

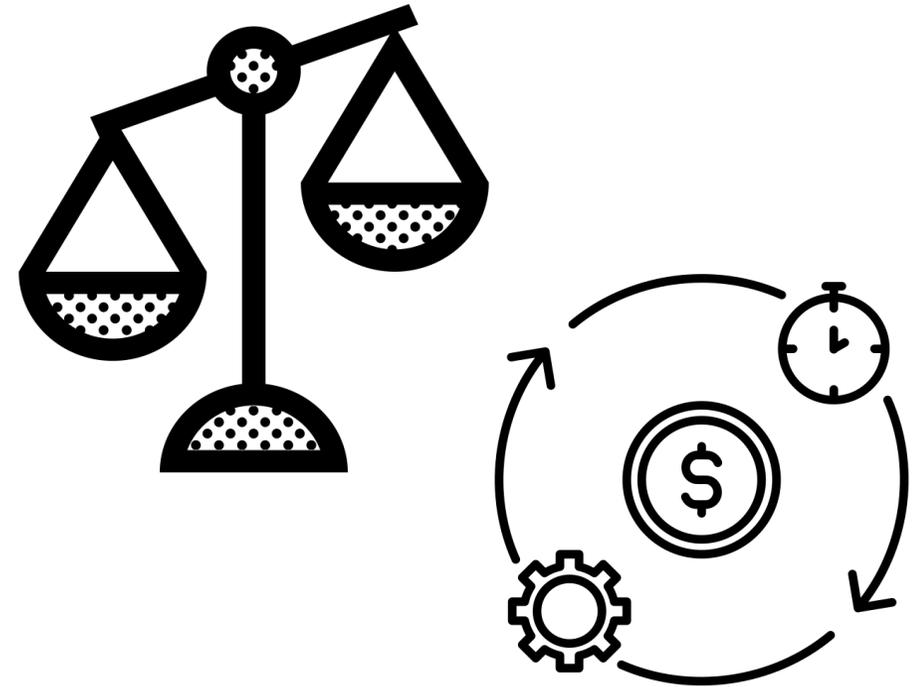
# When Efficiency meets Equity in Mobility Management

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Autonomous Systems Laboratory  
Stanford University

ITSC Workshop on “Autonomous, Connected and Electrified  
Mobility Systems: Modeling, Control, and Deployment”

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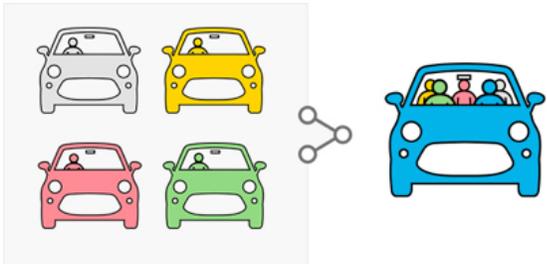


Stanford  
University



# AI-enabled optimization of future mobility systems

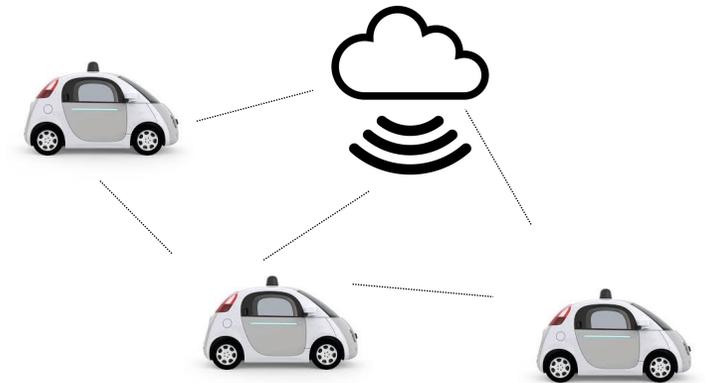
## Shared vehicles



## Autonomous vehicles



## The mobility internet



## Specific-purpose designs



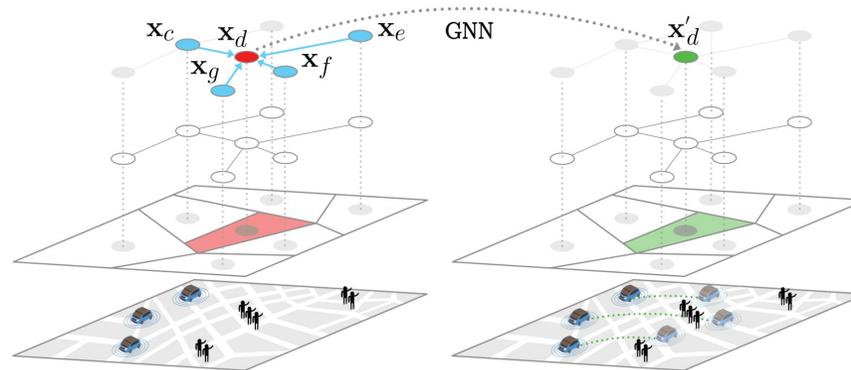
## Advanced propulsion



# Ongoing research activities

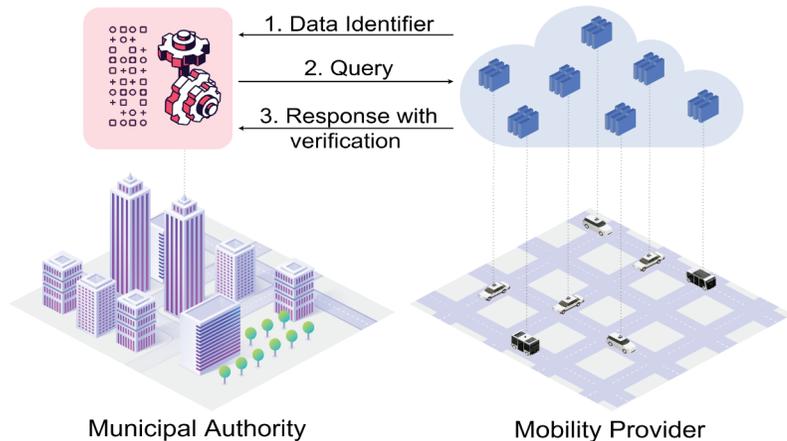
## Data-driven coordination algorithms, for example:

“Graph Neural Network Reinforcement Learning for Autonomous Mobility-on-Demand Systems,” CDC ‘21



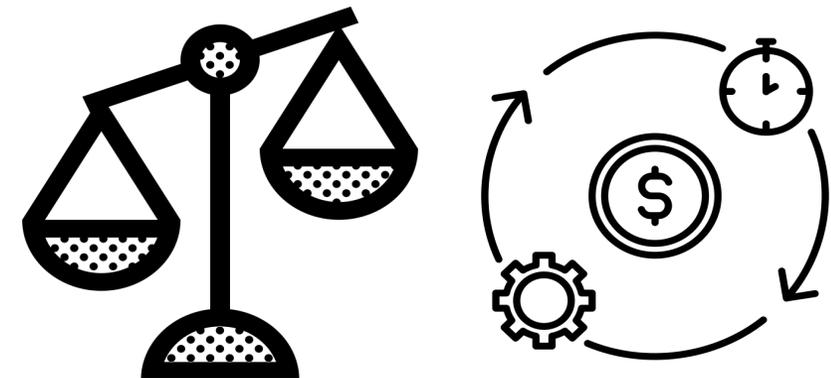
## Privacy in transportation, for example:

“Trust but Verify: Cryptographic Data Privacy for Mobility Management,” TCNS ‘21 (submitted)



## Equity in transportation, for example:

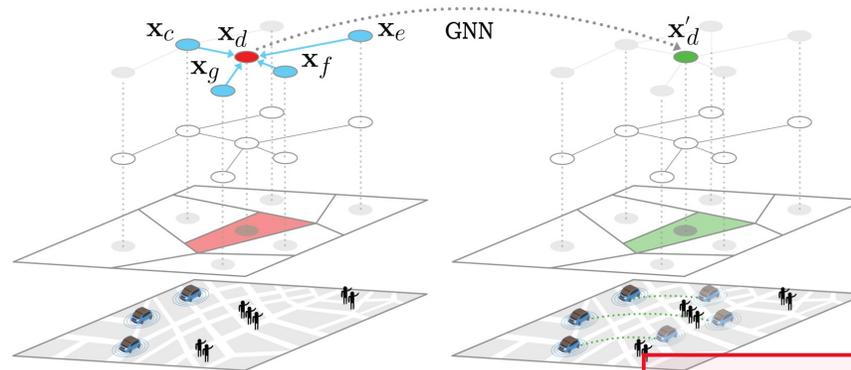
“When Efficiency meets Equity in Congestion Pricing and Revenue Refunding Schemes,” EAAMO ‘21



# Ongoing research activities

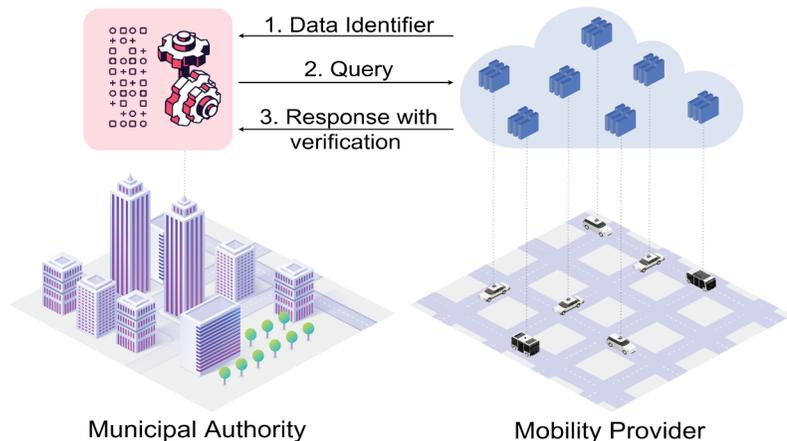
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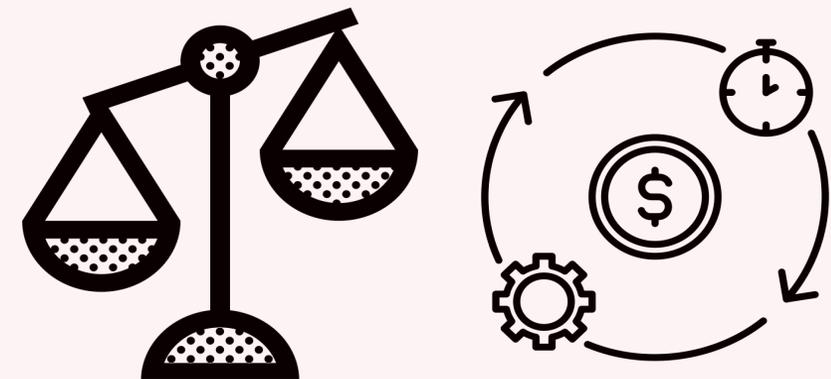
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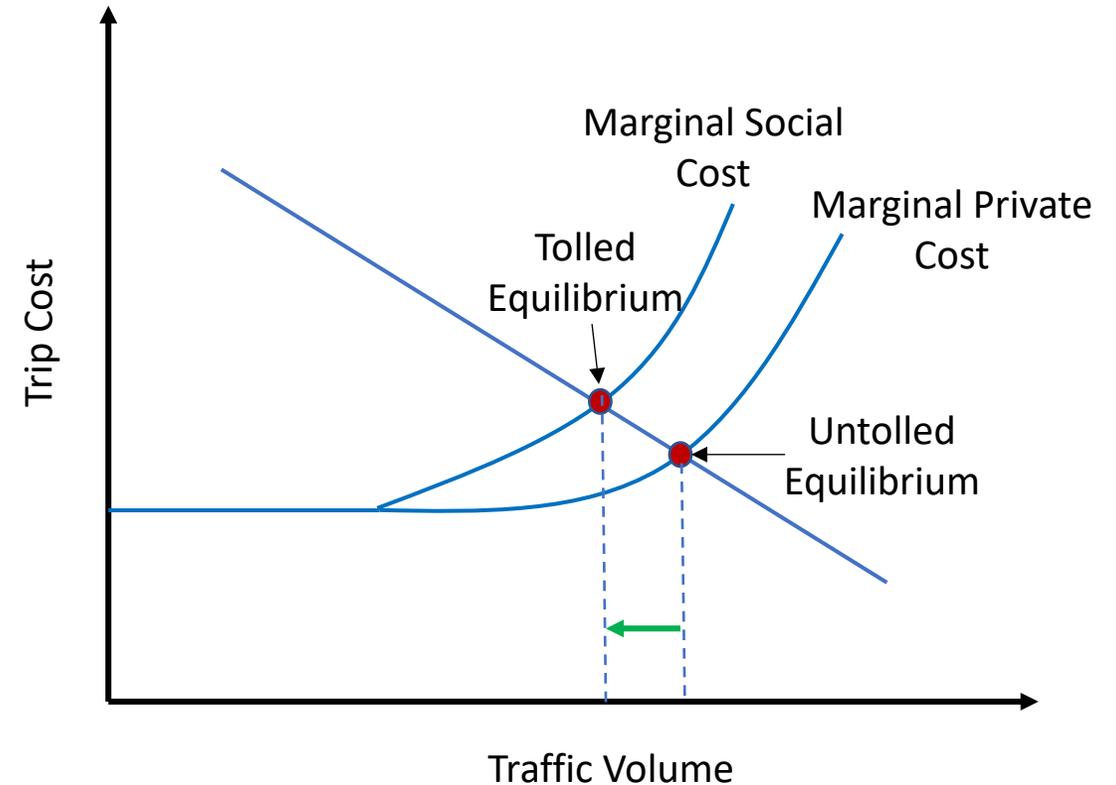
# Traffic congestion has become a ubiquitous part of daily travel in urban metropolises



Economist.com

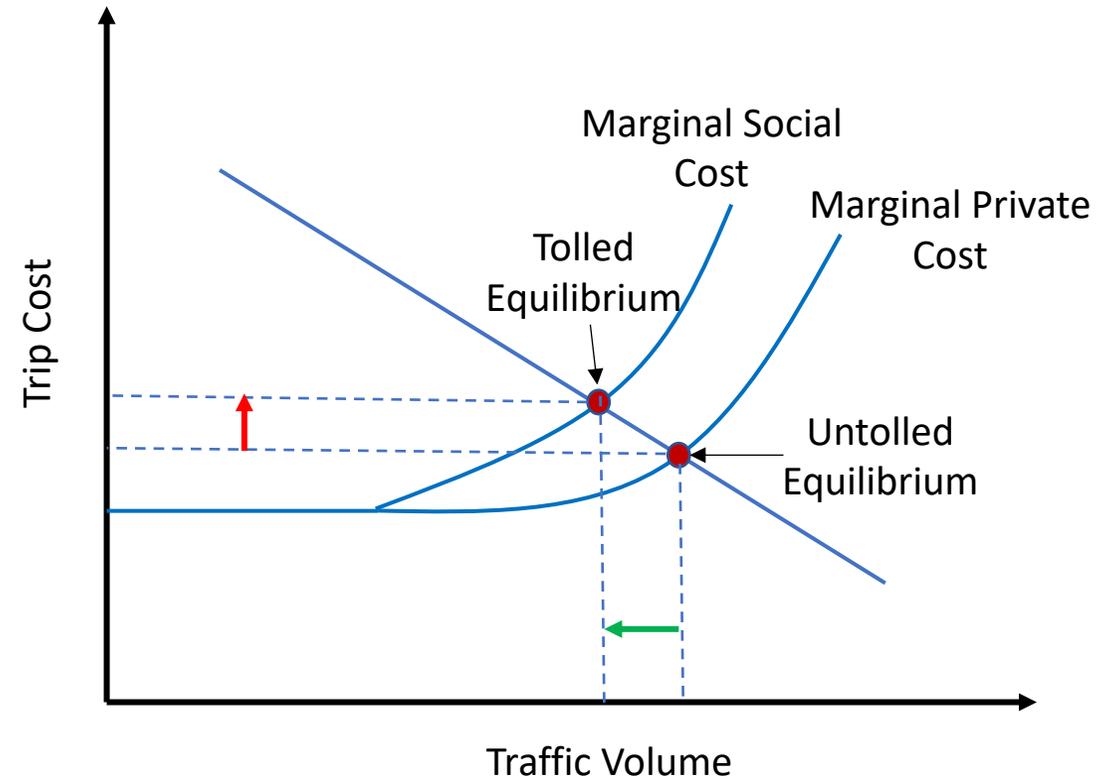


# Congestion pricing has been hailed as a means to alleviate traffic congestion



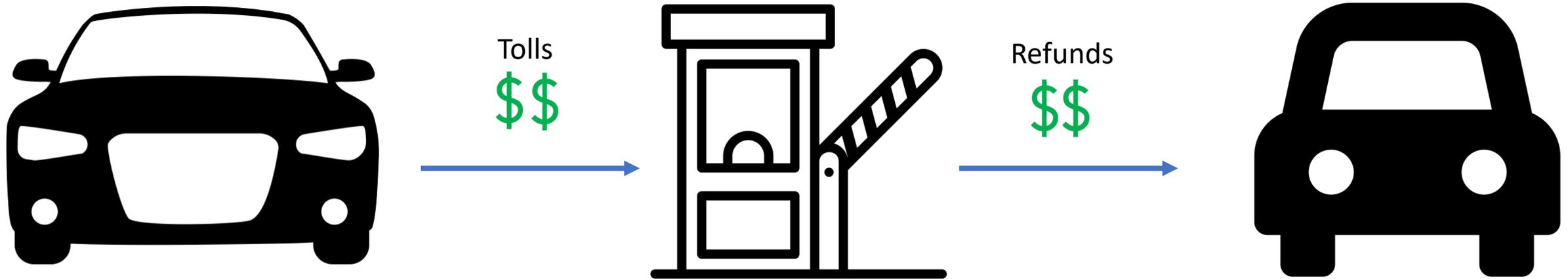
**“With autonomous transportation, intelligent system-wide road pricing becomes more attractive” (Ostrovsky and Schwarz, 2018)**

However, it results in social inequity issues as low-income users are priced out off certain roads



**“With autonomous transportation, intelligent system-wide road pricing becomes more attractive” (Ostrovsky and Schwarz, 2018)**

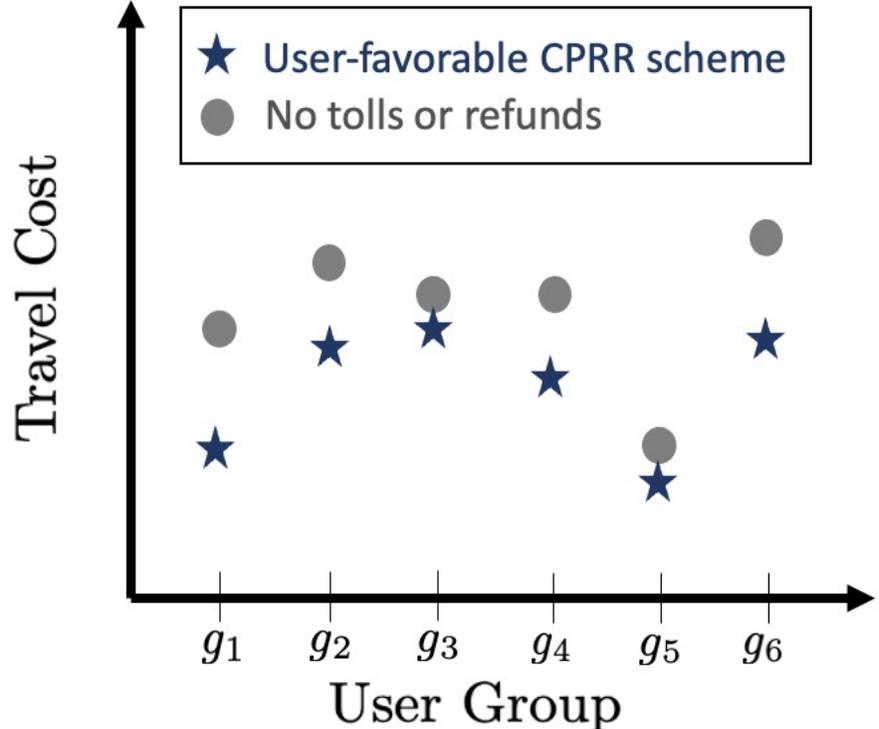
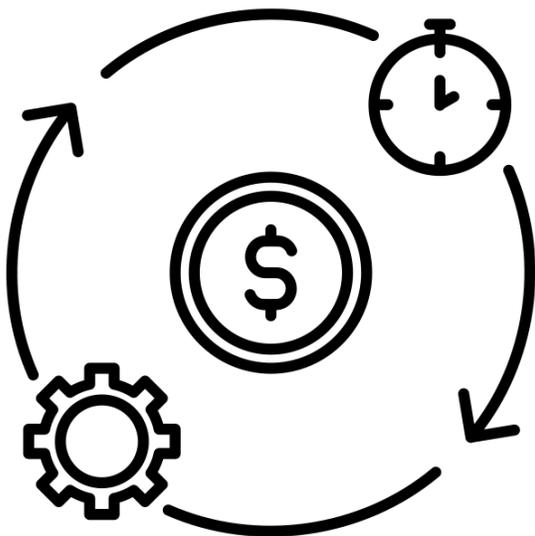
This has spurred interest in equitable mechanisms that refund and redistribute collected toll revenues



The successful deployment of a combined tolling and refunding policy will be aided by the deployment of a connected system of vehicles

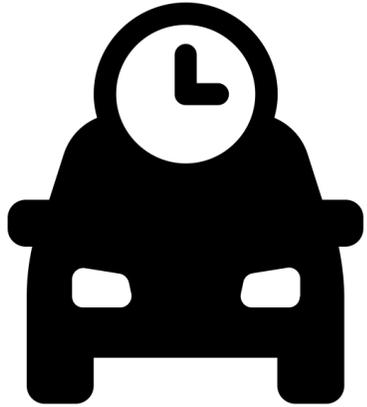
However, there has been no thorough characterization of the wealth inequality effects of congestion pricing and revenue refunding (CPRR) schemes

# We study wealth inequality effects of CPRR schemes and design ones that improve both system efficiency and wealth inequality

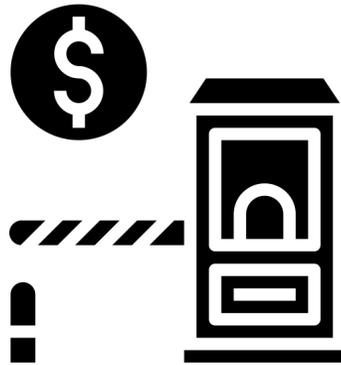


# We study two models of user behavior depending on whether users account for refunds when minimizing costs

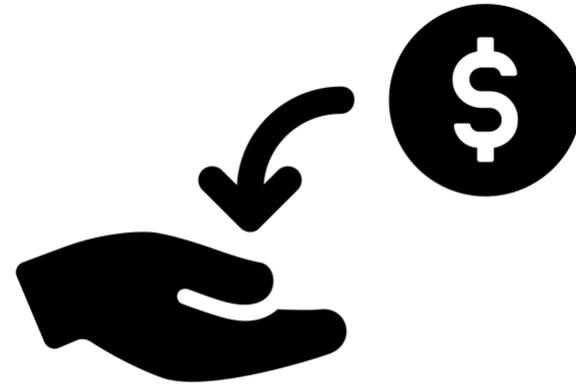
Travel Time



Tolls



Refunds



Classical Nash  
Equilibrium Setting

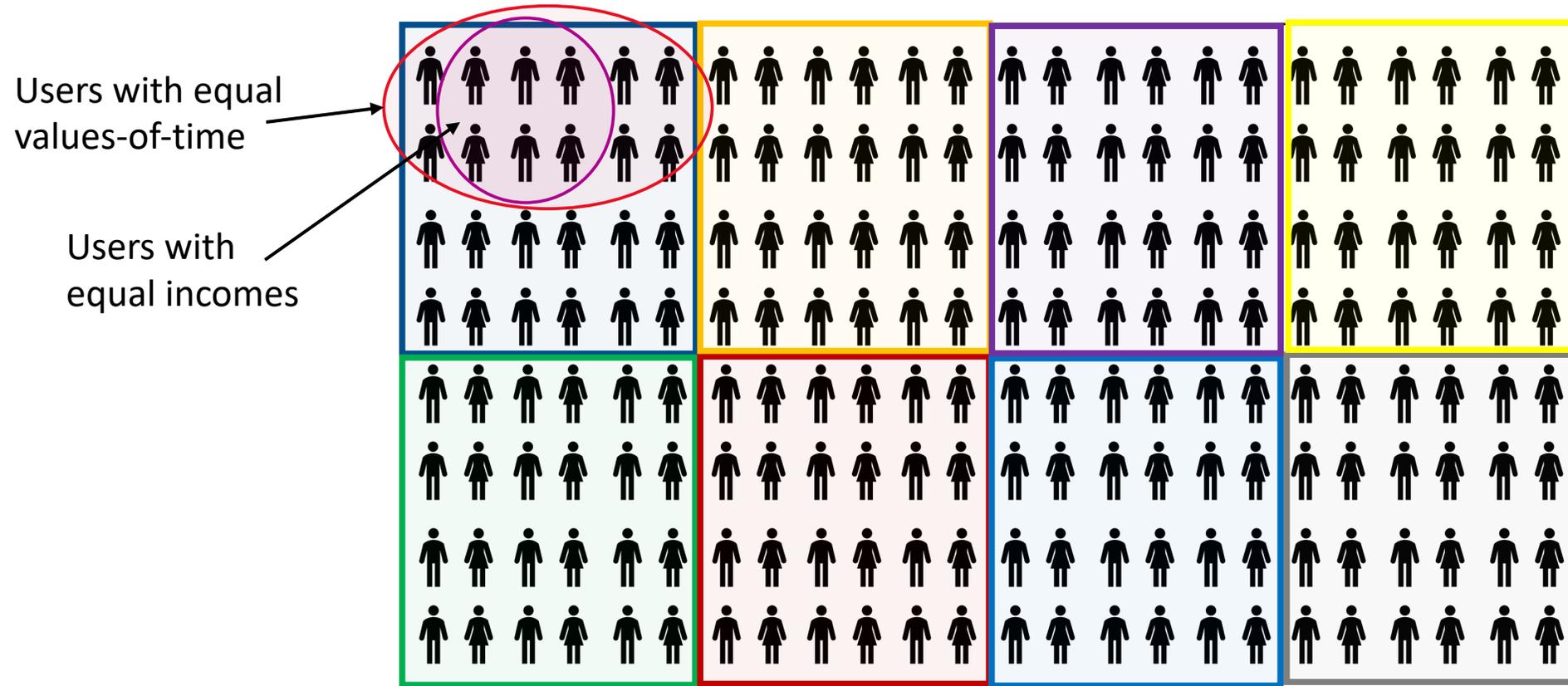
**Exogenous Equilibrium**

Users only consider travel time and tolls in their travel cost minimization

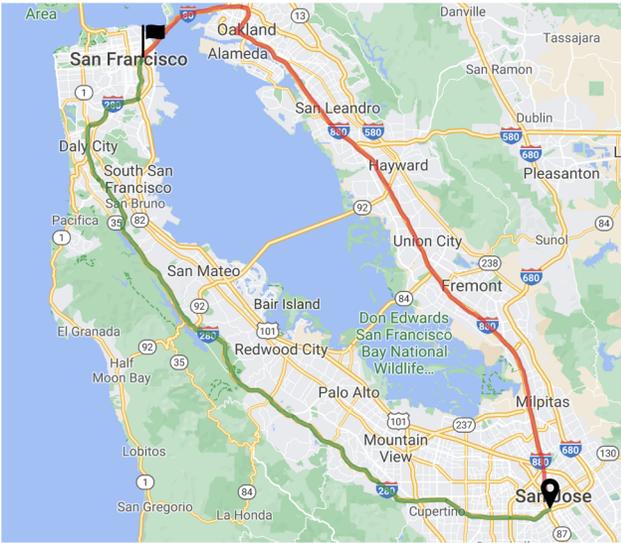
**Endogenous Equilibrium**

Users additionally endogenize the effect of refunds on their travel decisions

# Users are grouped based on their O-D pair, value-of-time and income level

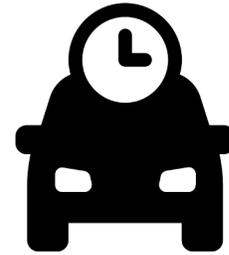


# Users incur a cost that is a linear function of their travel times, tolls and refunds



$x_e =$  Flow on Edge  $e$

$t_e(x_e) =$  Travel Time on Edge  $e$



Travel Time



Tolls



Refunds

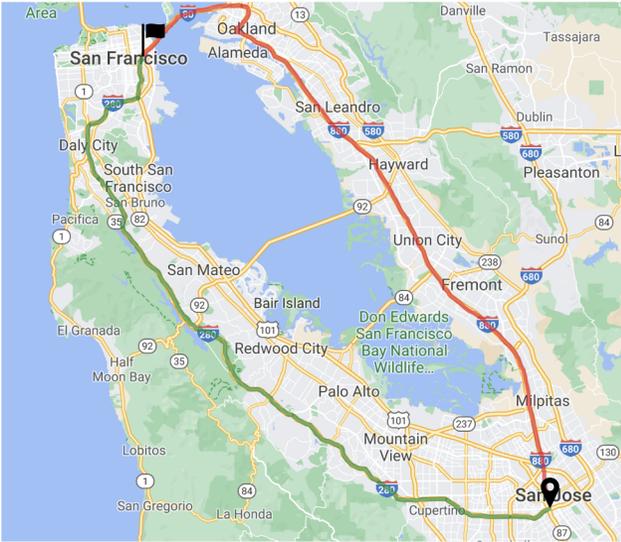
$$\mu^g(\tau, r) = v_g \sum_{e \in P} t_e(x_e) + \sum_{e \in P} \tau_e - r_g$$

Group  $g$       Refunds  $r_g$       Value of Time  $v_g$       Path  $P$       Toll on edge  $e$   $\tau_e$

For a refunding scheme to be valid, the sum of tolls collected must add up to sum of refunds given

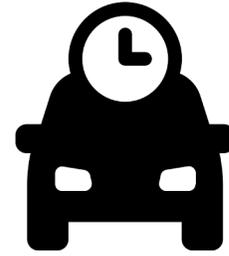
For an equilibrium flow pattern, each user's travel cost is independent of the realized path flows

In the exogenous equilibrium setting, users minimize a linear function of their travel time and tolls



$x_e =$  Flow on Edge  $e$

$t_e(x_e) =$  Travel Time on Edge  $e$



Travel Time



Tolls

$$\mu^g(\tau, \mathbf{0}) = v_g \sum_{e \in P} t_e(x_e) + \sum_{e \in P} \tau_e$$

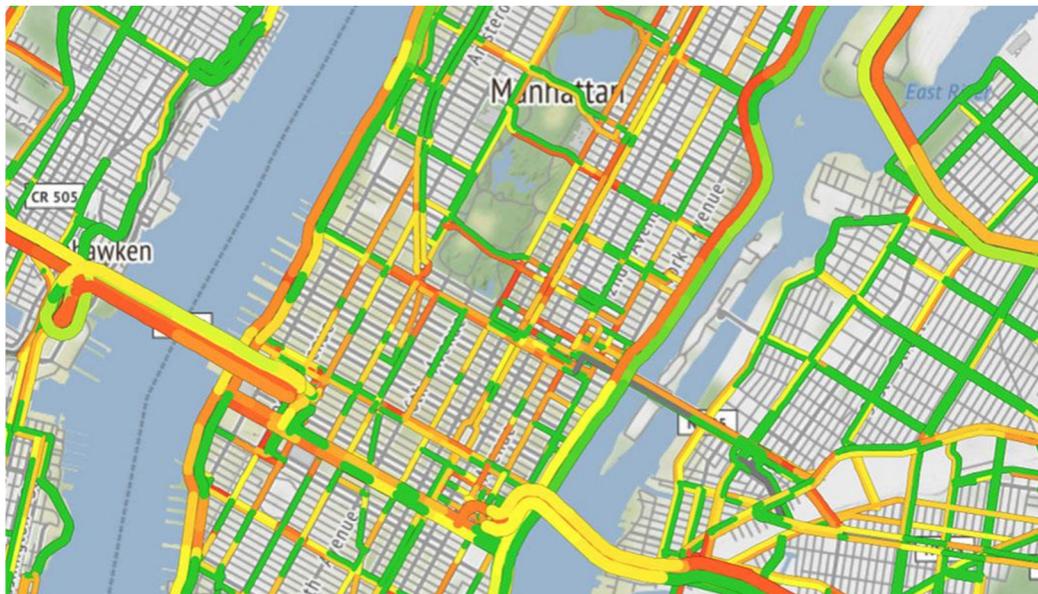
Value of Time

Toll on edge  $e$

# We evaluate the performance of a CPRR scheme through two metrics

## Efficiency

Total System Cost of a traffic assignment,  
i.e., the value of time weighted travel  
times of all users in the network



## Wealth Inequality

Level of wealth inequality of the ex-post income  
distribution after the implementation of a CPRR  
scheme relative to the no tolls and refunds  
setting

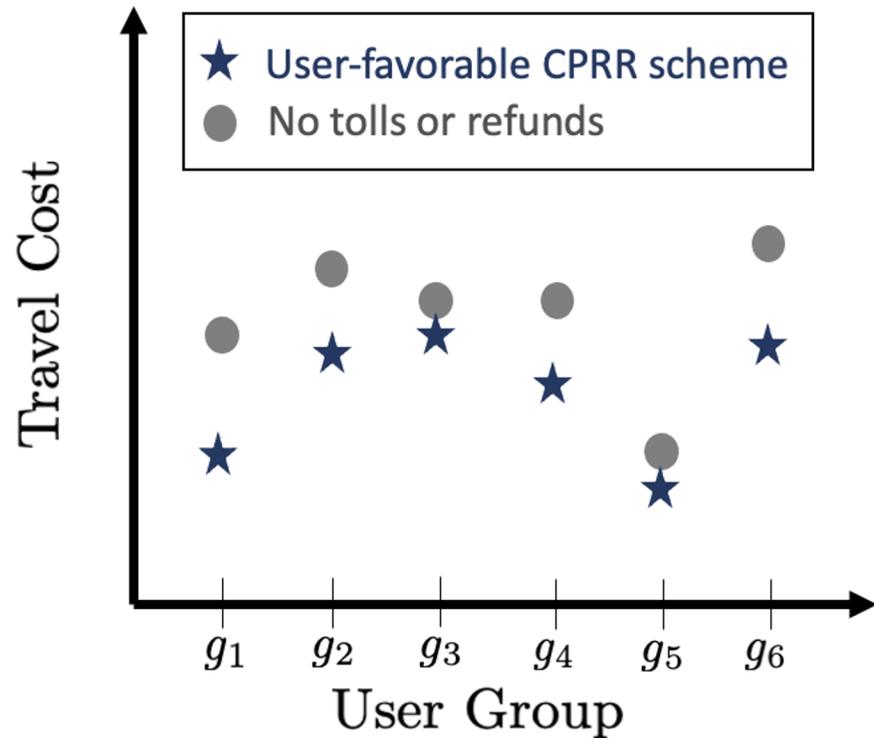
### Ex-Post Income Distribution

$$q_g(\tau, \mathbf{r}) = q_g^0 - \mu^g(\tau, \mathbf{r})$$

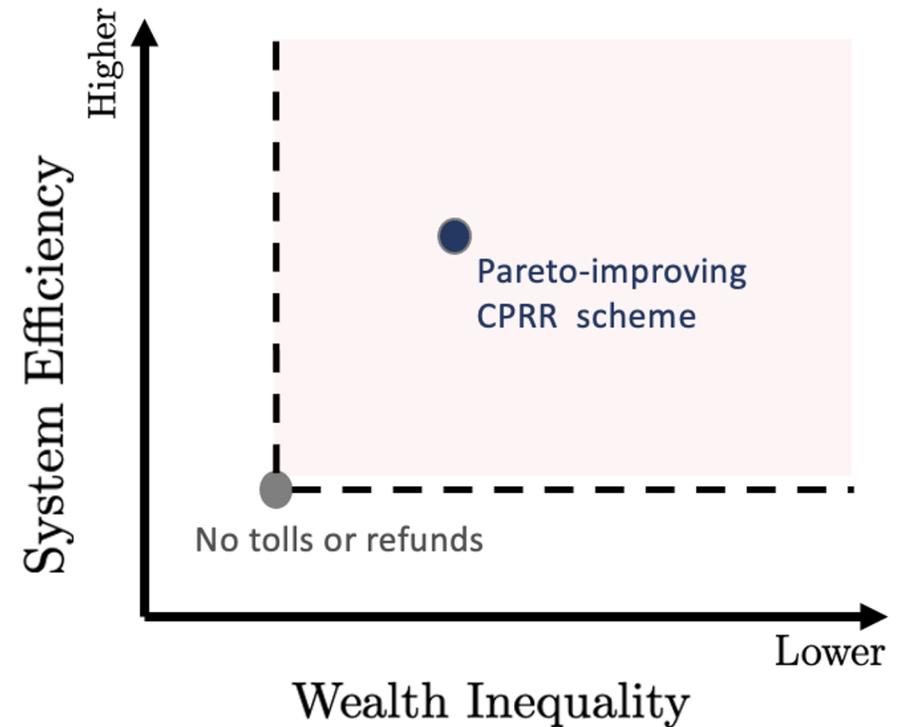
Ex-ante Income of  
users in group  $g$

Travel Cost of  
users in group  $g$

# We first establish the existence of Pareto improving CPRR schemes that are user favourable

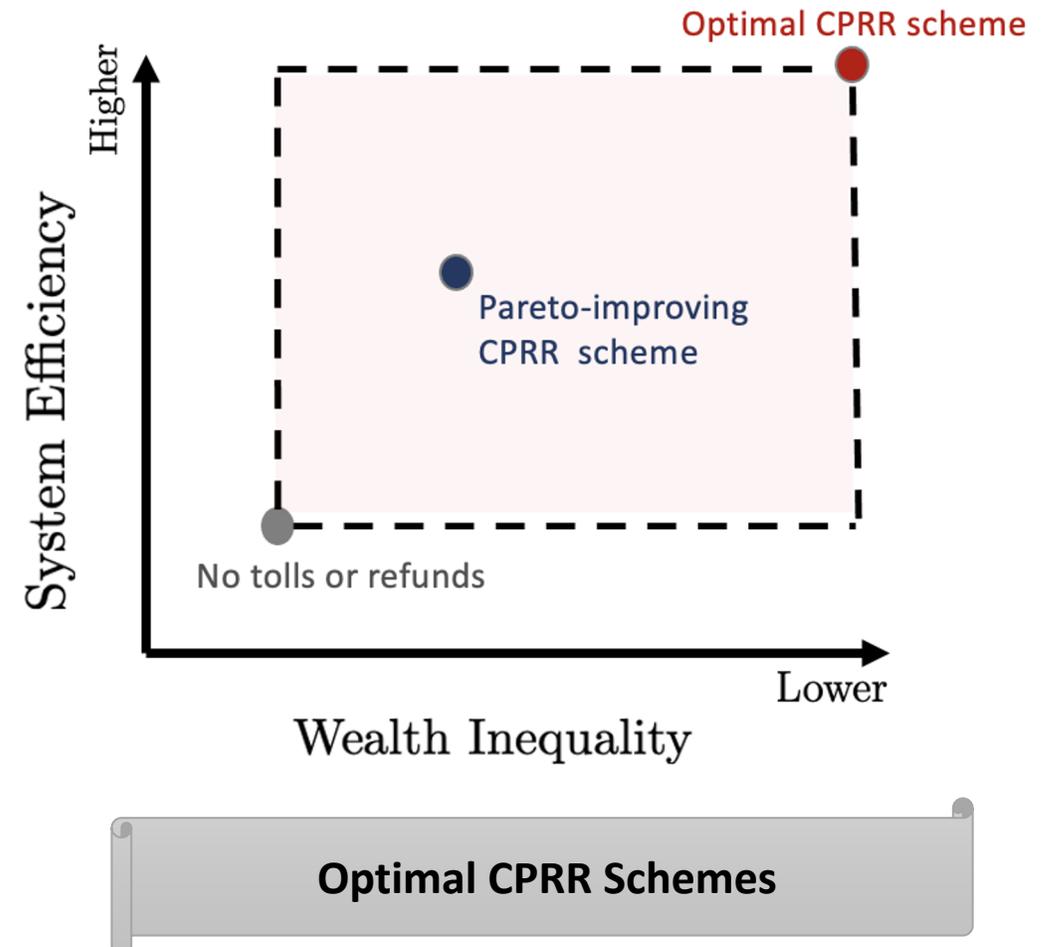
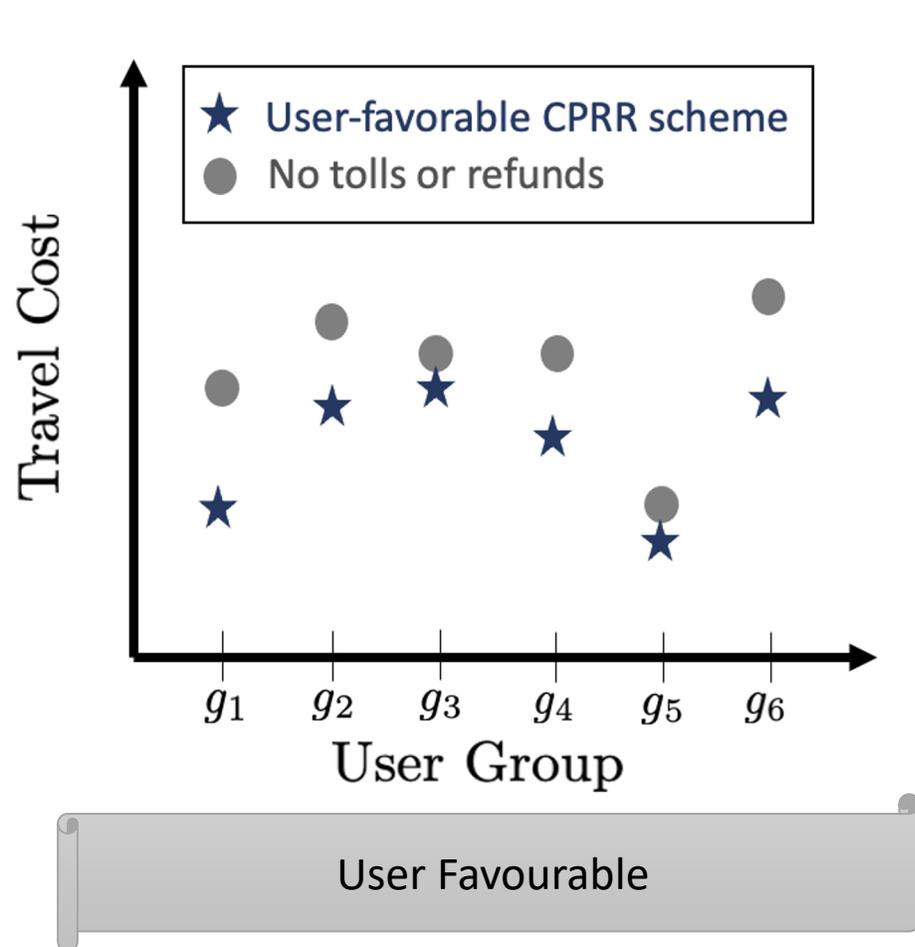


User Favourable

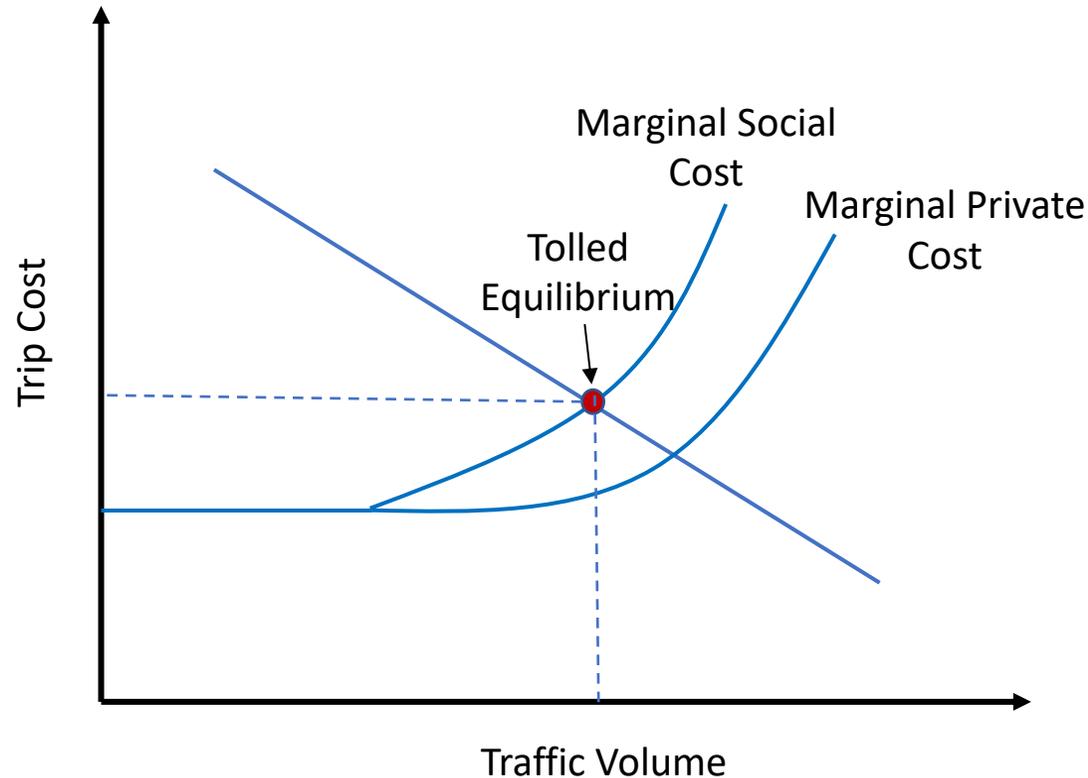


Pareto Improving

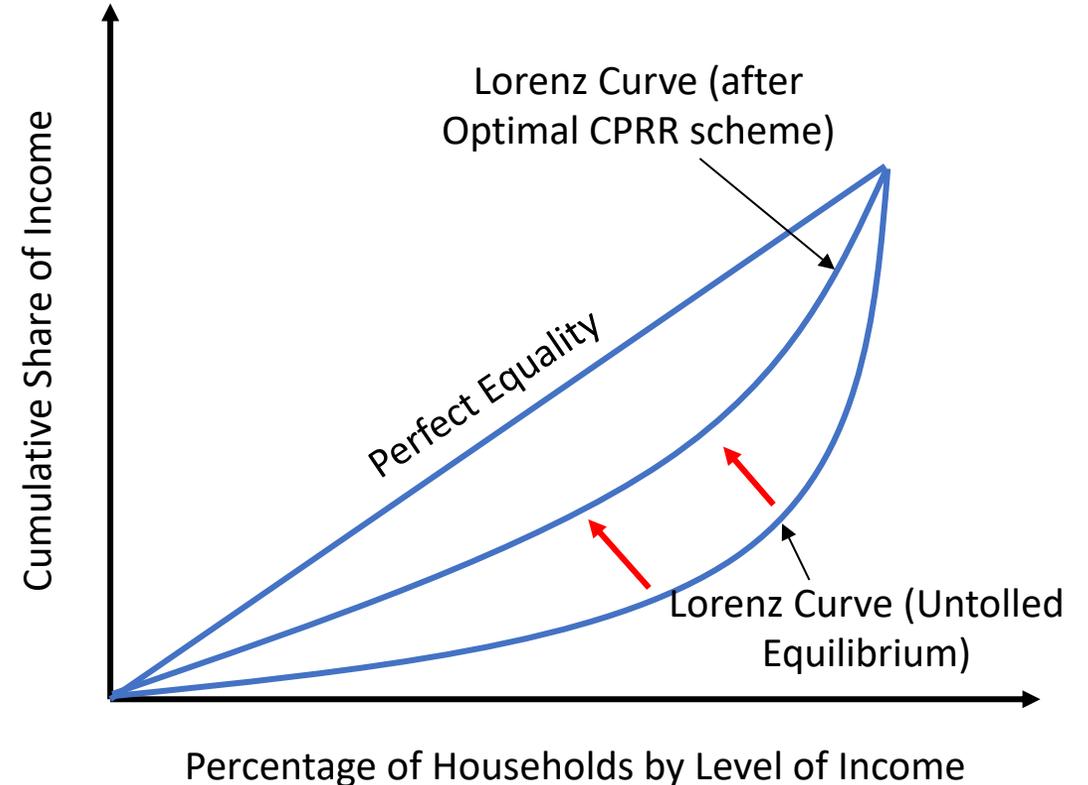
# We further characterize the set of optimal user favourable CPRR schemes



# We provide a two-step prescription on determining the optimal user-favourable CPRR scheme

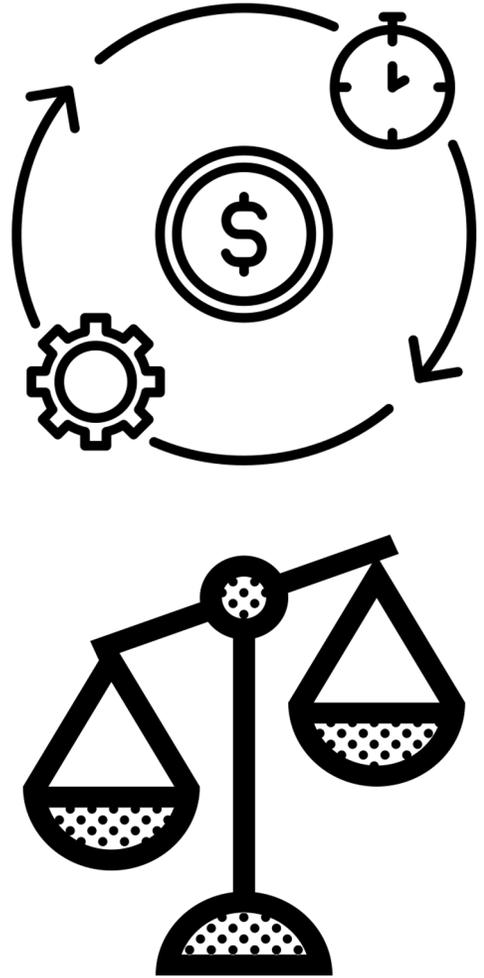


**Step 1: Find optimal Congestion prices  $\tau^*$  that induce a traffic flow pattern with minimum total system cost**

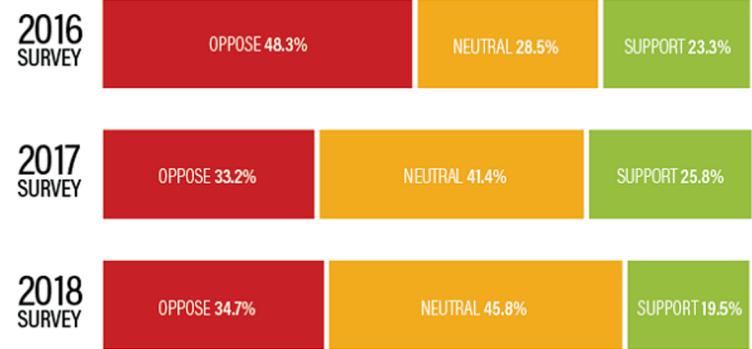


**Step 2: Optimally refund collected toll revenues while satisfying the user favourability condition**

# We make progress towards the equity and efficiency goals of sustainable transportation

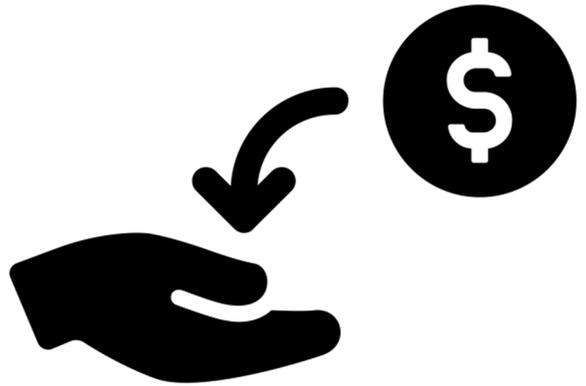


Public Attitudes Toward Congestion Charging

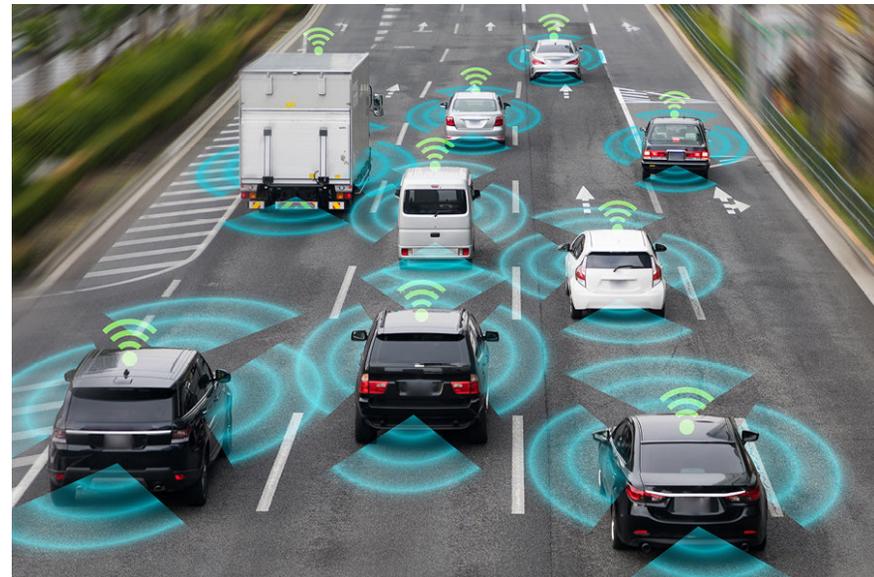
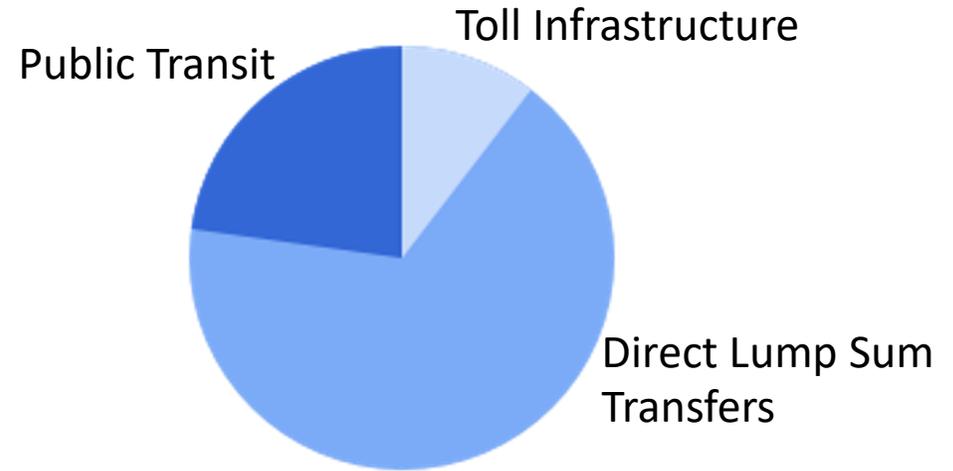
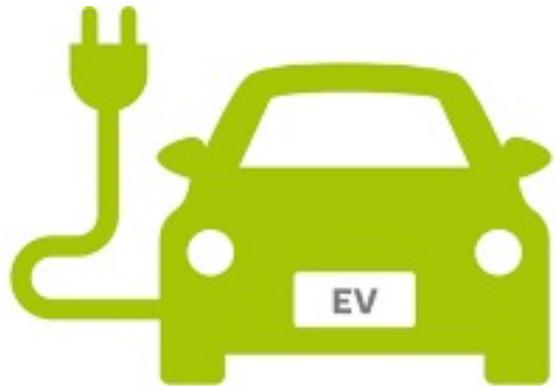


Source: WRI China.

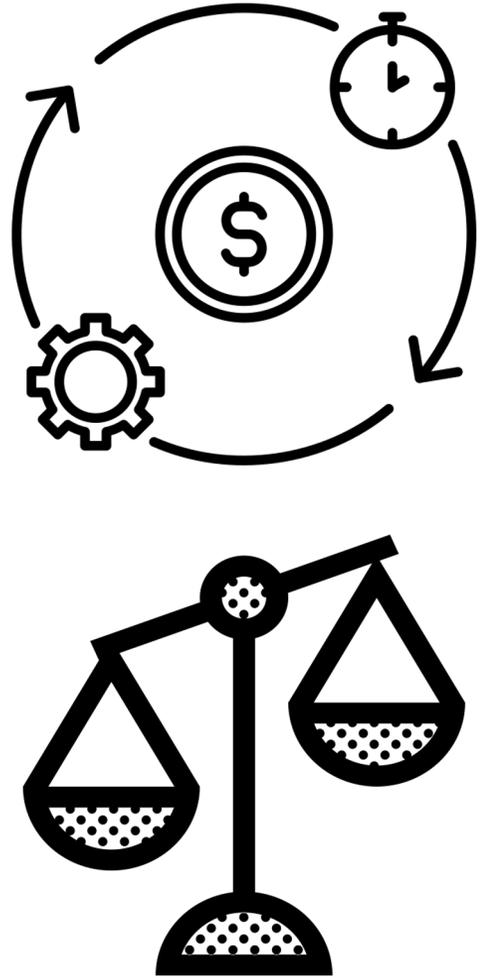
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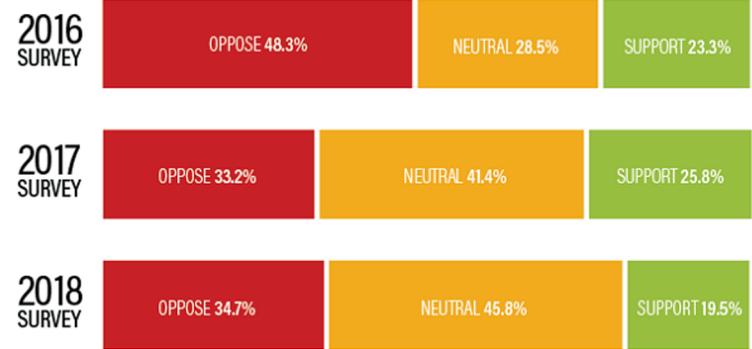
# Future Work



# We make progress towards the equity and efficiency goals of sustainable transportation

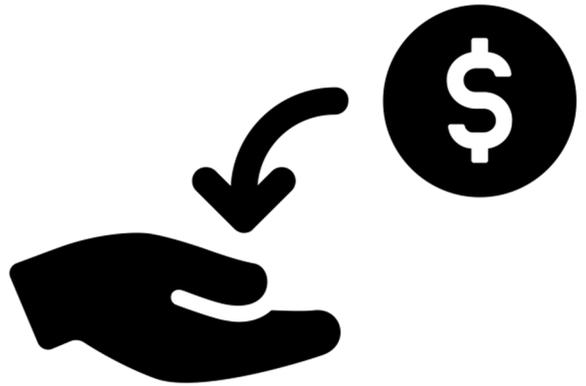


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arXiv Link: <https://arxiv.org/pdf/2106.10407.pdf>