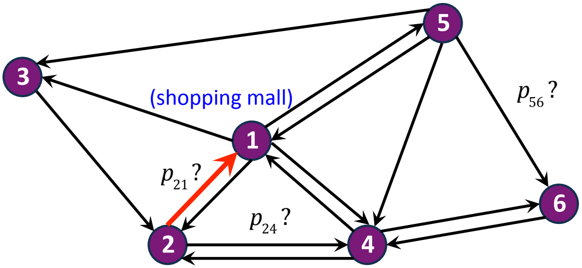

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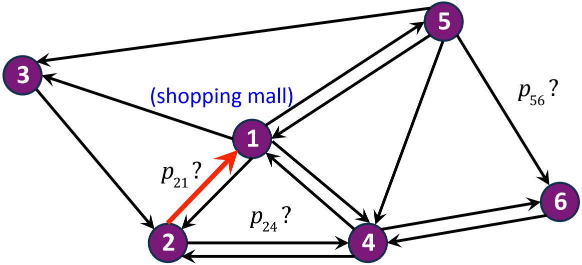

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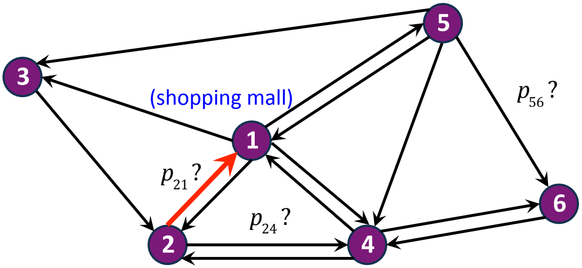

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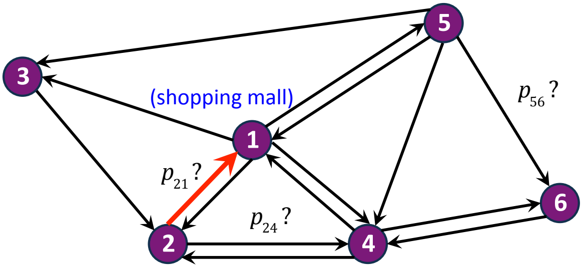

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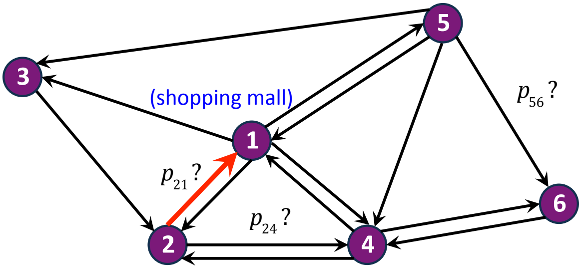

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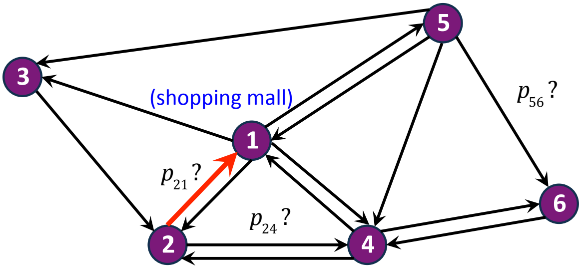

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Related Work

- Some prior work on advertising's impact on service prices:
  - Media service: [Kaiser and Wright 2006], [Peitz and Valletti 2008], [Godes *et al.* 2009], [Anderson and Jullien 2015]
  - Location-based service: [Yu *et al.* 2017]
  - Mobile app service: [Guo *et al.* 2018]
- Our work focuses on vehicle service.
  - There are multiple prices (each link in network has a price).
  - The advertising's impact is affected by the network topology.

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Model

Formulate provider's pricing problem considering ad revenues.

Model (Notations)

- Traffic network's parameters (constants)
  - $\theta_{ij} \geq 0$: number of users considering taking vehicle service on (i, j) in each time slot (e.g., one time slot = one minute).
  - $\xi_{ij} > 0$: travel time from i to j (measured by number of slots).
- Provider's decision variables
  - p_{ij}: service price for (i, j) ($ per time slot).
  - Routing full vehicles (carrying users), empty vehicles (no users)
    - $q_{ij}^{\text{full}} \geq 0$: full vehicles' departure rate for (i, j).
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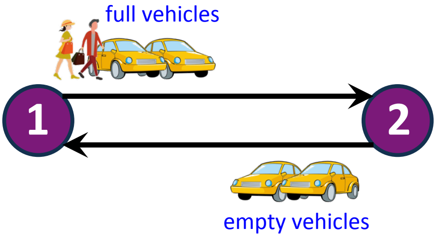
a toy example:

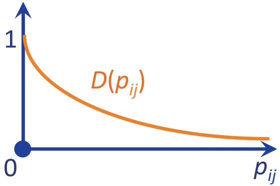


Model (Constraints)

- Demand constraint (decision variables are in blue)

$$q_{ij}^{\text{full}} \leq \theta_{ij} D\left(p_{ij}\right), \forall i, j.$$

  - $D\left(p_{ij}\right)$: fraction of users accepting p_{ij} and taking vehicle service.



Parameter: θ_{ij}: number of users considering service per slot.
Decisions: q_{ij}^{full}: full vehicle routing; p_{ij}: vehicle service price.

Model (Constraints)

- Vehicle flow balance constraint

$$\underbrace{\sum_j \left(q_{ij}^{\text{full}} + q_{ij}^{\text{empty}} \right)}_{\text{rate of vehicles departing from } i} = \underbrace{\sum_j \left(q_{ji}^{\text{full}} + q_{ji}^{\text{empty}} \right)}_{\text{rate of vehicles arriving at i}}, \forall i.$$

This couples the provider's decisions for different links.

Decisions: q_{ij}^{full}, q_{ij}^{empty}: full/empty vehicle routing.

Model (Objective)

- Objective (time-average profit from all links)

$$\max \sum_{(i,j)} \Big(\underbrace{\xi_{ij} q_{ij}^{\text{full}}}_{\text{number of full vehicles running on } (i,j) \text{ in any slot}} \left(p_{ij} + a_{ij} - c^{\text{full}}\right) - \xi_{ij} q_{ij}^{\text{empty}} c^{\text{empty}} \Big)$$

  - Some new parameters:
    - $a_{ij} \geq 0$: ad revenue per full vehicle per time slot on (i, j).
    - $c^{\text{full}}, c^{\text{empty}} > 0$: a (full/empty) vehicle's operation cost per slot.

Parameter: ξ_{ij}: travel time.
Decisions: $q_{ij}^{\text{full}}, q_{ij}^{\text{empty}}$: full/empty vehicle routing; p_{ij}: vehicle service price.

Problem Formulation

- The provider's problem:

$$\max \sum_{\text{each link } (i,j)} \left(\xi_{ij} q_{ij}^{\text{full}} \left(p_{ij} + a_{ij} - c^{\text{full}} \right) - \xi_{ij} q_{ij}^{\text{empty}} c^{\text{empty}} \right)$$

$$\text{s.t.} \quad q_{ij}^{\text{full}} \leq \theta_{ij} D\left(p_{ij}\right), \forall i, j, \text{(demand constraint)}$$

$$\sum_{j} \left(q_{ij}^{\text{full}} + q_{ij}^{\text{empty}} \right) = \sum_{j} \left(q_{ji}^{\text{full}} + q_{ji}^{\text{empty}} \right), \forall i, \text{(flow balance)}$$

$$\text{var.} \quad q_{ij}^{\text{full}}, q_{ij}^{\text{empty}} \geq 0, p_{ij}, \forall i, j.$$

- Question: What is $\frac{\partial p_{ij}^*}{\partial a_{xy}}$ (p_{ij}^* is optimal price; a_{xy} is ad revenue)?
  - Hard to directly compute p_{ij}^*: non-convex problem in general.
- Rest of talk
  - [Solution] design p_{ij}^{ϕ} and analyze $\frac{\partial p_{ij}^{\phi}}{\partial a_{xy}}$;
  - [Performance] study p_{ij}^{ϕ}'s optimality theoretically & numerically.

  - p_{ij}^{ϕ} achieves close-to-optimal profit $\Longrightarrow$ $\frac{\partial p_{ij}^{\phi}}{\partial a_{xy}}$ gives insights.

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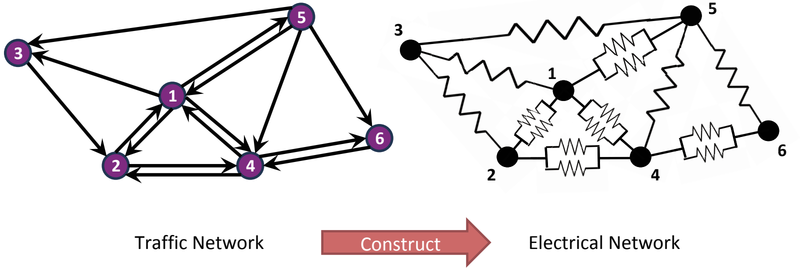
Solution

- We propose an innovative design of p_{ij}^{ϕ}.
  - Vehicle networks are similar to electrical networks (e.g., keeping vehicle/current flow balance at each node).
  - We will borrow notions from electrical networks to design p_{ij}^{ϕ}.

Construction of Electrical Network

- Construct an electrical network based on traffic network.



- link $(i, j) \Longrightarrow$ a resistor with resistance $r_{ij} = \frac{\xi_{ij}}{\theta_{ij}}$.

Parameters: θ_{ij}: number of users considering service per slot; ξ_{ij}: travel time.

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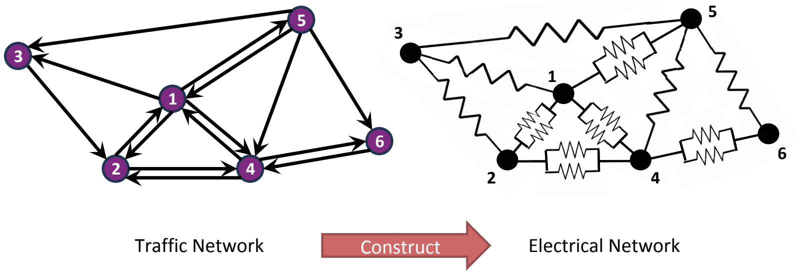

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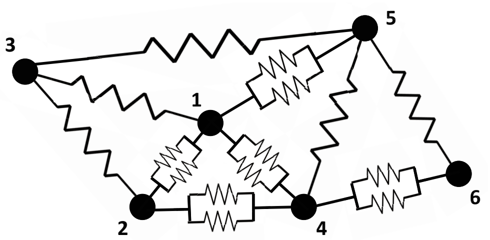
Effective Resistances

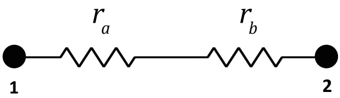
- Given an electrical network described by $\{r_{ij}\}_{i,j}$, we can compute *Effective Resistance* between any two nodes i and j.



Effective Resistances

- Examples of computing *Effective Resistance*.

effective resistance between 1 and 2



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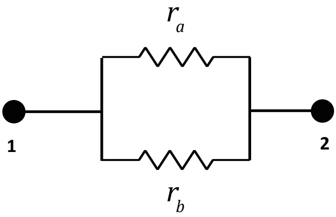
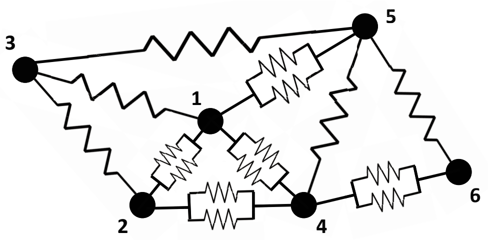


$$R_{12} = \frac{r_a r_b}{r_a + r_b}$$

Effective Resistances

- Let $R_{ij}(\theta, \xi)$ denote the effective resistance between i and j (can be computed in polynomial time).
  - e.g., $R_{34}(\theta, \xi)$'s value depends on all resistors.



- $R_{ij}(\theta, \xi)$ internalizes the network topology's influence.
  - Intuition: small $R_{ij}(\theta, \xi) \iff$ easy to route vehicles from i to j.
- We design prices based on $\{R_{ij}(\theta, \xi)\}_{i,j}$.

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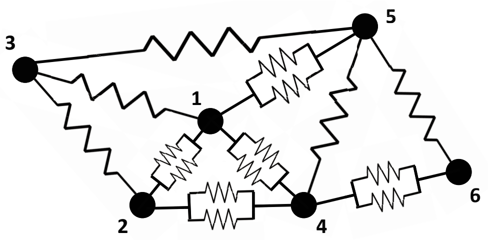

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Our Resistance-Based Pricing

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Let $\phi > 0$ be a control parameter. Our resistance-based price for (i, j) is given by

$$p_{ij}^{\phi} = \frac{1}{2} \underbrace{\left(\frac{1}{\phi} - a_{ij} + c^{\text{full}} \right)}_{\text{parameters of link } (i,j)} + \frac{1}{4\xi_{ij}} \sum_{x} \sum_{y} \underbrace{\rho_{ijxy}\left(\boldsymbol{\theta}, \boldsymbol{\xi}\right)}_{\text{weight function}} \underbrace{\theta_{xy} \left(\frac{1}{\phi} + a_{xy} - c^{\text{full}} \right)}_{\text{parameters of link } (x,y)},$$

where $\rho_{ijxy}\left(\boldsymbol{\theta}, \boldsymbol{\xi}\right) \triangleq R_{jx}\left(\boldsymbol{\theta}, \boldsymbol{\xi}\right) - R_{ix}\left(\boldsymbol{\theta}, \boldsymbol{\xi}\right) - R_{jy}\left(\boldsymbol{\theta}, \boldsymbol{\xi}\right) + R_{iy}\left(\boldsymbol{\theta}, \boldsymbol{\xi}\right)$.

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Advertising's Impact on Prices

- If $(x, y) \neq (i, j)$, we have

$$\frac{\partial p_{ij}^{\phi}}{\partial a_{xy}} = \frac{\theta_{xy}}{4\xi_{ij}} \left(R_{jx}(\theta, \xi) - R_{ix}(\theta, \xi) - R_{jy}(\theta, \xi) + R_{iy}(\theta, \xi) \right).$$

  - Come back to our example:

- Is p_{ij}^{ϕ} optimal or close-to-optimal?

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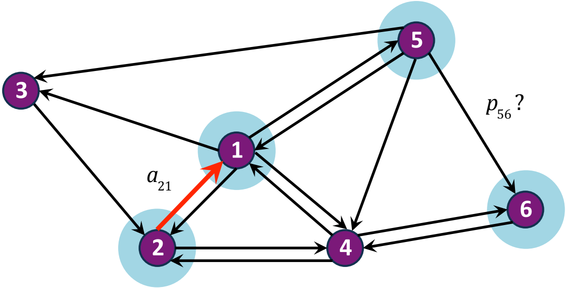

Sign of $\frac{\partial p_{56}^{\phi}}{\partial a_{21}}$ depends on $R_{62}(\boldsymbol{\theta},\boldsymbol{\xi}) - R_{52}(\boldsymbol{\theta},\boldsymbol{\xi}) - R_{61}(\boldsymbol{\theta},\boldsymbol{\xi}) + R_{51}(\boldsymbol{\theta},\boldsymbol{\xi})$.

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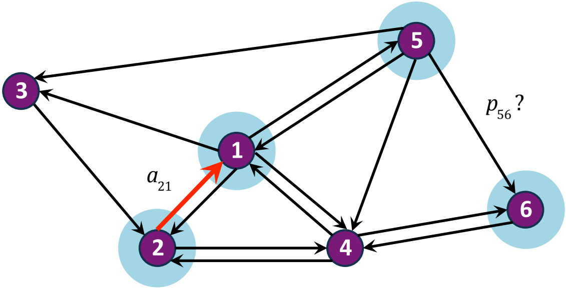

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Performance

- (Theoretical) *If demand function D is linear and provider cannot route empty vehicles, p_{ij}^{ϕ} is optimal.*
- (Experimental) *If demand function D is exponential and provider can route empty vehicles, p_{ij}^{ϕ} is close-to-optimal.*

Performance Evaluation (Theoretical)

Theorem

When the following three conditions hold:
(i) $D\left(p_{ij}\right) = \max\left\{1 - \psi p_{ij}, 0\right\}$ for $\psi > 0$ (linear demand function),
(ii) $c^{\text{empty}} \to \infty$,
(iii) The auxiliary constraint $p_{ij} \leq \frac{1}{\psi}$ is not binding,
the provider can achieve the maximum profit by choosing p_{ij}^{ψ}, $q_{ij}^{\text{full}} = \theta_{ij} D\left(p_{ij}^{\psi}\right)$, and $q_{ij}^{\text{empty}} = 0$ for all i, j.

Performance Evaluation (Theoretical)

Key Idea of Proof: When conditions are satisfied,

dual variables for flow balance

$$p^*_{ij} = \text{function}(\boldsymbol{\lambda}^*)$$

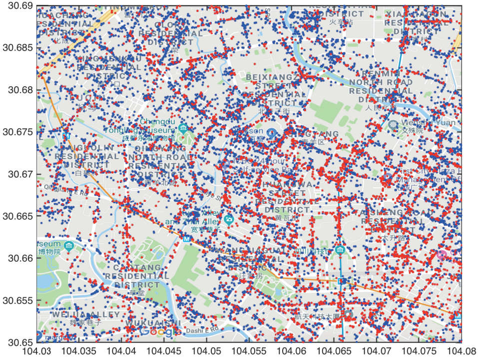
it's solution to $\mathbf{L}\,\boldsymbol{\lambda}^* = \mathbf{v}$

its generalized inverse satisfies $R_{ij} = l^+_{ii} + l^+_{jj} - 2l^+_{ij}$

Performance Evaluation (Experimental)

We consider non-linear $D(p_{ij})$ and finite c^{empty} in experiments.

- Real-world dataset (DiDi Chuxing GAIA Open Data Initiative)
  - Information of DiDi rides during November, 2016 in Chengdu. [1]



Pick-Up (Blue) and Drop-Off (Red) Dots During 7-9 am On Weekdays.

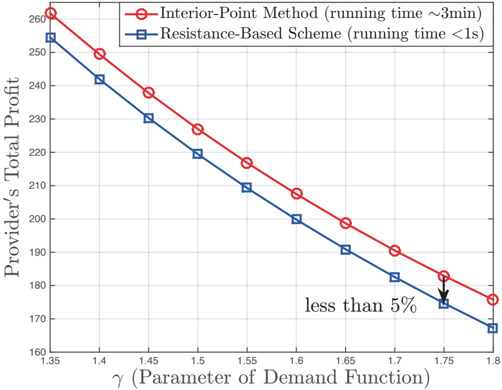
  - We divide an area into 15 locations and derive $\boldsymbol{\theta}$ and $\boldsymbol{\xi}$.

[1] DiDi Chuxing GAIA Open Data Initiative (https://gaia.didichuxing.com).

Performance Evaluation (Experimental)

- Other experiment settings
  - $D\left(p_{ij}\right) = e^{-\gamma p_{ij}}$ (verified by real data in [Fang *et al.* 2017]).
  - $c^{\text{full}} = c^{\text{empty}} = 0.4$.
  - a_{ij} follows an exponential distribution with mean 0.15.
- Evaluated schemes
  - Our resistance-based scheme (complexity: polynomial in number of locations):
    - Choose p_{ij}^{ϕ} for all i, j (where $\phi = \frac{\gamma}{2}$);
    - Choose $q_{ij}^{\text{full}} = \theta_{ij} D\left(p_{ij}^{\phi}\right)$ for all i, j;
    - Choose q_{ij}^{empty} by solving an LP problem.
  - Interior-point method

Performance Evaluation (Experimental)



Our resistance-based scheme achieves at least 95% of the profit achieved by the interior-point method.

Conclusion

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  - Use effective resistances (capturing network topology's influence) to design prices.
  - Provide a simple and effective approach to measure location-based advertising's impact on network pricing.
- Other results in our work
  - Investigate the advertising's impact on users' payoffs.
  - Study the provider's optimal advertiser selection strategy.
- Future directions
  - Consider driver-side design in ride-sharing systems.
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THANK YOU