An optimization setup of the decarbonization problem in the transportation sector

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France's Carbon Neutrality Target

Goal:

- Carbon neutrality by 2050

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How?

- **SRADDET:** Regional planning for sustainability, air quality, and climate action.

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Challenge:

Regional targets add up to more than France's national goal.

Investing in Decarbonization: A Government Dilemma

The Bigger Problem:

- Multiple agents (regions) compete for limited government budgets.
- Each agent has different needs and priorities for decarbonization.

The Goal:

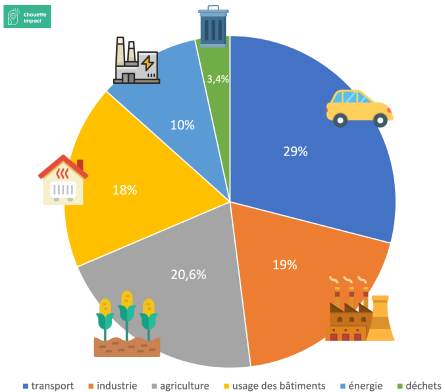
- Develop a process to **allocate resources efficiently** across competing regions to maximize decarbonization impact.

First Bricks:

- Make an optimization problem for each sector capturing its specificities.

France emissions

Which sector is driving France's climate crisis, and what can we do to change it?



Specificity of Transport Sector

Private Cars:

- Largest contributor to emissions.
- Electrification of private vehicle fleets is critical.



Change in usage:

- Increase the usage of soft mobility.

Public transport:

- Transitioning to electric and low-emission buses and trains.



Outline

1. Introduction

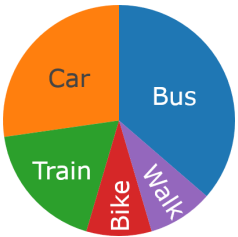
2. Problem formulation
   - Usage modelisation
   - Vehicles modeling
   - Infrastructure
   - Constraints and objective

3. Simulation

Usage

Let $\mathcal{K} = \{0, 1, \cdots, K\}$ be the set of transportation *modes*.

- $k = 0 \Rightarrow$ the sobriety
- $k = 1, \cdots, K \Rightarrow$ car, train, bus, etc.



Each mode has a usage x_t^k in passengers.km $\Rightarrow \tilde{x}_t^k$ is the proportion of usage in %.

$$\forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \qquad x_t^k = \tilde{x}_t^k X_t, \ \left(\tilde{x}_t^k\right)_{k \in \mathcal{K}} \in \Delta^{K+1}, \tag{1}$$

with Δ^{K+1} denoting the K-dimensional simplex.

Switch in usage

Modal switch:

- $\beta_t^{k,l} \Rightarrow$ the proportion of mode k replaced by mode l at time t,

Thus, the dynamics

$$\forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \qquad \tilde{x}_{t+1}^k = \tilde{x}_t^k - \sum_{l \in \mathcal{K}} \beta_t^{k,l} + \sum_{l \in \mathcal{K}} \beta_t^{l,k}. \tag{2}$$

- $\beta_t^{k,k} = 0$ at any time t
- $\beta_t^{k,l} \Rightarrow$ facilitation "process" (subsidies, communication, etc.) from mode k to l

Practical limitations are imposed

$$\forall k, l \in \mathcal{K}, \forall t \in \mathcal{T}, \qquad 0 \leq \beta_t^{k,l} \leq \overline{\beta}_t^{k,l} \;\; 0 \leq \underline{x}_t^k \leq x_t^k \leq \overline{x}_t^k. \tag{3}$$

Vehicle fleet formalism

Each mode $k \in \mathcal{K}$, has a set $\mathcal{I}_k$ of *vehicle types* aggregated as a fleet.

- Car = electric + gasoline + ...
- Train = electric + diesel + ...

Each mode has a number of vehicles v_t^i of type i at time t.

Impose a sufficient total number of vehicles per mode for usage:

$$\forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \qquad x_t^k \leq \sum_{i \in \mathcal{I}^k} d^i r^i v_t^i, \tag{4}$$

- $d^i \Rightarrow$ average *distance traveled* with a vehicle of type i
- $r^i \Rightarrow$ average *occupancy rate* of the vehicles of vehicle of type i

Change in the fleet

Vehicle decay:

- $\tau^i \Rightarrow$ life time expectancy of vehicle

Introducing vehicles:

- $\theta_t^i \Rightarrow$ *adding* vehicles into the fleet
- $\nu_t^{j,i} \Rightarrow$ *replacing* vehicle i with j
- $w_t^i \Rightarrow$ *new vehicle*:

$$\forall k \in \mathcal{K}, \forall i \in \mathcal{I}^k, \forall t \in \mathcal{T}, \qquad w_t^i = \theta_t^i + \sum_{j \in \mathcal{I}^k} \nu_t^{j,i}. \tag{5}$$

The vehicle dynamics express:

$$\forall k \in \mathcal{K}, \forall i \in \mathcal{I}^k, \forall t \in \mathcal{T}, \qquad v_{t+1}^i = v_t^i - w_{t-\tau^i}^i + w_t^i, \tag{6}$$

$$\forall k \in \mathcal{K}, \forall i \in \mathcal{I}^k, \forall t \in \mathcal{T}, \qquad 0 \leq \theta_t^i, \quad 0 \leq \sum_{j \in \mathcal{I}^k} \nu_t^{i,j} \leq w_{t-\tau^i}^i \,. \tag{7}$$

Graphical summary of fleet dynamics

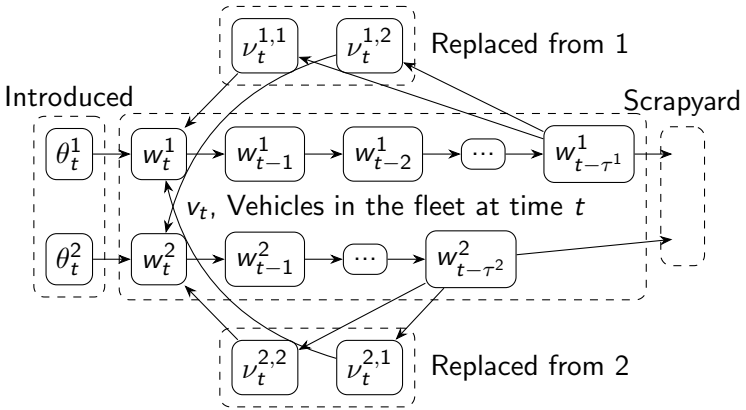


Figure: Schematic fleet aging dynamics for 2 types of vehicles.

Infrastructure formalism

Each mode $k \in \mathcal{K}$, has infrastructure y_t^k as vehicles.km

Assumption

Infrastructures are independent between the different modes.

e.g. cars and buses do not drive on the "same roads".

Fleet and infrastructure are related:

$$\forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \qquad \sum_{i \in \mathcal{I}^k} d^i v_t^i \leq y_t^k. \tag{8}$$

- $d^i \Rightarrow$ average *distance traveled* with a vehicle of type i

Investment in infrastructure

Investment:

- $\mu_t^k \Rightarrow$ the expansion of the infrastructure.

The dynamics of infrastructure is then given by:

$$\forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \qquad y_{t+1}^k = \delta^k y_t^k + \mu_t^k,\ 0 \leq \mu_t^k \leq \overline{\mu}_t^k, \tag{9}$$

Infrastructures decay:

- $0 < \delta^k \leq 1 \Rightarrow$ the depreciation rate of infrastructure of mode k.

Budgets

Everything has a cost:

- $c^{k,l}_{t,\text{switch}} \Rightarrow$ incentives users' transition from transportation mode k to l
- $c^{i}_{t,\text{buy}} \Rightarrow$ costs of adding one vehicle
- $c^{i,j}_{t,\text{conv}} \Rightarrow$ conversion prime for old vehicle
- $c^{k}_{t,\text{inv}} \Rightarrow$ costs of infrastructure investments.

$$\sum_{k\in\mathcal{K}}\left[c^{k}_{t,\text{inv}}\mu^{k}_{t} + \sum_{l\in\mathcal{K}} c^{k,l}_{t,\text{switch}}\beta^{k,l}_{t}X_{t} + \sum_{i\in\mathcal{I}^k}\left[c^{i}_{t,\text{buy}}\theta^{i}_{t} + \sum_{j\in\mathcal{I}^k} c^{i,j}_{t,\text{conv}}\nu^{i,j}_{t}\right]\right] + x^{0}_{t}c^{\text{sob}}_{t} \leq B^{\max}_{t}. \tag{10}$$

Everything have emissions:

- $e_i \Rightarrow$ emission of CO2 per km.vehicle of vehicle i

$$\forall t \in \mathcal{T}, \qquad \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{I}^k} d^{i}e^{i}v^{i}_{t} \leq E^{\max}_{t}. \tag{11}$$

Quality of Service (QoS) with congestion

Maximizing the Quality of Service

From a user perspective, the measurement unit is *time*! $\Rightarrow$ Congestion is an important metric

$$\mathrm{QoS}(x, y, v) = \sum_{k \in \mathcal{K} \setminus \{0\}} q^k x^k \left(1 - \sum_{i \in \mathcal{I}^k} \frac{d^i v^i}{y^k}\right) - q^0 x^0, \tag{12}$$

- $q^k > 0$ is a weight of user preference for mode k:
  - comfort
  - accessibility
  - affinity

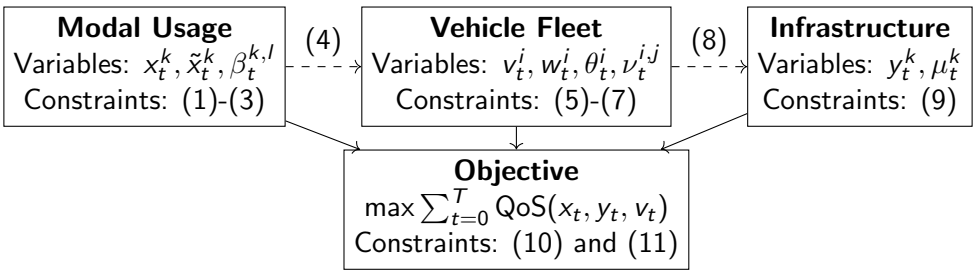
This objective function is nonlinear.

Optimization problem formulation

The OP is then:

$$\max \quad \sum_{t \in \mathcal{T}} \text{QoS}(x_t, y_t, v_t)$$

s. t. **Modal usage:** (1)-(3), **Vehicle fleets:** (4)-(7), **Infrastructure:** (8)-(9), **Monetary and CO_2 emissions budgets:** (10) and (11).



Simulation and Data

Data: Use the latest data available for the Bretagne region in France.

- Vehicle fleet: from Crit'air database [1]
- Infrastructure: from CEREMA database [2]
- Emission factors: from ADEME database [3]
- Costs: from the socio-economical study [4]

Assumption:

- Constant costs over time
- Quality of service coefficient q^k: taken to reflect observed behaviors

Comparaison between scenario

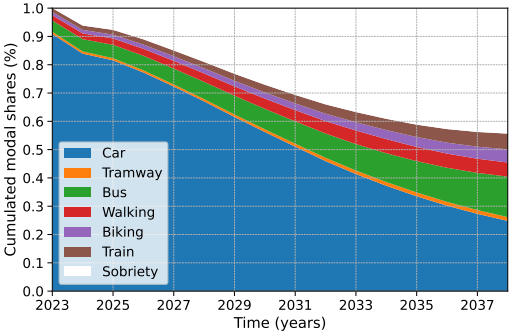
	Low Budget Scenario		High Budget Scenario	
	Budget	Used (%)	Budget	Used (%)
Emissions (Mteq.CO_2)	36.04	33.79 (93.8%)	36.04	33.5 (93.1%)
Monetary (M€)	800	800 (100%)	8000	8000 (100%)

Table: Budget Emission and Monetary

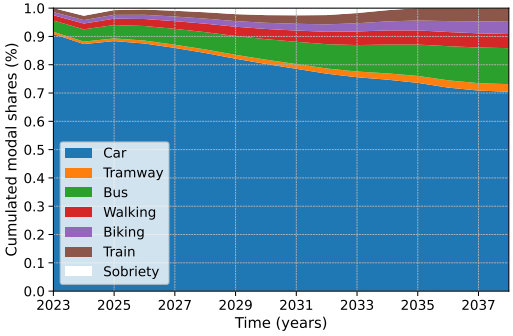
	Allocation between levers	
	Low	High
Sobriety	48.16%	1.66%
Modes	23.14%	1.35%
Vehicles	7.86%	85.14%
Infrastructures	20.84%	11.85%

Table: Distribution for Low and High Budget Scenarios

Usage evolution

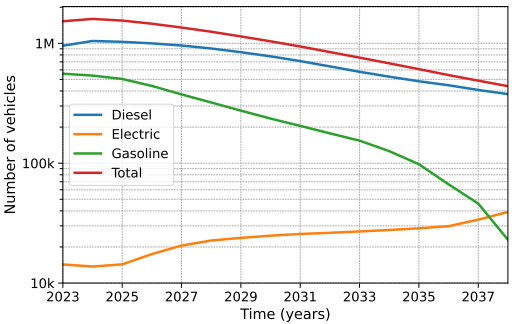


(a) Low budget: modal shares

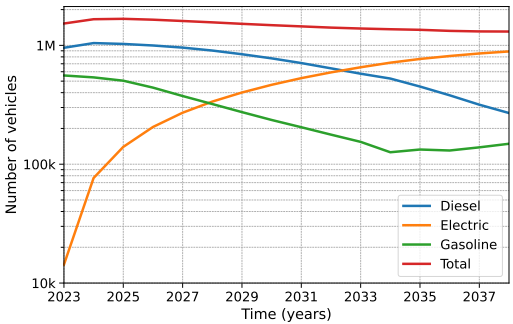


(b) High budget: modal shares

Car fleet evolution



(a) Low budget: vehicle fleet



(b) High budget: vehicle fleet

Feasibility

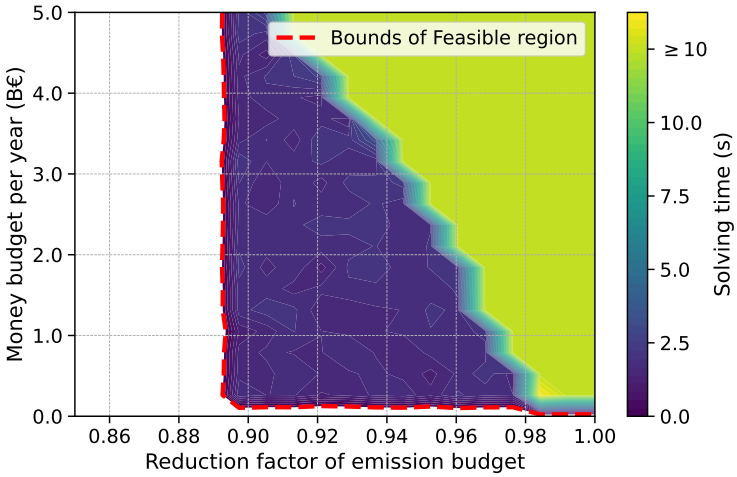


Figure: Computation times and feasibility.

Conclusion and Perspectives

Conclusion:

- The optimization problem is **solvable and practical** for guiding decarbonization strategies.
- Provides a **first foundation** for future work in decarbonization resource allocation.
- Provides a methodology for building other sector decarbonization OP.

Perspectives:

- Model the other emitting sectors (building sector already done).
- Design the Stackelberg game between the region/sector and the government.

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