Large-Scale Allocation of Personalized Incentives

CY Transport & Urban Seminar

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Introduction

Bonus-Malus Écologique

- In France, the "eco-friendly" cars are subsidized and the most polluting cars are taxed.
- **Non-personalized policy:** everyone is facing the same subsidy or tax for the same vehicle model.
- Example: For electric cars, there is a subsidy of 6000 euros.
- **Inefficient policy:** individuals receive the same subsidy or pay the same tax, independently of their preferences or car usage.

Introduction

Tripod Policy

Araldo, A., Gao, S., Seshadri, R., Azevedo, C.L., Ghafourian, H., Sui, Y., Ayaz, S., Sukhin, D. and Ben-Akiva, M., 2019. System-Level Optimization of Multi-Modal Transportation Networks for Energy Efficiency using Personalized Incentives: Formulation, Implementation, and Performance. *Transportation Research Record, 2673*(12), pp.425-438.

- Smartphone app proposing different alternatives (mode, departure time and route) to perform a trip.
- **Incentives** are proposed for energy-efficient alternatives.
- Incentive amount is the product of the energy savings with a **universal Token Energy Efficiency (TEE)**.
- Optimization problem to compute the best TEE, given a **limited budget**.
- Account for exact trip characteristics but **ignore individuals preferences**.

Introduction

Example

Alternative / Individual	Alice WTP	Alice CO_2	Bob WTP	Bob CO_2
Car	**3**	**4**	**4**	**5**
PT	2	1	2	1
Walk	1	0	1	0

Introduction

Example

Alternative / Individual	Alice WTP	Alice CO_2	Bob WTP	Bob CO_2
Car	3	4	4	5
PT	**2+2**	**1**	**2+2**	**1**
Walk	1+2	0	1+2	0

- Subsidy of 2 euros for PT and for Walking: *expenses of 4 euros, CO_2 reduced by 7.*

Introduction

Example

	Alice		Bob	
Alternative / Individual	WTP	CO_2	WTP	CO_2
Car	3	4	4	5
PT	**2+1.5**	**1**	**2+2**	**1**
Walk	1+2	0	1+2.5	0

- Subsidy of 2 euros for PT and for Walking: *expenses of 4 euros, CO_2 reduced by 7.*
- Tripod with a TEE of 1/2: *expenses of 3.5 euros, CO_2 reduced by 7.*

Introduction

Example

	Alice		Bob	
Alternative / Individual	WTP	CO_2	WTP	CO_2
Car	3	4	4	5
PT	**2+1**	**1**	**2+2**	**1**
Walk	1	0	1	0

- Subsidy of 2 euros for PT and for Walking:
  expenses of 4 euros, CO_2 reduced by 7.
- Tripod with a TEE of 1/2:
  expenses of 3.5 euros, CO_2 reduced by 7.
- Incentive of 1 euro to Alice and 2 euros to Bob for PT:
  expenses of 3 euros, CO_2 reduced by 7.

Introduction

Goals and Framework

- **How to construct an efficient personalized policy, accounting for individual preferences?**
- **How much money is saved compared to non-personalized policies?**
- We focus on **incentive policies**, in a **discrete-choice framework**.
- A regulator uses his **limited budget** to improve a **social indicator** (e.g., CO_2 emissions reduction).

Introduction

Contributions

- The problem of finding an **optimal personalized-incentive policy** is a **Multiple-Choice Knapsack Problem**.
- We propose an algorithm to find a near-optimal policy with a large number of individuals and alternatives.
- **Numerical application** to mode choice in Lyon (France).
- Comparison with other policies.
- Discussion of **Perfect information** assumption.

Framework and Policy

Model and Notations

- Population of m individuals.
- Individual-specific choice-sets.
- $V_{i,j}$ is the **intrinsic utility** of alternative j of individual i (expressed in monetary units).
- $b_{i,j}$ is the **social indicator** of alternative j of individual i.

Framework and Policy

Incentives and Behavior

- $y_{i,j} \geq 0$ is the **monetary incentive** given to individual i if she accepts to choose alternative j
- Total **utility** of i when choosing j is thus

$$U_{i,j} = V_{i,j} + y_{i,j}.$$

- The alternative chosen by individual i is such that

$$j_i^* \in \arg\max_j U_{i,j}.$$

Framework and Policy

Regulator

- A regulator is endowed with a **budget** Q.
- His budget constraint is

$$Y = \sum_i y_{i,j_i^*} \leq Q.$$

- His goal is to maximize the **global social indicator**:

$$B = \sum_i b_{i,j_i^*}.$$

- To do so, the regulator can choose the set of incentives $\{y_{i,j}\}_{i,j}$.

Framework and Policy

Assumptions

- **Independent intrinsic utilities:** $V_{i,j}$ is independent of the choice of any individual $i' \neq i$.
- **Independent social indicators:** $b_{i,j}$ is independent of the choice of any individual $i' \neq i$.
- **Perfect information:** the regulator knows perfectly $V_{i,j}$ and $b_{i,j}$, $\forall i, j$.

Optimal Policy

Example

	Alice		Bob	
Alternative / Individual	V	b	V	b
Car	0	0	1	0
PT	-1	3	-1	4
Walk	-2	4	-2	5

- With incentives $y_{\text{Alice,PT}} = 1 + \varepsilon$ (and nothing else), Alice will switch to public transit and it will cost $1 + \varepsilon$ to the regulator.
- With incentives $y_{\text{Alice,Walk}} = 2 + \varepsilon$ (and nothing else), Alice will switch to walking and it will cost $2 + \varepsilon$ to the regulator.
- Similarly, it will cost $2 + \varepsilon$ to make Bob switch to public transit, and $3 + \varepsilon$ to make him switch to walking.

Optimal Policy

Example

	Alice		Bob	
Alternative / Individual	w	b	w	b
Car	**0**	**0**	**0**	**0**
PT	1	3	2	4
Walk	2	4	3	5

Optimal Policy

Example

Alternative / Individual	Alice w	Alice b	Bob w	Bob b
Car	0	0	**0**	**0**
PT	**1**	**3**	2	4
Walk	2	4	3	5

- With budget $Q = 1$, the optimal policy is to induce Alice to switch to PT ($B = 3$).

Optimal Policy

Example

	Alice		Bob	
Alternative / Individual	w	b	w	b
Car	**0**	**0**	0	0
PT	1	3	**2**	**4**
Walk	2	4	3	5

- With budget $Q = 1$, the optimal policy is to induce Alice to switch to PT ($B = 3$).
- With budget $Q = 2$, the optimal policy is to induce Bob to switch to PT ($B = 4$).

Optimal Policy

Example

Alternative / Individual	Alice w	Alice b	Bob w	Bob b
Car	0	0	0	0
PT	**1**	**3**	**2**	**4**
Walk	2	4	3	5

- With budget $Q = 1$, the optimal policy is to induce Alice to switch to PT ($B = 3$).
- With budget $Q = 2$, the optimal policy is to induce Bob to switch to PT ($B = 4$).
- With budget $Q = 3$, the optimal policy is to induce both Alice and Bob to switch to PT ($B = 7$).

Optimal Policy

Example

Expenses Y and social welfare B of all possible states.

(Alice, Bob)	Y	B
(Car, Car)	0	0
(Car, PT)	2	4
(Car, Walk)	3	5
(PT, Car)	1	3
(PT, PT)	3	7
(PT, Walk)	4	8
(Walk, Car)	2	4
(Walk, PT)	4	9
(Walk, Walk)	5	10

Optimal Policy

Optimal Policy Characteristics

- The **smallest incentive needed** to induce i to switch to alternative j is

$$w_{i,j} = V_{i,j_i^0} - V_{i,j},$$

where V_{i,j_i^0} is the intrinsic utility of the alternative chosen in absence of policy.

- One optimal policy is to set either $y_{i,j} = 0$ or $y_{i,j} = w_{i,j}$, $\forall i, j$, with at most one alternative j such that $y_{i,j} > 0$, $\forall i$.
- Instead of choosing the incentive policy $\{y_{i,j}\}_{i,j}$, we can choose directly the set of alternatives chosen.
- **No individual gains or loses utility** with this policy.

Optimal Policy

Optimization Problem

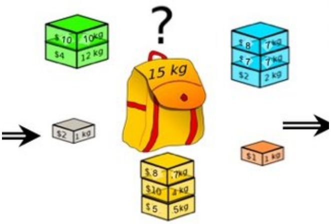
- The optimization problem of the regulator can be written as

$$\left\{\begin{array}{lll} \max_{\{x_{i,j}\}_{i,j}} & \sum_i \sum_j b_{i,j} x_{i,j} & \\ \text{s.t.} & \sum_i \sum_j w_{i,j} x_{i,j} \leq Q & \\ & \sum_j x_{i,j} = 1, & \forall i \\ & x_{i,j} \in \{0,1\}, & \forall i,\ \forall j \end{array}\right. .$$

- This is a **Multiple-Choice Knapsack-Problem**.
- An approximate solution can be found in polynomial time.

Optimal Policy

Multiple-Choice Knapsack-Problem



Multiple-choice knapsack problem

Source: Xu, S., Chen, X., Pi, X., Joe-Wong, C., Zhang, P. and Noh, H.Y., 2019, March. Incentivizing vehicular crowdsensing system for large scale smart city applications. *In Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2019 (Vol. 10970, p. 109701C).* International Society for Optics and Photonics.

Optimal Policy

Efficiency and Greedy Algorithm

- The **efficiency** of switching individual i from alternative j to alternative j' is

$$\tilde{e}_{i,j\to j'} = \frac{b_{i,j'} - b_{i,j}}{w_{i,j'} - w_{i,j}}.$$

- **Iterative procedure:** we "switch" individuals one by one to their subsequent alternative, according to decreasing efficiency, until the budget is depleted.

Optimal Policy

Example

Budget: $Q = 3$

Alternative / Individual	Alice w	Alice b	Alice $\tilde{e}$	Bob w	Bob b	Bob $\tilde{e}$
Car	**0**	**0**		**0**	**0**	
PT	1	3	3	2	4	2
Walk	2	4	1	3	5	1

Optimal Policy

Example

Budget: $Q = 3$

	Alice			Bob		
Alternative / Individual	w	b	$\tilde{e}$	w	b	$\tilde{e}$
Car	0	0		**0**	**0**	
PT	**1**	**3**	**3**	2	4	2
Walk	2	4	1	3	5	1

- Iteration 1: Best switch is Alice from Car to PT (efficiency 3, remaining budget 2).

Optimal Policy

Example

Budget: $Q = 3$

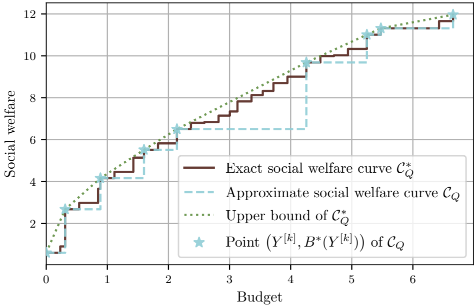
	Alice			Bob		
Alternative / Individual	w	b	$\tilde{e}$	w	b	$\tilde{e}$
Car	0	0		0	0	
PT	**1**	**3**	**3**	**2**	**4**	**2**
Walk	2	4	1	3	5	1

- Iteration 1: Best switch is Alice from Car to PT (efficiency 3, remaining budget 2).
- Iteration 2: Best switch is Bob from Car to PT (efficiency 2, remaining budget 0).

Optimal Policy

Properties

- Solution is boundedly close to the optimum.
- Solution is optimal for the budget spent at any iteration.
- **Diminishing returns:** social welfare is concave with the expenses of the regulator.



Application to Mode Choice

Data

- Census data for **220k individuals** in Lyon's area (France): home, workplace, mode of transportation for commuting, socio-demographic variables.
- Travel times computed from OpenStreetMap and HERE data.
- **5 modes of transportation:** car, public transit, walking, cycling and motorcycle.
- For 16k individuals, public transit is not an alternative (no route).

Application to Mode Choice

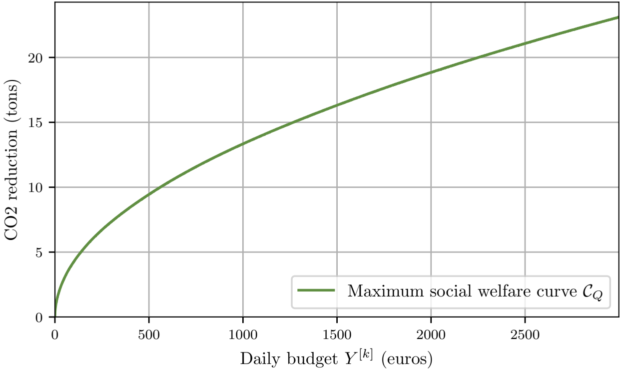
Intrinsic Utilities and Social Indicators

- Intrinsic utilities are estimated from a Multinomial Logit model.
- Social indicators are the **CO_2 emissions**, computed with data from ADEME.

Daily CO_2 emissions	595.26 tons of CO_2
Yearly CO_2 emissions (200 days)	119050 tons of CO_2
Average yearly individual CO_2 emissions	0.54 tons of CO_2

Application to Mode Choice

Social Welfare Curve

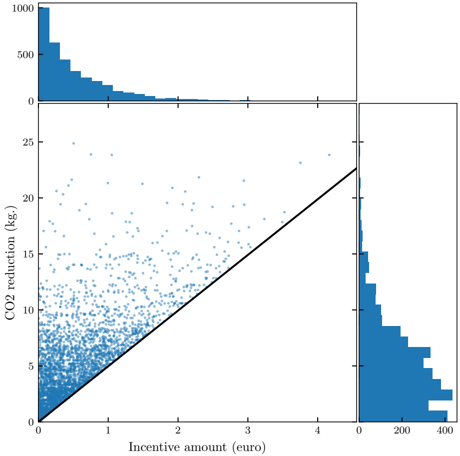


Application to Mode Choice

Results

- Budget is set to $Q = 1800$ euros (per day).
- After 3500 iterations, 1798.59 euros are spent.
- Only **1.57 % of individuals receive incentives**.
- Reduction of CO_2 of 18 tons per day (3 % of total emissions).
- Average cost is 100 euros per ton of CO_2.

Application to Mode Choice
Results



Application to Mode Choice

Results

Mode choice after the policy (columns); Mode choice before the policy (rows)

	car	public transit	walking	cycling	motorcycle	total
car	55.839%	1.163%	0.099%	0.128%	0.097%	57.326%
public transit	0.005%	27.29%	0.037%	0.032%	0.005%	27.368%
walking	0%	0%	9.481%	0%	0%	9.481%
cycling	0%	0%	0%	4.339%	0%	4.339%
motorcycle	0%	0.005%	0.001%	0.001%	1.479%	1.486%
total	55.843%	28.458%	9.618%	4.5%	1.581%	100%

Comparison with Other Policies

Application Results

- Enforcement: Individuals are forced to choose an alternative.
- Proportional tax: Alternatives are taxed proportionally to their CO_2 emissions.
- Tripod incentives: Incentives proportional to the CO_2 emissions of the alternatives.

Policy	Expenses Y	Ind. utility $\Delta V = \sum_i V_{i,j_i^*}$	Surplus $\Delta V - Y$	CO_2 reduction B
Pers. incentives	1798.59	0	-1798.59	17.878
Enforcement	0	-1798.59	-1798.59	17.878
Proportional tax	-114368.89	-116167.48	-1798.59	17.878
Tripod incentives	3596.97	1798.38	-1798.59	17.878

Conclusion

Summary

- Personalized-incentive policy boundedly close to optimum can be computed with **MCKP algorithms from Operations research**.
- The policy shows **diminishing returns** behavior.
- The allocation can be reached with **proportional taxation** or with **Tripod**.
- Numerical results show that the personalized policy can reach the same social target than non-personalized policies with **half the budget**.

Conclusion

Future Works

- With **imperfect information**, we can use the same algorithm and set the incentive amounts to the expected utility difference. Results could be improved by learning from the responses of the individuals to the incentives.
- **Congestion** can be accounted for with an iterative procedure.