THE UNIVERSITY OF NEWCASTLE AUSTRALIA

THNS2024: Transforming Transportation

Strategizing sustainability and profitability in electric Mobility-as-a-Service (E-MaaS) ecosystems with carbon incentives: A multi-leader multi-follower game

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Contents

Mobility-as-a-Service

The biggest transport revolution of the 21st century

"The key concept behind MaaS is to put the users at the core of transport services, offering them tailor made mobility solutions based on their individual needs. This means, for the first time, easy access to the most appropriate transport mode or service will be included in a bundle of flexible travel service options for end users."

The European Mobility as a Service Alliance

The concept of electric Mobility-as-a-Service (E-MaaS)

eMAAS

"E-MaaS is the integration of multiple forms of eco-friendly transportation modes—including human-powered vehicles and electric public transport—and shared electric mobility services (e.g., e-car sharing, e-bike sharing, e-scooter sharing, e-bus, e-taxi) into a single mobility service that allows travelers to plan and travel in an eco-friendly and seamless way. The service is offered through a single customer-centered interface, and it also involves the prearrangement of electric mobility technologies and infrastructure (e.g., charging stations, energy contracts)."

Reyes Garc´ıa et al. (2019)

EV subsidy incentives

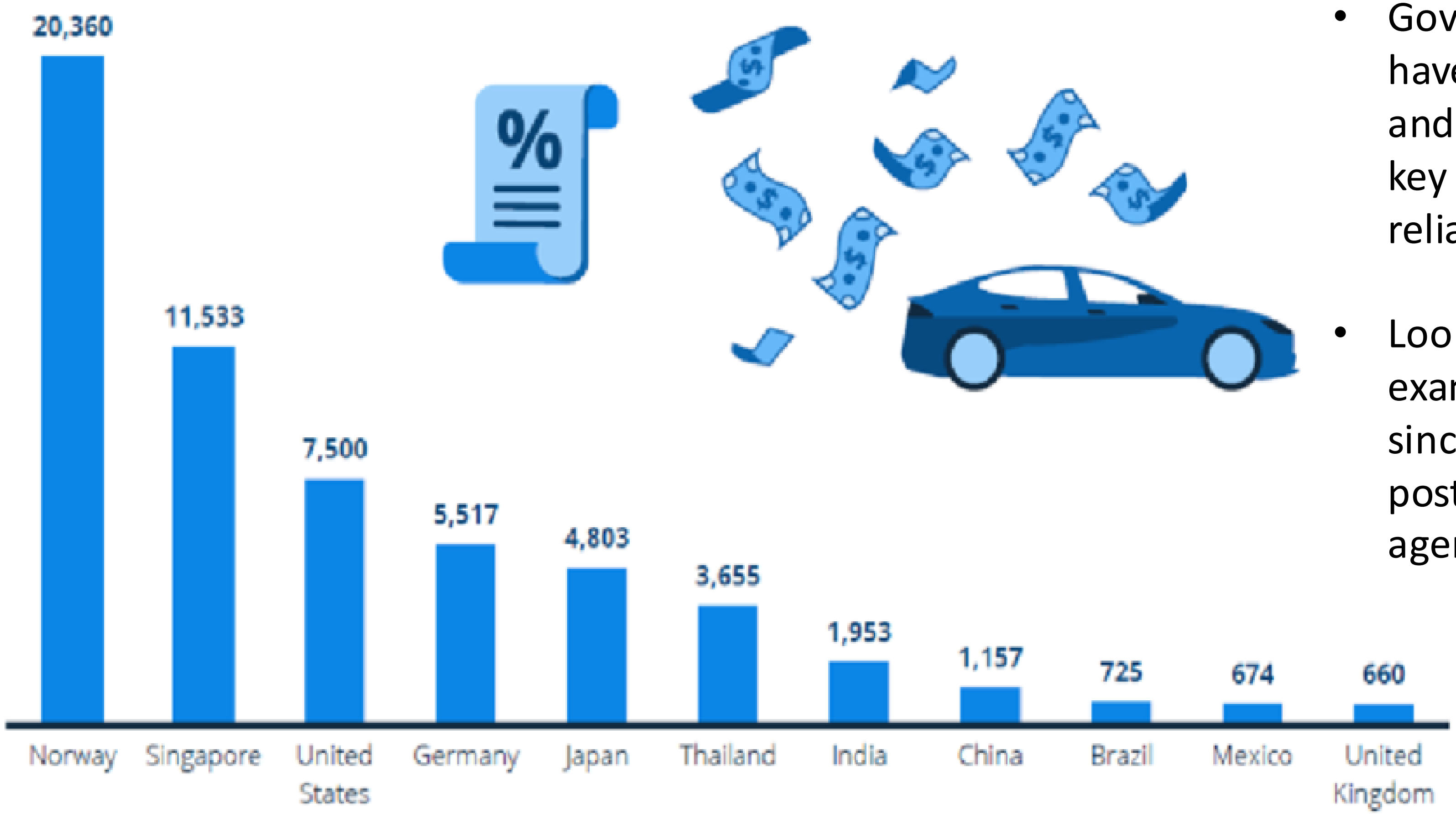
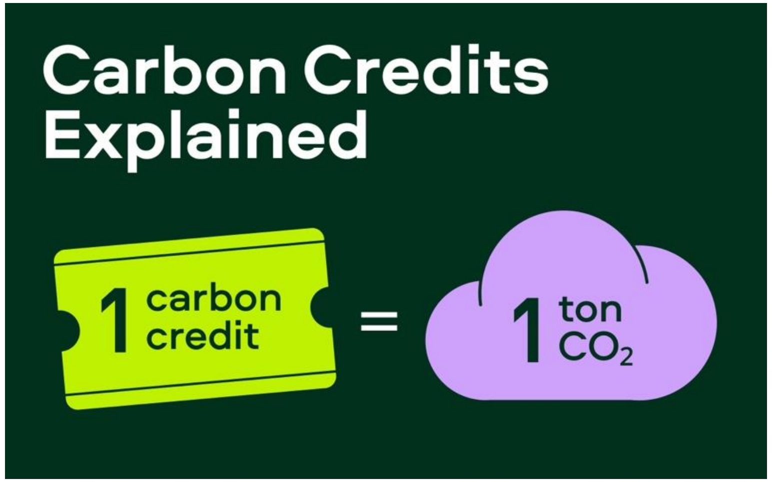


Figure. Average global electric vehicle subsidies at purchase in selected countries in 2023 (in US dollars)

Source: [Electric vehicles: A global overview 2023]

- Governments and organizations worldwide have introduced incentives like subsidies and carbon credits, positioning EVs as a key technology to reduce fossil fuel reliance and GHG emissions.
- Looking globally, Singh et al. (2023) examined research trends on EV adoption since the 1980s, noting a surge in interest post-2010 and proposing a research agenda to further promote EVs.

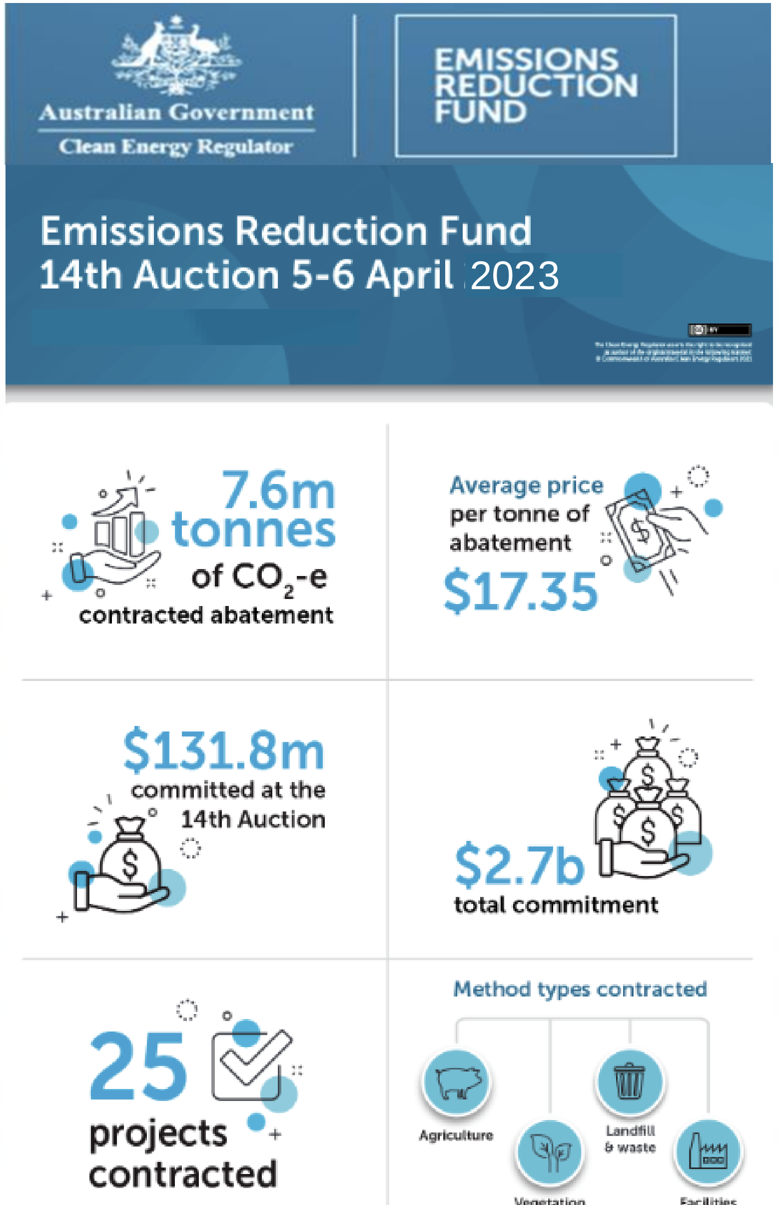
Carbon credits incentives



Carbon Credit Pricing Chart: Updated 2023 (Source: World bank)

Project Type:	Average Price:	Price Range:
Transportation	$2.9	$2.2 - $6.8

Emission reduction fund in Australia



Beijing MaaS platform with carbon incentives

2019:
•Launched China's first **green MaaS platform**.

2020:
•Introduced an innovative **carbon inclusion scheme** based on MaaS.
•Rolled out the **"MaaS Travel, Green Movement Across the City"** carbon incentive initiative.
•Users accumulate **carbon emission reductions** by using public transport, bikes, or walking via an app.
•Rewards include **public transportation vouchers** and **shopping coupons**, promoting green travel behavior.

2021:
•Completed the **world's first green travel carbon inclusion transaction**.

2022:
•Supported **over 100 million trips** during the Winter Olympics.

Over 30 million users

Carbon credits online shop

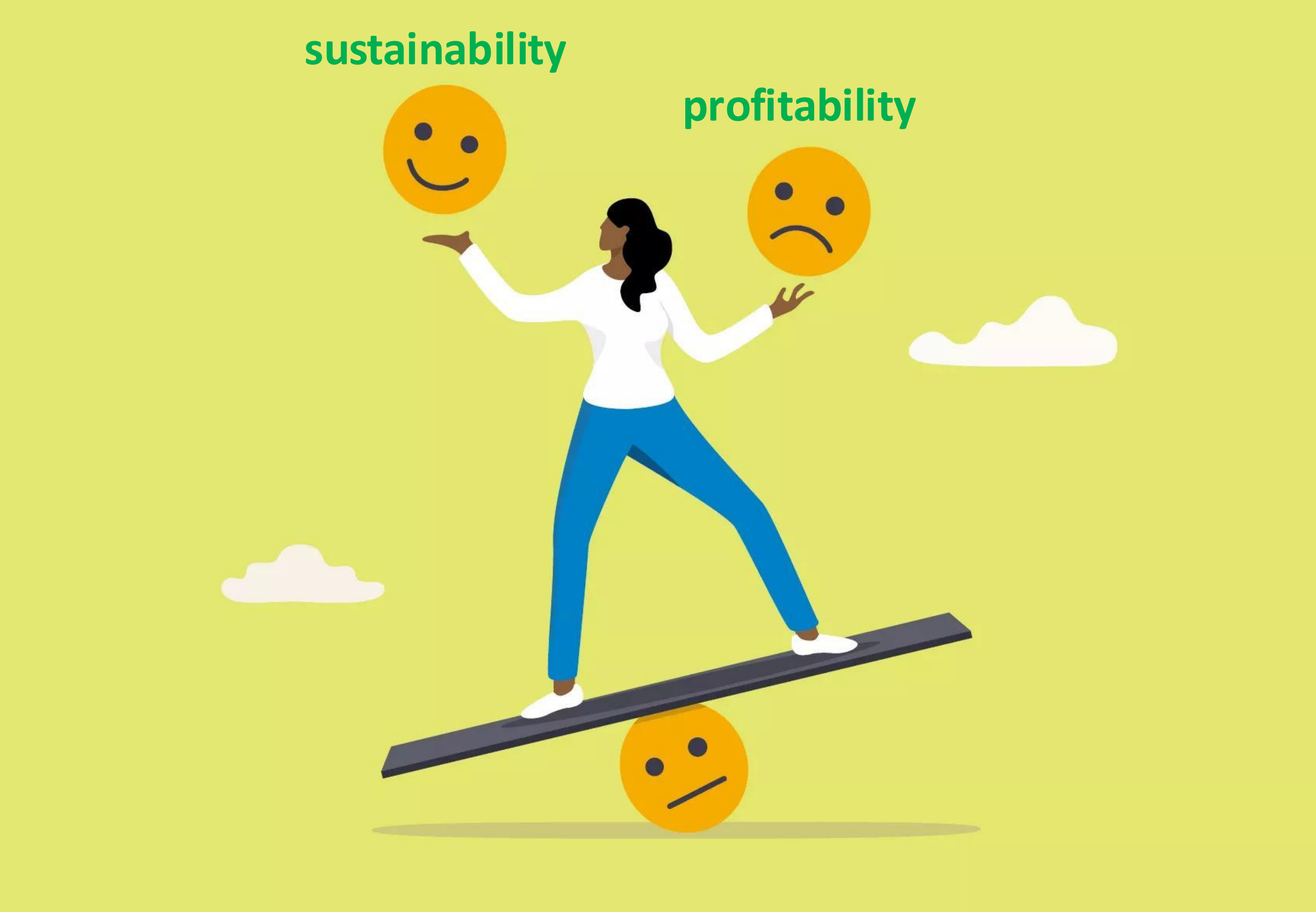
MaaS Global has filed for bankruptcy

MaaS Global, a Finnish mobility startup founded in 2015, has filed for bankruptcy today, according to Helsinki District Court records. The company raised more than $162m from investors.
Its city travel app Whim enabled customers to see all the available travel options in a city in one place.

Finnish newspaper Helsingin Sanomat reports that the company had around 10k active users in Helsinki, but lost €9.3m in 2022, making revenues of €3.8m that year, according to its latest financial report.

The news comes at a difficult time for mobility startups, with companies merging and making layoffs as they chase profitable unit economics.

How to balance sustainability and profitability in E-MaaS ecosystem?



Problem statement

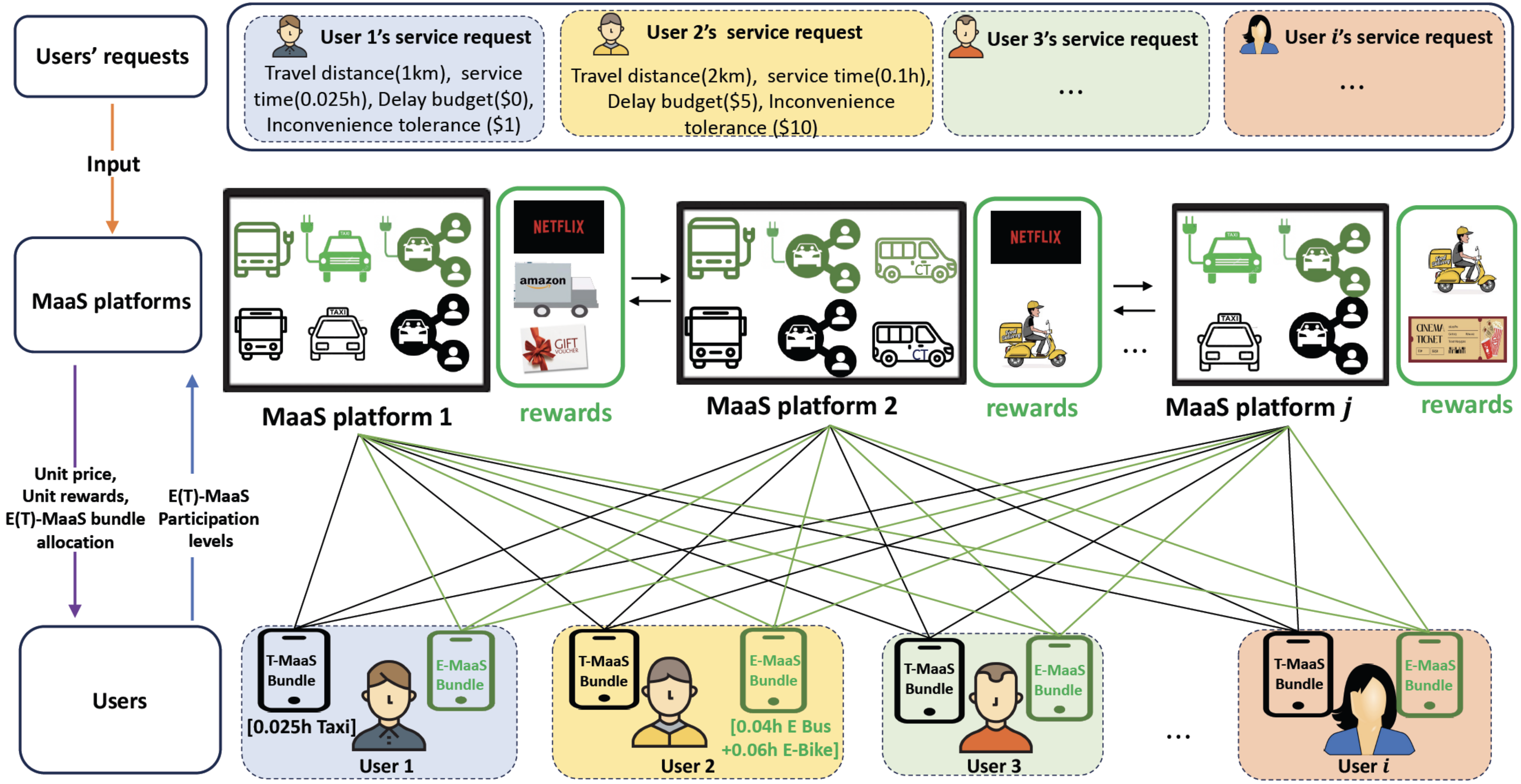
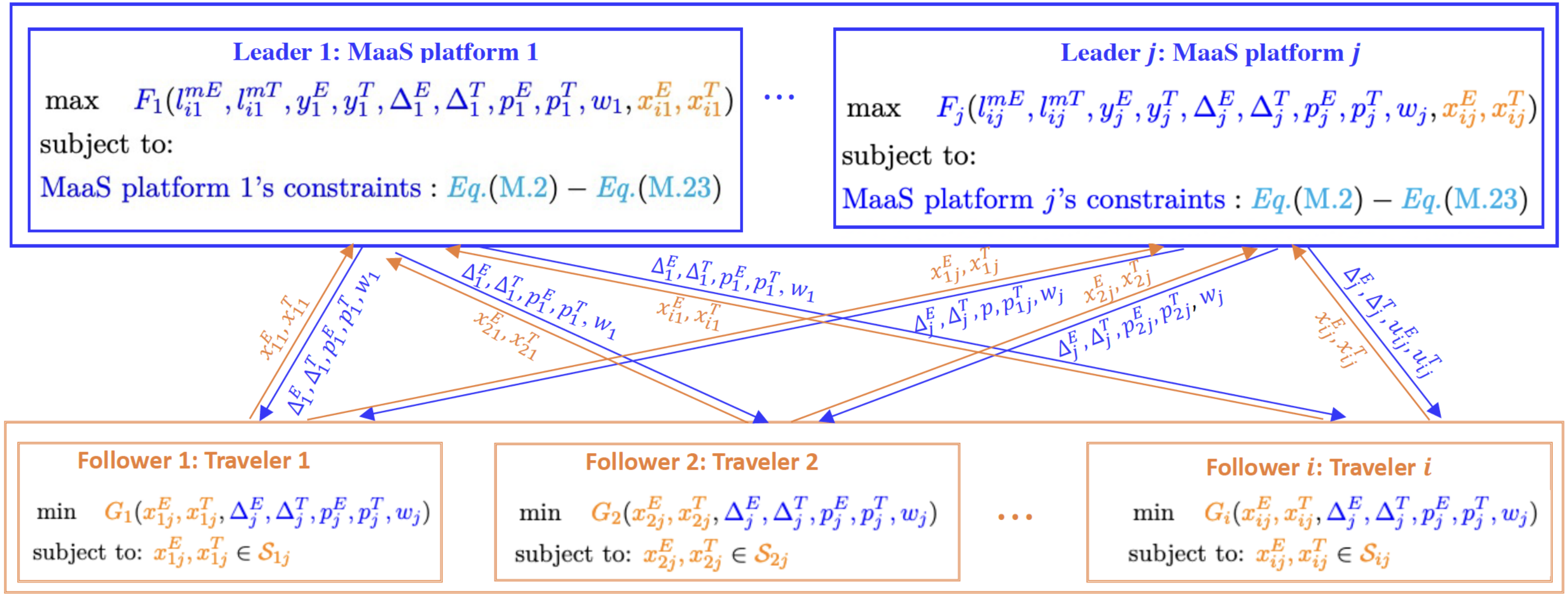


Figure. An E-MaaS ecosystem with multiple MaaS platforms and travelers

Multi-leader multi-follower game (MLMFG)



Decision variables	
p_j^E	Real variable denoting the unit price for electric mobility resources
p_j^T	Real variable denoting the unit price for traditional mobility resources
w_j	Real variable denoting the platform j's unit rewards for travelers using E-MaaS services
l_{ij}^{mE}	Real variable denoting service time of travel mode m in the platform j's E-MaaS bundle allocated to traveler i
l_{ij}^{mT}	Real variable denoting service time of travel mode m in the platform j's T-MaaS bundle allocated to traveler i
Δ_j^E	Real variable denoting supply-demand gap of E-MaaS services in the platform j
Δ_j^T	Real variable denoting the supply-demand gap of T-MaaS services in the platform j
x_{ij}^E	Real variable denoting traveler i's participation level for MaaS platform j's E-MaaS services
x_{ij}^T	Real variable denoting traveler i's participation level for MaaS platform j's T-MaaS services
y_{mj}	Real variable denoting platform j's EV acquisition ratio for travel mode m

Multi-leader problems (Objective function)

$$\max \quad F_j(\boldsymbol{l}^E, \boldsymbol{l}^T, \boldsymbol{y}, \boldsymbol{\Delta}^E, \boldsymbol{\Delta}^T, \boldsymbol{p}^E, \boldsymbol{p}^T, \boldsymbol{w}) = \underbrace{\sum_{i\in\mathcal{I}} p_j^E Q_i x_{ij}^E}_{\text{E-MaaS revenue}} + \underbrace{\sum_{i\in\mathcal{I}} p_j^T Q_i x_{ij}^T}_{\text{T-MaaS revenue}} + \underbrace{\eta \sum_{i\in\mathcal{I}} \sum_{m\in\mathcal{M}_j} e_m v_m^2 l_{ij}^{mE}}_{\text{Carbon credits revenue}}$$

$$\underbrace{-\sum_{m\in\mathcal{M}_j} \left[(1-\epsilon_{mj})\frac{A(y_{mj})}{L} + f_{mj} y_{mj}(c_m^E + c_l)\right] - \sum_{i\in\mathcal{I}} w_j Q_i x_{ij}^E}_{\text{Asset, operation and reward costs for E-MaaS}} - \underbrace{\sum_{m\in\mathcal{M}_j} \left[f_{mj}(c_m^T + c_l)\right]}_{\text{Operation costs for T-MaaS}}. \qquad \text{(M.1)}$$

where Q_i denotes traveler i's requested mobility resources, η denotes the unit price of carbon credits, e_m denotes the amount of CO_2 emissions produced by travel mode m per unit of mobility resource utilized, calculated on a per-person basis, v_m denotes the commercial speed of travel mode m, ϵ_{mj} denotes the government's subsidy rate on acquiring new EVs of mode m for platform j, f_{mj} denotes MaaS platform j's fleet size for mode m, c_m^E and c_m^T denotes the unit electricity cost for charging EVs and fuel cost for TVs per day, and c_l denotes the unit labor cost per day.

Multi-leader problems (Constraints)

ERF budget constraint:

$$\eta \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} \sum_{m\in\mathcal{M}_j} e_m v_m^2 l_{ij}^{mE} \le B^{ERF} \quad \text{(M.2)}$$

EV subsidy constraint:

$$\sum_{j\in\mathcal{J}} \sum_{m\in\mathcal{M}_j} \epsilon_{mj} \frac{A(y_{mj})}{L} \le B^{fleet}. \quad \text{(M.3)}$$

EV acquisition constraint:

$$\sum_{m\in\mathcal{M}_j} \frac{A(y_{mj})}{L}(1-\epsilon_{mj}) \le B_j^{MaaS}, \qquad \forall j\in\mathcal{J}. \quad \text{(M.4)}$$

Travel distance requirement for E(T)-MaaS bundle

$$D_i x_{ij}^E = \sum_{m\in\mathcal{M}_j} v_m l_{ij}^{mE}, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}. \quad \text{(M.5)}$$

$$D_i x_{ij}^T = \sum_{m\in\mathcal{M}_j} v_m l_{ij}^{mT}, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}. \quad \text{(M.6)}$$

Service time and delay time requirement for E(T)-MaaS bundle:

$$0 \le \sum_{m\in\mathcal{M}_j} l_{ij}^{mE} - t_i x_{ij}^E \le R_i, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}. \quad \text{(M.7)}$$

$$0 \le \sum_{m\in\mathcal{M}_j} l_{ij}^{mT} - t_i x_{ij}^T \le R_i, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}. \quad \text{(M.8)}$$

Inconvenience requirement for E(T)-MaaS bundle

$$\sum_{m\in\mathcal{M}_j} \delta_m l_{ij}^{mE} \le \Gamma_i, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}. \quad \text{(M.9)}$$

$$\sum_{m\in\mathcal{M}_j} \delta_m l_{ij}^{mT} \le \Gamma_i, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}. \quad \text{(M.10)}$$

Supply capacity constraint:

$$\sum_{i\in\mathcal{I}} Q_i x_{ij}^E \le C_{mj} y_{mj}, \qquad \forall m\in\mathcal{M}_j, j\in\mathcal{J}. \quad \text{(M.11)}$$

$$\sum_{i\in\mathcal{I}} Q_i x_{ij}^T \le C_{mj}, \qquad \forall m\in\mathcal{M}_j, j\in\mathcal{J}. \quad \text{(M.12)}$$

Supply-demand gap:

$$\Delta_j^E = \sum_{m\in\mathcal{M}_j} C_{mj} y_{mj} - \sum_{i\in\mathcal{I}} Q_i x_{ij}^E, \qquad \forall j\in\mathcal{J}, \quad \text{(M.13)}$$

$$\Delta_j^T = \sum_{m\in\mathcal{M}_j} C_{mj} - \sum_{i\in\mathcal{I}} Q_i x_{ij}^T, \qquad \forall j\in\mathcal{J}. \quad \text{(M.14)}$$

Unit price:

$$p_j^E(\Delta_j^E) = p_j^{E\min} + (p_j^{E\max} - p_j^{E\min}) e^{-\Delta_j^E} \qquad \forall j\in\mathcal{J}, \quad \text{(M.15)}$$

$$p_j^T(\Delta_j^T) = p_j^{T\min} + (p_j^{T\max} - p_j^{T\min}) e^{-\Delta_j^T} \qquad \forall j\in\mathcal{J}, \quad \text{(M.16)}$$

Unit rewards:

$$w_j^E(\Delta_j^E) = w_j^{\min} + (w_j^{\max} - w_j^{\min}) e^{-\Delta_j^E} \qquad \forall j\in\mathcal{J}, \quad \text{(M.17)}$$

Bound constraints on leader variables

$$l_{ij}^{mE}, l_{ij}^{mT} \ge 0, \qquad \forall i\in\mathcal{I}, j\in\mathcal{J}, \forall m\in\mathcal{M}_j, \quad \text{(M.18)}$$

$$0 \le y_{mj} \le 1, \qquad \forall m\in\mathcal{M}_j, j\in\mathcal{J}, \quad \text{(M.19)}$$

$$p_j^{E\min} < p_j^E < p_j^{E\max}, \qquad \forall j\in\mathcal{J}, \quad \text{(M.20)}$$

$$p_j^{T\min} < p_j^T < p_j^{T\max}, \qquad \forall j\in\mathcal{J}, \quad \text{(M.21)}$$

$$w_j^{\min} < w_j < w_j^{\max}, \qquad \forall j\in\mathcal{J}, \quad \text{(M.22)}$$

$$\Delta_j^E, \Delta_j^T \ge 0 \qquad \forall j\in\mathcal{J}. \quad \text{(M.23)}$$

Follower-problems

$$\min_{x^E, x^T} \quad G_i(x_{ij}^E, x_{ij}^T, \Delta_j^E, \Delta_j^T, p_j^E, p_j^T, w_j) = \underbrace{\sum_{j \in \mathcal{J}} p_j^E Q_i x_{ij}^E}_{\text{E-MaaS travel cost}} - \underbrace{\sum_{j \in \mathcal{J}} w_j Q_i x_{ij}^E}_{\text{E-MaaS rewards}} + \underbrace{\sum_{j \in \mathcal{J}} p_i^T Q_i x_{ij}^T}_{\text{T-MaaS travel cost}}$$

$$+ \underbrace{\sum_{j \in \mathcal{J}} r_i Q_i (1 - x_{ij}^E - x_{ij}^T)}_{\text{Reserve travel cost}} + \underbrace{\sum_{j \in \mathcal{J}} \alpha_i \Psi_{ij}(x_{ij}^E, \Delta_j^E)}_{\text{E-MaaS waiting time cost}} + \underbrace{\sum_{j \in \mathcal{J}} \alpha_i \Psi_{ij}(x_{ij}^T, \Delta_j^T)}_{\text{T-MaaS waiting time cost}} . \quad \text{(T.1)}$$

Recall that B_i is traveler i's travel expenditure budget; hence we require:

$$\sum_{j \in \mathcal{J}} Q_i (p_j^E x_{ij}^E + p_j^T x_{ij}^T) \leq B_i, \qquad \forall i \in \mathcal{I}. \quad \text{(T.2)}$$

Traveler i's participation levels for platform j's E-MaaS and T-MaaS services cannot exceed 1:

$$x_{ij}^E + x_{ij}^T \leq 1, \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \quad \text{(T.3)}$$

$$x_{ij}^E, x_{ij}^T \geq 0, \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}. \quad \text{(T.4)}$$

Multi-leader multi-follower game (MLMFG)

Model 1 (Multi-leader multi-follower game).

$$\max_{\boldsymbol{p}^E,\boldsymbol{p}^T,\boldsymbol{l}^E,\boldsymbol{l}^T,\boldsymbol{w},\boldsymbol{\Delta},\boldsymbol{y},\boldsymbol{x}} \quad \text{MaaS platform } j\text{'s profits} \quad (\text{M.1}),$$

subject to:

MaaS platform j's budget constraints (M.2)-(M.4)

MaaS platform j's E(T)-MaaS bundles allocation (M.5)-(M.10)

MaaS platform j's capacity constraints (M.11)-(M.12)

Supply-demand gap (M.13)-(M.14)

Unit Price and rewards (M.15)-(M.17)

MaaS platform j's variable bounds (M.18)-(M.23)

$$\text{Traveler } i\text{'s follower problem} \quad x_{ij}^E, x_{ij}^T \in \underset{\hat{x}_{ij}^E,\hat{x}_{ij}^T \in \mathcal{S}_{ij}}{\arg\min}\ G_i(\hat{x}_{ij}^E, \hat{x}_{ij}^T, \Delta_j^E, \Delta_j^T, p_j^E, p_j^T, w_j), \forall i \in \mathcal{I}, j \in \mathcal{J}.$$

Multi-leader multi-follower game (MLMFG)

Definition 2. *The solution of Model 1* $(\boldsymbol{p}^{E*}, \boldsymbol{p}^{T*}, \boldsymbol{l}^{E*}, \boldsymbol{l}^{T*}, \boldsymbol{\Delta}^{E*}, \boldsymbol{\Delta}^{T*}, \boldsymbol{w}^*, \boldsymbol{y}^*, \boldsymbol{x}^{E*}, \boldsymbol{x}^{T*})$ *is a Stackelberg equilibrium under the following conditions,*

$F_j(p_j^{E*}, p_j^{T*}, \Delta_j^{E*}, \Delta_j^{T*}, w_j^*, \boldsymbol{l}_j^{E*}, \boldsymbol{l}_j^{T*}, \boldsymbol{y}_j^*, \boldsymbol{x}^{E*}, \boldsymbol{x}^{T*}) \geq F_j(p_j^E, p_j^T, \Delta_j^E, \Delta_j^T, w_j, \boldsymbol{l}_j^E, \boldsymbol{l}_j^T, \boldsymbol{y}_j, \boldsymbol{x}^{E*}, \boldsymbol{x}^{T*})$, $\forall j \in \mathcal{J}$, *and*

$G_i(x_i^{E*}, x_i^{T*}, \boldsymbol{p}^{E*}, \boldsymbol{p}^{T*}, \boldsymbol{\Delta}^{E*}, \boldsymbol{\Delta}^{T*}, \boldsymbol{w}^*, \boldsymbol{y}^*) \leq G_i(x_i^E, x_i^T, \boldsymbol{p}^{E*}, \boldsymbol{p}^{T*}, \boldsymbol{\Delta}^{E*}, \boldsymbol{\Delta}^{T*}, \boldsymbol{w}^*, \boldsymbol{y}^*), \forall i \in \mathcal{I}.$

In this E-MaaS ecosystem framework, E(T)-MaaS bundles are the results of mobility resource allocation among various electric (resp. traditional) travel modes, tailored to satisfy a traveler's heterogeneous trip requests.

Definition 3. *For any traveler* $i \in \mathcal{I}, j \in \mathcal{J}$, *let* $\boldsymbol{l}_{ij}^E = [l_{ij}^{mE}]_{m\in\mathcal{M}}$, *and* $\boldsymbol{l}_{ij}^T = [l_{ij}^{mT}]_{m\in\mathcal{M}}$. *Let* $\mathcal{L}_{ij}^E$ *and* $\mathcal{L}_{ij}^T$ *be the E-MaaS and G-MaaS bundle set defined as:*

$$\mathcal{L}_{ij}^E \triangleq \left\{\boldsymbol{l}_{ij}^E \in \mathbb{R}^{|\mathcal{M}|} : (\text{M.2}), (\text{M.5}), (\text{M.7}), (\text{M.9})\right\}, \forall i \in \mathcal{I}, j \in \mathcal{J}, \tag{11a}$$

$$\mathcal{L}_{ij}^T \triangleq \left\{\boldsymbol{l}_{ij}^T \in \mathbb{R}^{|\mathcal{M}|} : (\text{M.6}), (\text{M.8}), (\text{M.10})\right\}, \forall i \in \mathcal{I}, j \in \mathcal{J}. \tag{11b}$$

We say that $\mathcal{L}_{ij}^E$ *and* $\mathcal{L}_{ij}^T$ *are the set of feasible E-MaaS and T-MaaS bundles allocated to traveler* i *by MaaS platform* j, $\forall i \in \mathcal{I}, j \in \mathcal{J}$.

Decomposition of MLMFG model

Proposition 2. *Given followers' decisions on participation levels* $(\bar{\boldsymbol{x}}^E, \bar{\boldsymbol{x}}^T)$*, each leader problem* $\forall j \in \mathcal{J}$*, in the MLMFG (Model 1) can be decomposed into the following two subproblems:*

Subproblem 1 (MaaS platform strategy optimization)

$$\min_{\boldsymbol{y}} \quad F_j^{sub1}(y_{mj}) = \sum_{i\in\mathcal{I}} \left[p_{\min} + p_{\max} e^{-\left(\sum_{m\in\mathcal{M}} C_m y_{mj} - \sum_{i\in\mathcal{I}} Q_i \bar{x}_{ij}{}^E\right)}\right] Q_i \bar{x}_{ij}^E$$
$$+ \sum_{i\in\mathcal{I}} \left[p_{\min} + p_{\max} e^{-\left(\sum_{m\in\mathcal{M}} C_m - \sum_{i\in\mathcal{I}} Q_i \bar{x}_{ij}^T\right)}\right] Q_i \bar{x}_{ij}^T - \sum_{m\in\mathcal{M}} \left[(1-\epsilon_m)\frac{(\gamma y_{mj} + Z_m)}{L}\right.$$
$$\left. + f_m c_m^E y_m + f_m\left(c_m^T + c_l\right)\right] - \sum_{i\in\mathcal{I}} \left[w^{\min} + w^{\max} e^{-\left(\sum_{m\in\mathcal{M}} C_m y_{mj} - \sum_{i\in\mathcal{I}} Q_i \bar{x}_{ij}^E\right)}\right] Q_i \bar{x}_{ij}^E \qquad \text{(Sub.1)}$$

subject to:

$$\mathcal{Y}_j \triangleq \left\{y_{mj} \in \mathbb{R}^{|\mathcal{M}|} : (\text{M.3}) - (\text{M.4}), (\text{M.11}) - (\text{M.17}), (\text{M.19}) - (\text{M.23})\right\}, \forall j \in \mathcal{J}.$$

Subproblem 2 (Feasible MaaS bundles customization)

$$\max_{l^E, l^T} \quad F_j^{sub2}(l_{ij}^{mE}, l_{ij}^{mT}) = \eta \sum_{i\in\mathcal{I}} \sum_{m\in\mathcal{M}_j} e_m v_m^2 l_{ij}^{mE} \qquad \text{(Sub.2)}$$

subject to:

E-MaaS bundle allocation: (M.2), (M.5), (M.7), (M.9), $\forall i \in \mathcal{I}, j \in \mathcal{J}$,

T-MaaS bundle allocation: (M.6), (M.8), (M.10), $\forall i \in \mathcal{I}, j \in \mathcal{J}$,

Variable bounds: (M.18), $\forall i \in \mathcal{I}, j \in \mathcal{J}, \forall m \in \mathcal{M}_j$.

Alternating direction method of multipliers (ADMM) algorithm

Input and Initialization

External Loop (solve MLMFG model):

  Middle Loop (solve each platform's subproblem 1):

    Inner Loop (solve follower problems within each platform):

      check convergence criteria

  Update variables based on the solutions from the middle loop

Check convergence of the entire MLMFG solutions.

Output: Optimal solutions

Algorithm 1: ADMM Algorithm for the MLMFG (Model 1)

Input: B^{ERF}, B_i, B_j^{fleet}, C_{mj}, f_{mj}, D_i, Q_i, r_i, R_i, t_i, L, e_m, η, c_m^E, c_m^T, c_l, v_m, ϵ_m, α_i, Γ_i, δ_m, p_{max}, p_{min}, w_{max}, w_{min}

Obtain initial solutions of MLMFG $x_{ij}^{E(0)}$, $x_{ij}^{T(0)}$, $y_{mj}^{(0)}$, $\boldsymbol{\mu}^{(0,0)}$, $\boldsymbol{\lambda}^{(0,0)}$, $G_i^{(0,0)}$, and $F_j^{(0)}$ through (Initial.1)

$\boldsymbol{F}^{(n)} \leftarrow \left[F_1^{(0)}, \cdots, F_j^{(0)}\right]$, $\boldsymbol{x}^{E(n)} \leftarrow \left[x_{i1}^{E(0)}, \cdots, x_{ij}^{E(0)}\right]$, $\boldsymbol{x}^{T(n)} \leftarrow \left[x_{i1}^{T(0)}, \cdots, x_{ij}^{T(0)}\right]$, $\boldsymbol{y}^{(n)} \leftarrow \left[y_{m1}^{(0)}, \cdots, y_{mj}^{(0)}\right]$

$n \leftarrow 0, \delta_1 \leftarrow 1, \epsilon \leftarrow 10e^{-4}$ ▷ Initialization

while $\delta_1 \geq \epsilon$ **do**

  ▷ Solve MLMFG problem (External loop)

  for $j \in \mathcal{J}$ **do**

    Fix x_{it}^E, x_{it}^T, y_{mt}, l_{it}^{mE}, l_{it}^{mT}, and $F_t, \forall t \in \mathcal{J} \setminus \{j\}, m \in \mathcal{M}_t, i \in \mathcal{I}$:

    $x_{it}^{E(n)} \leftarrow \boldsymbol{x}^{E(n)}[t-1]$, $x_{it}^{T(n)} \leftarrow \boldsymbol{x}^{T(n)}[t-1]$, $y_{mt}^{(n)} \leftarrow \boldsymbol{y}^{(n)}[t-1], \forall t \in \mathcal{J} \setminus \{j\}, m \in \mathcal{M}_t, i \in \mathcal{I}$

    $q \leftarrow 0$, $\delta_2 \leftarrow 1$

    ▷ Solve each platform's subproblem 1 (Middle loop)

    while $\delta_2 \geq \epsilon$ **do**

      $k \leftarrow 0$, $\delta_3 \leftarrow 1$

      ▷ Solve follower problems (Inner loop)

      while $\delta_3 \geq \epsilon$ **do**

        $x_{ij}^{E(q,k+1)} \leftarrow \arg\min_{\boldsymbol{x}^E} \mathcal{L}_2\left(x_{ij}^E, x_{ij}^{T(q,k)}, \boldsymbol{\mu}^{(q,k)}, y_{mj}^{(q)}\right), \forall i \in \mathcal{I}$

        $x_{ij}^{T(q,k+1)} \leftarrow \arg\min_{\boldsymbol{x}^T} \mathcal{L}_2\left(x_{ij}^{E(q,k+1)}, x_{ij}^T, \boldsymbol{\mu}^{(q,k)}, y_{mj}^{(q)}\right), \forall i \in \mathcal{I}$

        $\boldsymbol{\mu}^{(q,k+1)} \leftarrow \boldsymbol{\mu}^{(q,k)} + \rho \boldsymbol{h}\left(x_{ij}^{E(q,k+1)}, x_{ij}^{T(q,k+1)}\right)$

        $G_i^{(q,k+1)} \leftarrow G_i\left(x_{ij}^{E(q,k+1)}, x_{ij}^{T(q,k+1)}, y_{mj}^{(q)}\right), \forall i \in \mathcal{I}$

        $\delta_3 \leftarrow \|\sum_{i\in\mathcal{I}} G_i^{(q,k+1)} - \sum_{i\in\mathcal{I}} G_i^{(q,k)}\|$ ▷ follower problems' convergence criteria

        $k \leftarrow k+1$

      $\bar{x}_{ij*}^E \leftarrow x_{ij}^{E(q,k+1)}$, $\bar{x}_{ij*}^T \leftarrow x_{ij}^{T(q,k+1)}, \forall i \in \mathcal{I}$

      $y_{mj}^{(q+1)} \leftarrow \arg\min_{\boldsymbol{y}} \mathcal{L}_1\left(y_{mj}^{(q)}, \boldsymbol{\lambda}^{(q)}, \bar{x}_{ij*}^E, \bar{x}_{ij*}^T\right), \forall m \in \mathcal{M}_j$

      $\boldsymbol{\lambda}^{(q+1)} \leftarrow \boldsymbol{\lambda}^{(q)} + \rho g\left(y_{mj}, \bar{x}_{ij*}^E, \bar{x}_{ij*}^T\right)$

      $\delta_2 \leftarrow \|F_j^{\text{sub1}}(y_{mj}^{(q+1)}) - F_j^{\text{sub1}}(y_{mj}^{(q)})\|$ ▷ Each platform (Eq.(Sub.1))'s convergence criteria

      $q \leftarrow q+1$

    $y_{mj*} \leftarrow y_{mj}^{(q+1)}$

    $l_{ij*}^{mE}, l_{ij*}^{mT} :=$ argmax **Subproblem 2** $\left(l_{ij}^{mE}, l_{ij}^{mT}, \bar{x}_{ij*}^E, \bar{x}_{ij*}^T\right)$

    $F_{j*} \leftarrow F_j^{\text{sub1}}(y_{mj*}) + F_j^{\text{sub2}}(l_{ij*}^{mE}, l_{ij*}^{mT})$

    $\boldsymbol{F}^{(n+1)}[j-1] \leftarrow F_{j*}$, $\boldsymbol{x}^{E(n+1)}[j-1] \leftarrow \bar{x}_{ij*}^E$, $\boldsymbol{x}^{T(n+1)}[j-1] \leftarrow \bar{x}_{ij*}^T$, $\boldsymbol{y}^{(n+1)}[j-1] \leftarrow y_{mj*}$,

    $\boldsymbol{l}^{E(n+1)}[j-1] \leftarrow l_{ij*}^{mE}$, $\boldsymbol{l}^{T(n+1)}[j-1] \leftarrow l_{ij*}^{mT}$

  Update $\boldsymbol{F}^{(n+1)}, \boldsymbol{x}^{E(n+1)}, \boldsymbol{x}^{T(n+1)}, \boldsymbol{l}^{E(n+1)}, \boldsymbol{l}^{T(n+1)}, \boldsymbol{y}^{(n+1)}, \boldsymbol{\lambda}^{(n+1)}$

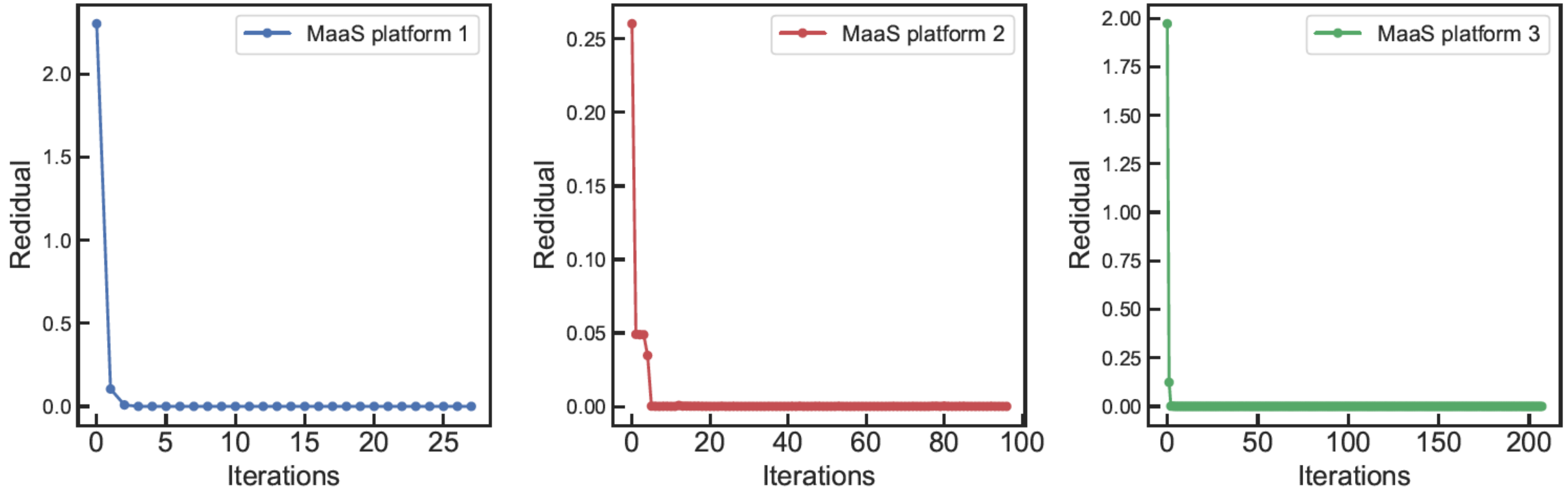
  $\delta_1 \leftarrow \|\boldsymbol{F}^{(n+1)} - \boldsymbol{F}^{(n)}\|$ ▷ MLMFG's convergence criteria

  $n \leftarrow n+1$

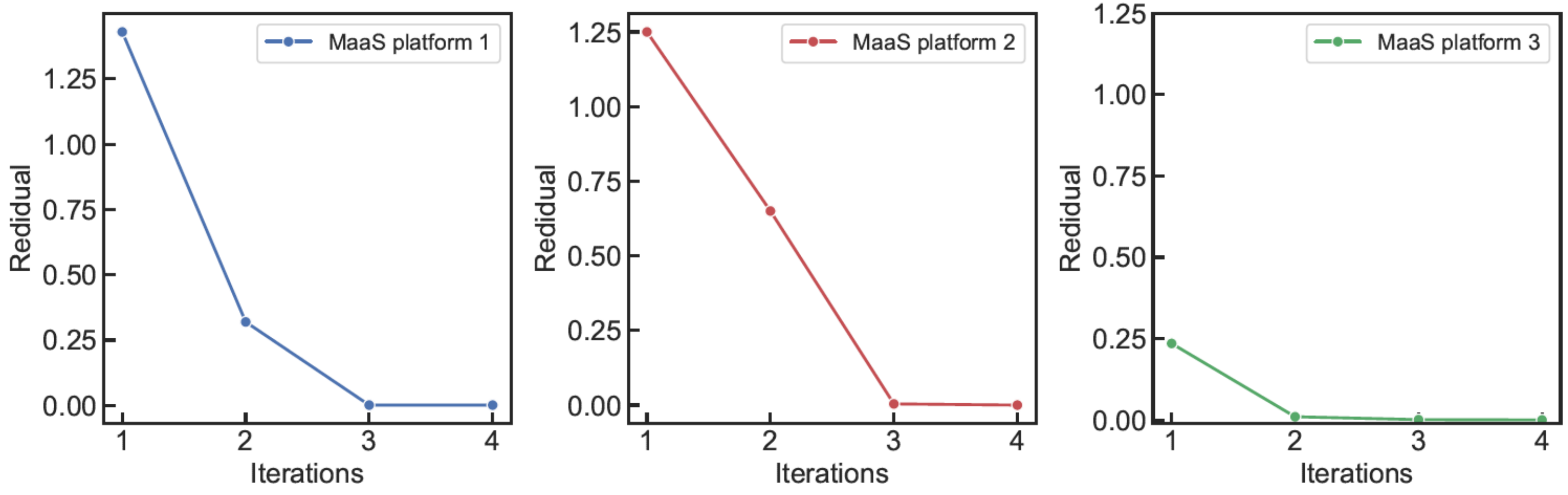
$\boldsymbol{x}^{E*} \leftarrow \boldsymbol{x}^{E(n+1)}, \boldsymbol{x}^{T*} \leftarrow \boldsymbol{x}^{T(n+1)}, \boldsymbol{y}^* \leftarrow \boldsymbol{y}^{(n+1)}, \boldsymbol{l}^{E*} \leftarrow \boldsymbol{l}^{E(n+1)}, \boldsymbol{l}^{T*} \leftarrow \boldsymbol{l}^{T(n+1)}, \boldsymbol{F}^* \leftarrow \boldsymbol{F}^{(n+1)}$

$\boldsymbol{\Delta}^{E*} \leftarrow \Delta_j^E(\boldsymbol{y}^*, \boldsymbol{x}^{E*}), \boldsymbol{\Delta}^{T*} \leftarrow \Delta_j^T(\boldsymbol{x}^{T*}), \boldsymbol{p}^{E*} \leftarrow p_j^E(\boldsymbol{\Delta}^{E*}), \boldsymbol{p}^{T*} \leftarrow p_j^T(\boldsymbol{\Delta}^{T*}), \boldsymbol{w}^* \leftarrow w_j(\boldsymbol{\Delta}^{E*}), \forall j \in \mathcal{J}.$

return $\boldsymbol{F}^*, \boldsymbol{y}^*, \boldsymbol{l}^{E*}, \boldsymbol{l}^{T*}, \boldsymbol{\Delta}^{E*}, \boldsymbol{\Delta}^{T*}, \boldsymbol{p}^{E*}, \boldsymbol{p}^{T*}, \boldsymbol{w}^*, \boldsymbol{x}^{E*}, \boldsymbol{x}^{T*}$



(a) Convergence residuals of middle loop for each MaaS platform in the iterative process



(b) Convergence residuals of external loop for each MaaS platform in the iterative process

Figure: Convergence residuals of external and middle loop in Algorithm 1

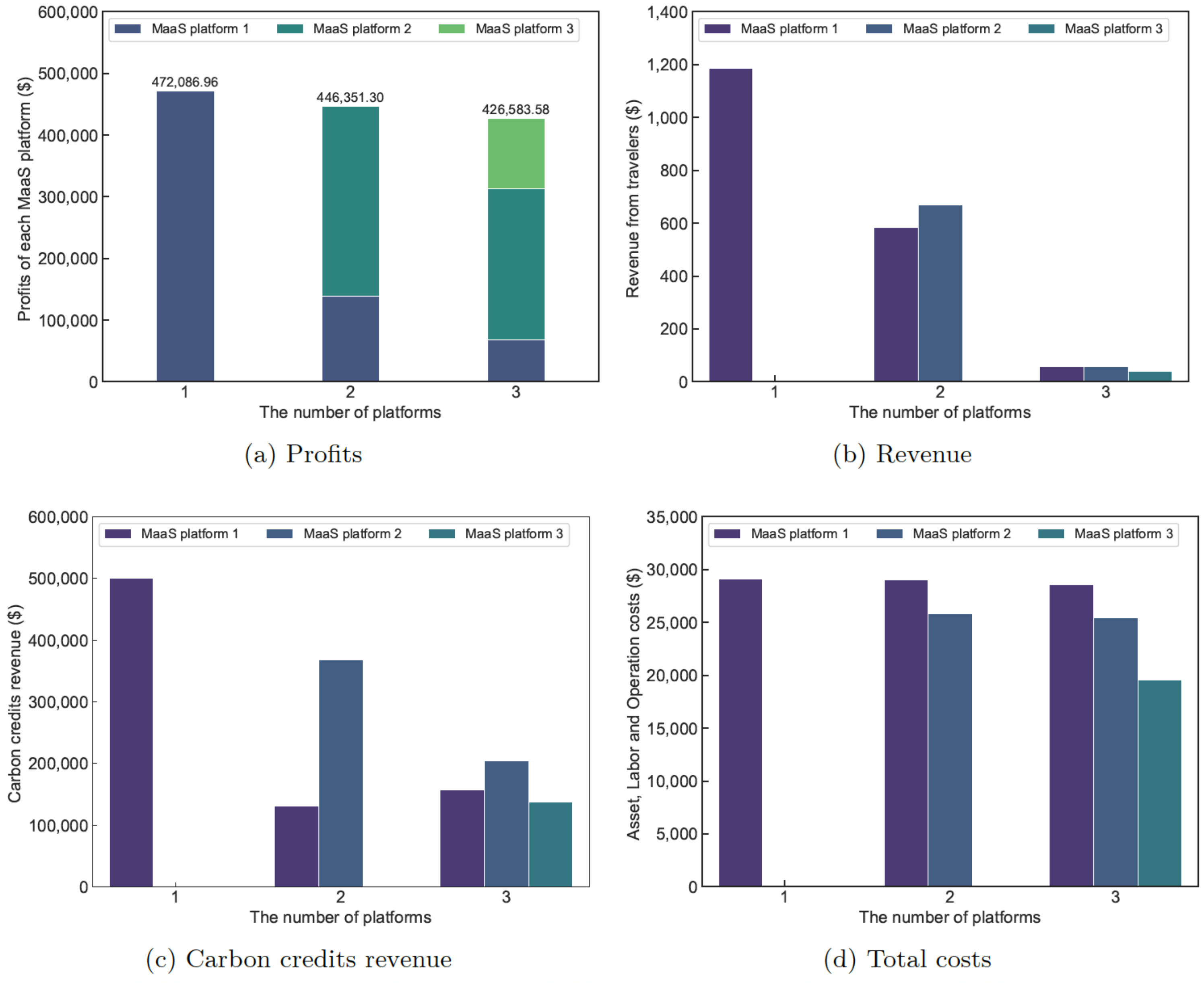
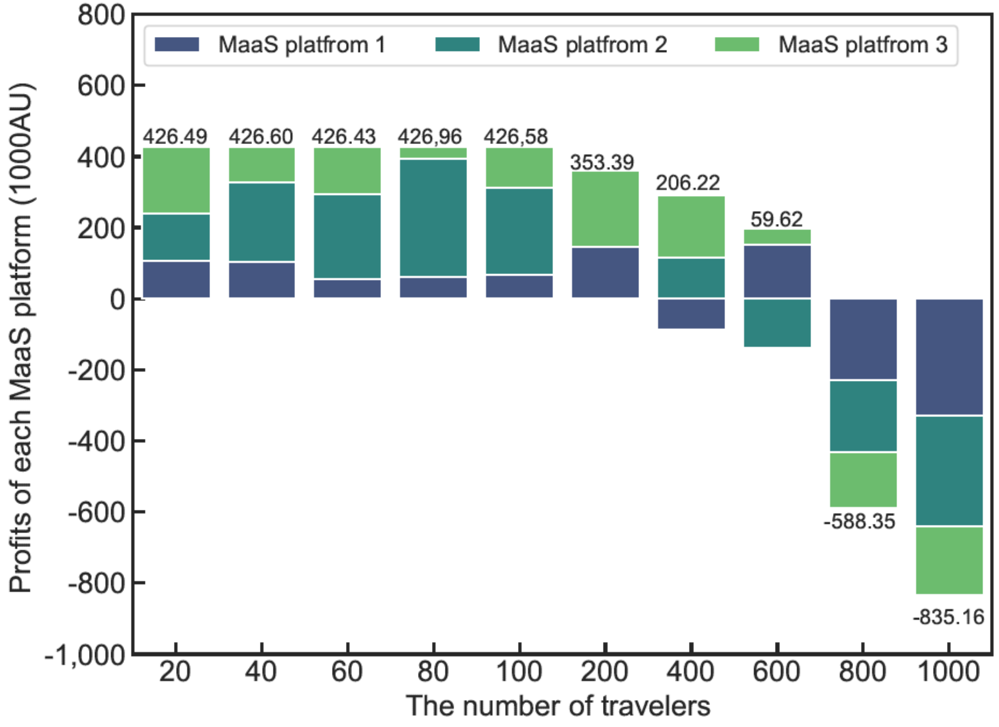
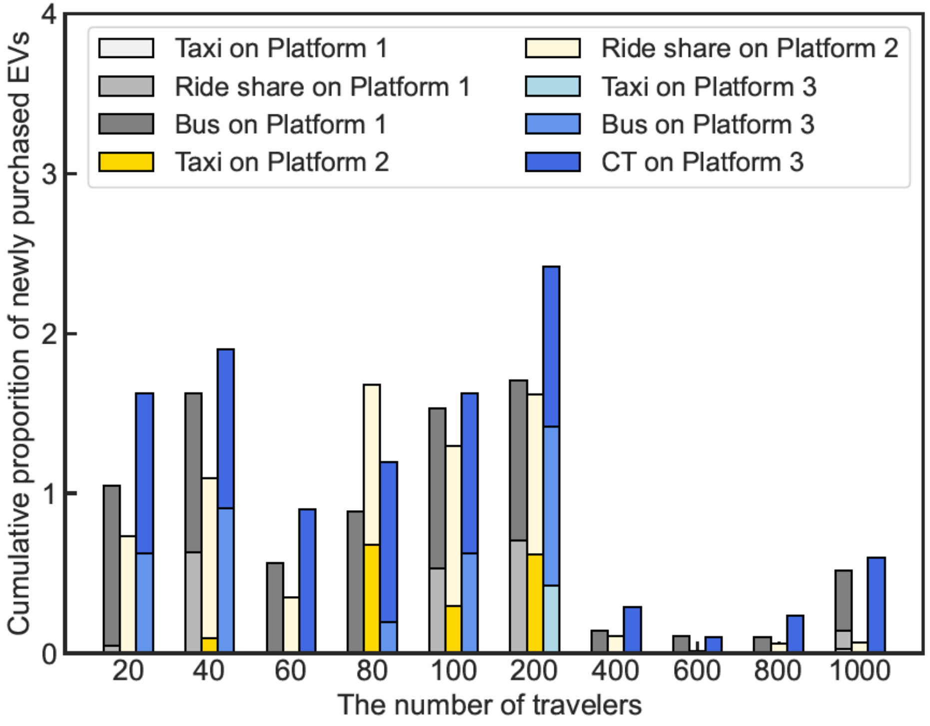


Figure: Profits, revenue and costs of three MaaS platforms

Observation. In the MaaS market, increasing the number of platforms leads to fiercer competition and potentially lower profits. In a monopolistic market, a single platform can achieve higher profits; however, this advantage diminishes with the entry of multiple platforms, each engaging in competition.



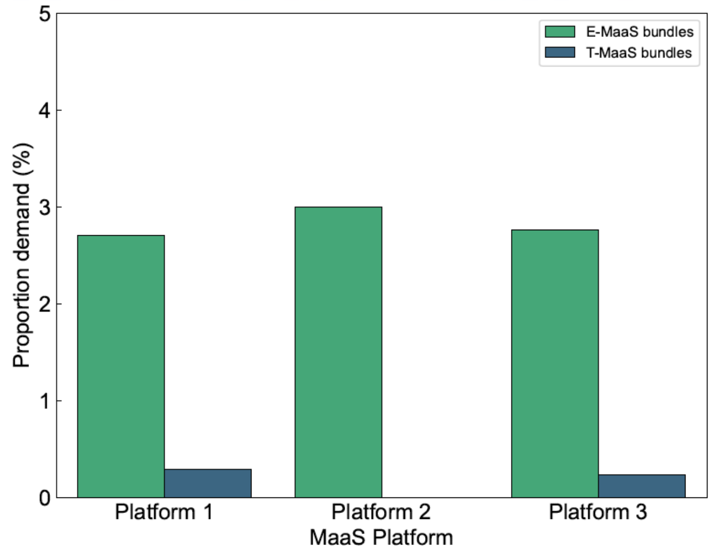
(a) Profits



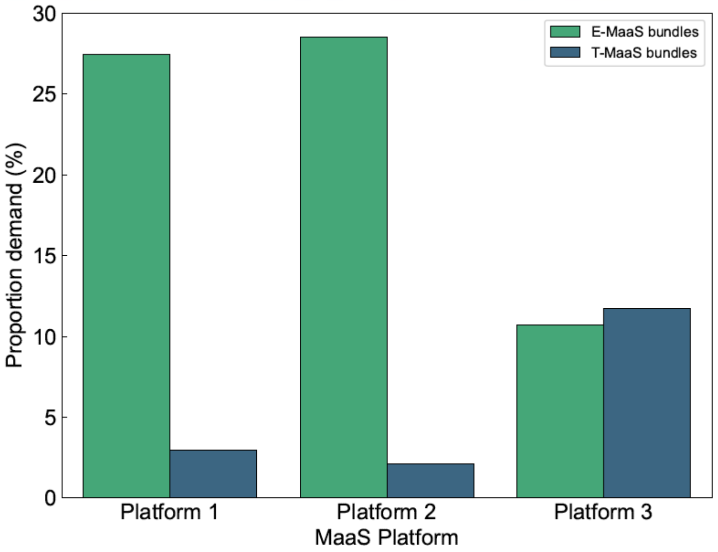
(b) Proportion of newly purchased EVs

Figure: Profits, and EV acquisition ratio of MaaS platforms with different number users

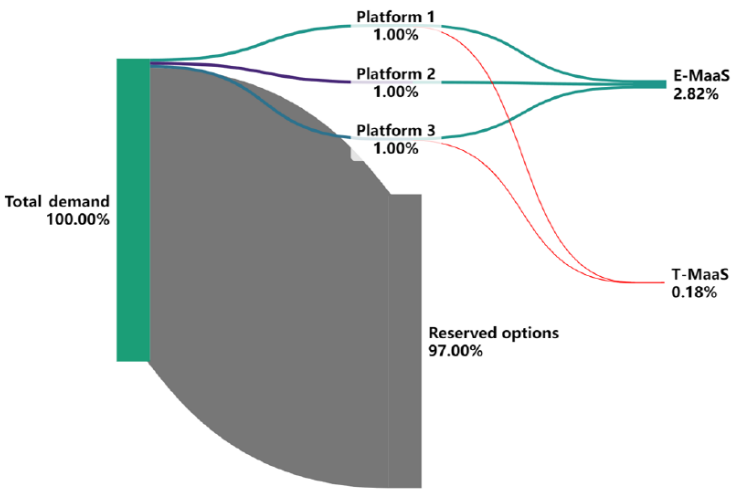
Observation. In smaller markets, MaaS platforms heavily rely on the government's ERF for profits. As the market expands, MaaS platforms shift their focus towards cost-efficiency, providing a variety of travel modes. In larger markets with limited ERF budgets, platforms will strategically integrate different electric modes to balance operation costs and carbon credits revenue.



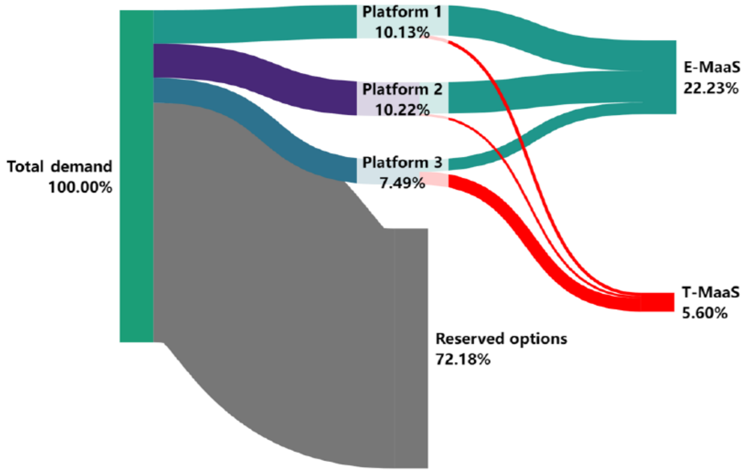
(a) Participation levels under $400,000 ERF



(b) Participation levels under $500,000 ERF



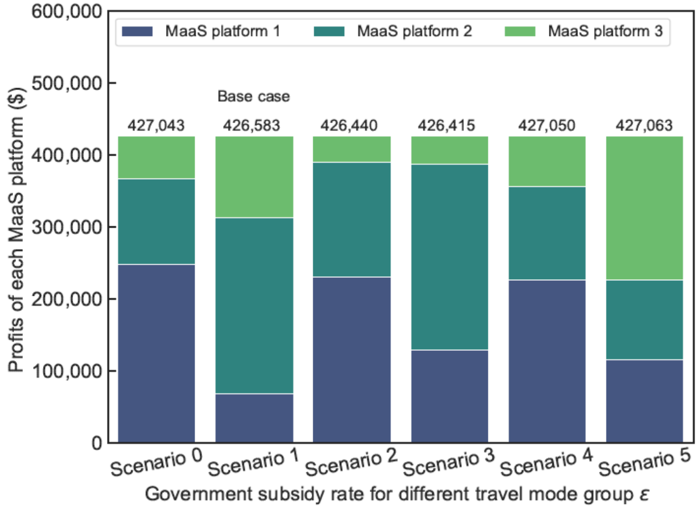
(c) Flow of users' participation under $400,000 ERF



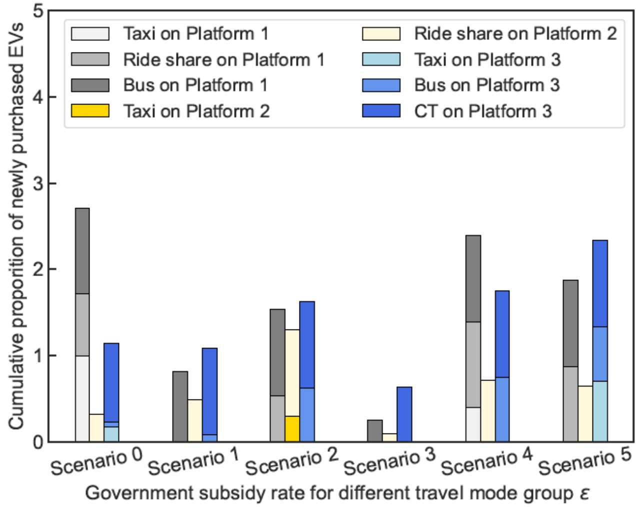
(d) Flow of users' participation under $500,000 ERF

Figure: Users' participation levels for E(T)-MaaS bundles and other options under various ERF budgets

Observation. Higher ERF budgets can simultaneously boost the profitability of MaaS platforms and encourage eco-friendly travel behavior, achieving the synergy between profitable and environmental goals. MaaS platforms can strategically invest in different electric modes and incentivize more users to select E-MaaS services, thereby generating more carbon credits.



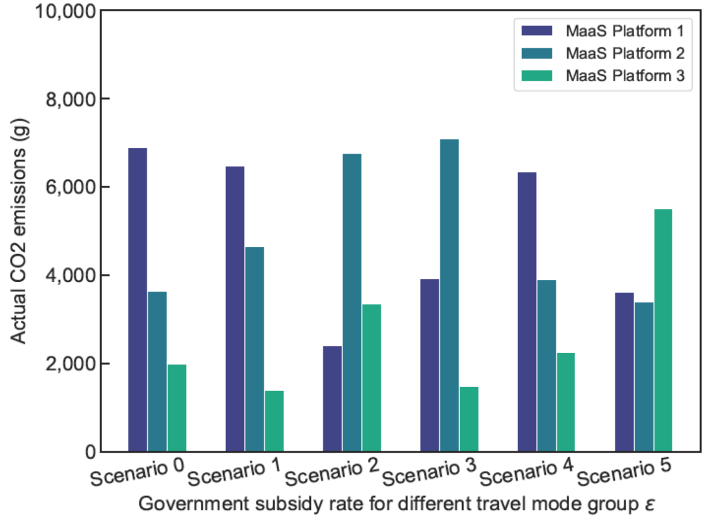
(a) Profits



(b) Proportion of new purchased EVs

Table: Government's subsidy rate under 6 scenarios

Scenarios	Taxi	Rideshare (with two riders)	Bus	CT	Description
0	0.20	0.20	0.20	0.20	Identical
1	0.20	0.50	0.85	0.90	Base case
2	0.20	0.50	0.90	0.90	Increase Bus's subsidy rate
3	0.20	0.50	0.85	0.95	Increase CT's subsidy rate
4	0.20	0.55	0.85	0.90	Increase Rideshare's subsidy rate
5	0.25	0.50	0.85	0.90	Increase Taxi's subsidy rate



(c) Reduced CO2 emissions

Observation. The government's subsidy rates for EV acquisition can significantly impact MaaS platforms' profits and market dynamics. Over-subsidizing specific modes, such as CT, can reduce market diversity and potentially lead to user attrition (Scenarios 2 and 3). On the other hand, increasing subsidy rates for modes with higher emissions like Taxi and Rideshare can motivate MaaS platforms to invest more in EVs, thereby achieving the dual benefits of earning carbon credits and increasing revenue from users' payments (Scenarios 0, 4 and 5).

Figure: MaaS platforms' profits, EV acquisition ratio, and reduced CO2 emission under 6 scenarios levels for E(T)-MaaS bundles across three platforms and their reserved options under various unit

Conclusion

- We consider an E-MaaS ecosystem where multiple MaaS platforms leverage carbon credit payments from governments' emissions reduction fund (ERF) as an alternative revenue stream by incentivizing users to opt for more E-MaaS bundles with rewards, turning a sustainability initiative into financial benefits. This E-MaaS ecosystem offers a vital lifeline to MaaS operators facing the challenges of economic and environmental sustainability.

- We introduce a multi-leader multi-follower game: Each leader (MaaS platform) competes to maximize its profits by determining the unit price for E(T)-MaaS services, unit rewards for E-MaaS users, EV acquisition ratio, E(T)-MaaS bundle allocation, and the supply-demand gap, by anticipating the participation levels of all travelers for the platform. In response to the leaders' decisions, each follower (traveler) decides her participation level for E(T)-MaaS services across multiple MaaS platforms, minimizing travel costs.

- We customize an alternating direction method of multipliers (ADMM) algorithm to address the challenges of solving a large-scale MLMFG model involving multiple MaaS platforms and travelers with conflicting payoffs. By decomposing each leader's problem into two subproblems, the customized ADMM algorithm allows for distributed and parallel processing and shows rapid convergence, therefore significantly reducing the computational burden and obtaining the optimal solutions of the proposed MLMFG efficiently.

Strategizing sustainability and profitability in electric Mobility-as-a-Service (E-MaaS) ecosystems with carbon incentives: A multi-leader multi-follower game

Q&A

Thank you for your kind attention!