When Efficiency meets Equity in Mobility Management

Marco Pavone and Devansh Jalota
Autonomous Systems Laboratory
Stanford University

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

September 19, 2021

pavone@stanford.edu, djalota@stanford.edu
AI-enabled optimization of future mobility systems

- Shared vehicles
- Specific-purpose designs
- Autonomous vehicles
- The mobility internet
- 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

**Data-driven coordination algorithms**, for example:

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

**Equity in transportation**, for example:

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

**Privacy in transportation**, for example:

“Trust but Verify: Cryptographic Data Privacy for Mobility Management,” TCNS ‘21 (submitted)
Traffic congestion has become a ubiquitous part of daily travel in urban metropolises.
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 of 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.

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

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

**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

\[ x_e = \text{Flow on Edge } e \]

\[ t_e(x_e) = \text{Travel Time on Edge } e \]

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.

\[ x_e = \text{Flow on Edge } e \]
\[ t_e(x_e) = \text{Travel Time on Edge } e \]

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

- Travel Time
- Tolls
- 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

\[
q_g(\tau, r) = q_g^0 - \mu^g(\tau, r)
\]

- **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.
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.
Future Work

- Public Transit
- Toll Infrastructure
- Direct Lump Sum Transfers
We make progress towards the equity and efficiency goals of sustainable transportation