CHAIR REEL.i

UNIVERSITÉ MARIE & LOUIS PASTEUR

Working Paper

N°3 / Sep. 2026

Beyond Carbon Pricing: Intelligent Multimodal Coordination as a Policy Lever for Transport Decarbonization in France

Moustapha Mounmemi[1,2,*], Vincent Bertrand[1,2,†], Fihavanantsoa Kristiana Manitriniaina[1,2, ‡]

Abstract: Decarbonizing transport in low-density territories is constrained not only by price signals but also by coordination frictions between transport modes. This study examines the relative roles of economic incentives and multimodal coordination in shaping mobility equilibria, CO_2 emissions, and welfare outcomes in the Nord Franche-Comté region of France. We develop a multimodal equilibrium framework incorporating private cars, regular carpooling, and public transport while accounting for coordination costs in multimodal travel chains. Alternative policy regimes combine conventional carpooling, carbon-related incentives, fuel taxation, and Mu-CAR, an intelligent Mobility-as-a-Service infrastructure designed to reduce intermodal transaction costs. Pricing instruments alone generate limited changes in modal shares and emissions, whereas Mu-CAR induces a structural shift from solo driving towards carpooling and public transport. Mu-CAR achieves an annual CO_2 abatement of 2,429.96 tCO_2, compared with 222.62 tCO_2 under regular carpooling, representing more than a tenfold increase in emissions abatement. The Mu-CAR + CR + FT scenario reaches 2,619.30 tCO_2/year while maintaining a net welfare gain, although additional pricing instruments yield diminishing environmental benefits and reduce welfare gains. Sensitivity analysis further show that Mu-CAR's relative environmental and economic performance is strongly conditioned by travel distance, with environmental and economic advantages occurring over different distance ranges. These findings indicate that transport decarbonization depends fundamentally on the coordination architecture of mobility systems, with pricing instruments playing a complementary role. Conceptually, the study extends the Avoid–Shift–Improve framework by identifying coordination as an enabling mechanism for shifting travellers towards lower-carbon and integrated mobility

KEYWORDS:

#Intellingent Multimodal Coordination #Carpooling #Structural Determinant #Transport Decarbonization #Carbon Pricing #Abatement Cost

[1] Université Marie et Louis Pasteur, CRESE (UR 3190), F-25000 Besançon, France.

[2] REEL.i chair and Réseau EDEN.i research network, Université Marie et Louis Pasteur, Belfort, France.

* moustapha.mounmemi@umlp.fr / † vincent.bertrand@umlp.fr / ‡ manitrafih@gmail.com

Renewable
Energy
Economics and
Law
for **.i**ndustry

The **REEL.i Chair** is hosted by **Université Marie et Louis Pasteur** under the auspice of the **FC'INNOV Foundation** and with the support of **Origo**.

Associated to the **Réseau EDEN.i** research network, REEL.i adopts a multidisciplinary approach to analyze the economic and legal questions related to renewable energy, with a special interest for energy decentralization in industrial territories.

1. Introduction

Transport decarbonization represents one of the major challenges of the European climate transition (European Commission, 2023). Despite recent technological progress, road passenger transport remains a major source of CO_2 emissions (Wadud et al., 2024; Schäfer and Yeh, 2020), particularly in rural and peri-urban areas where dependence on private cars remains structurally high. In these low-density territories, climate policies targeting the transport sector often yield limited results due to the lack of accessible, reliable, and sufficiently coordinated low-carbon alternatives (Banister, 2011).

Current decarbonization strategies primarily rely on three categories of policy instruments: (i) carbon pricing and energy taxation (Shaheen & Cohen, 2013; Laroche & Schemeleva, 2026), (ii) technological improvements and vehicle electrification, and (iii) modal shift policies promoting public transport and shared mobility solutions (Astier et al., 2023; Laroche, 2022). Within the framework of the "Avoid–Shift–Improve" (ASI) paradigm, these approaches essentially aim to modify relative prices or improve the technological performance of transport modes (Bakker et al., 2014). However, they implicitly assume that alternatives to private car use are already operational and can be mobilized with little difficulty.

However, in low-density areas, the main barriers to modal transition arise less from price signals than from coordination difficulties among users, transport modes, and mobility networks (Lah, 2015). Public transport services are often characterized by low frequency and schedules poorly aligned with travel needs. Carpooling depends on a critical mass of users that is rarely achieved at the local level. Intermodal connections remain uncertain, while first- and last-mile constraints reduce the effective accessibility of transport networks. In this context, coordination costs—including matching friction among carpooling users, trip synchronization, information management, and transfer reliability—constitute a structural constraint on low-carbon mobility (Tønnesen et al., 2022).

In this context, multimodal coordination appears to be a largely underappreciated structural determinant of transport decarbonization. In contrast to conventional policies that primarily act on monetary costs (Konishi & Mun, 2010; Julagasigorn et al., 2021; Salihou et al., 2026; Wang & Monchambert, 2026), integrated mobility systems are likely to reshape mobility outcomes by reducing the organizational frictions that constrain the use of low-carbon alternatives. The transition therefore depends not only on trade-offs between isolated transport modes, but on the system's ability to enable integrated multimodal travel chains.

We examine this hypothesis using the Mu-CAR project, which is applied to data from the Nord Franche-Comté region. Mu-CAR is an academic project that provides an intelligent multimodal carpooling system intended to integrate with public transport services (Gaspoz and Canalda, 2025; Joliot et al., 2025). Beyond conventional carpooling platforms, it provides real-time coordination of trips and multimodal integration. Mu-CAR is therefore conceptualized as an intelligent multimodal coordination infrastructure that connects carpooling and public transport within an integrated mobility architecture. Private car use serves as the reference scenario against which modal shifts, emission reductions, and system-level outcomes are evaluated. From this perspective, the relevant unit of analysis is no longer the isolated transport mode, but coordinated travel chains combining multiple modes within a single trip.

The main contribution of the Mu-CAR project lies in its ability to reduce coordination frictions that constrain the feasibility of multimodal trips in spatially dispersed territories. Its effect does not stem solely from reductions in monetary costs, but from a transformation of intermodal accessibility conditions (See figure 1). By lowering generalized coordination costs, the system enables mobility configurations that were previously difficult or infeasible. To assess these mechanisms, we develop a structural multimodal simulation framework that estimates abatement and abatement costs under scenarios generating different allocations across transport modes. We integrate private cars, carpooling, and public transport, with coordination costs that depend on spatial structure. The model compares conventional decarbonization policies based on price signals with an intelligent multimodal coordination system of the Mu-CAR type.

The results highlight a fundamental difference between these approaches. Conventional policies generate primarily marginal adjustments in modal shares and emissions, without altering the overall organization of the mobility system. In contrast, reductions in coordination frictions induce a structural transformation, characterized by the emergence of coordinated multimodal travel chains combining carpooling and public transport. The resulting emission reductions are substantially higher than those achieved under conventional policy scenarios, while welfare analysis reveals net gains and potentially negative abatement costs driven by reductions in generalized mobility costs.

Beyond the specific case studied, this paper advances a more general argument: in low-density territories, the effectiveness of decarbonization policies depends less on price signals than on the coordination architecture linking different mobility modes. The low-carbon transition thus appears not only as a technological or economic problem, but also as a question of systemic organization of transport networks. This paper contributes to the literature in four main ways. First, we develop a stylized structural simulation framework to examine how coordination frictions shape modal allocation outcomes and emissions. Second, we show that reducing coordination frictions yields substantially larger decarbonization effects than conventional pricing-based policies. Third, we show that multimodal coordination can mitigate the negative environmental effects of spatial dispersion by making low-carbon mobility options more feasible in low-density territories. Finally, we highlight that integrated Mobility-as-a-Service (MaaS) systems can generate negative abatement costs through reductions in generalized travel costs.

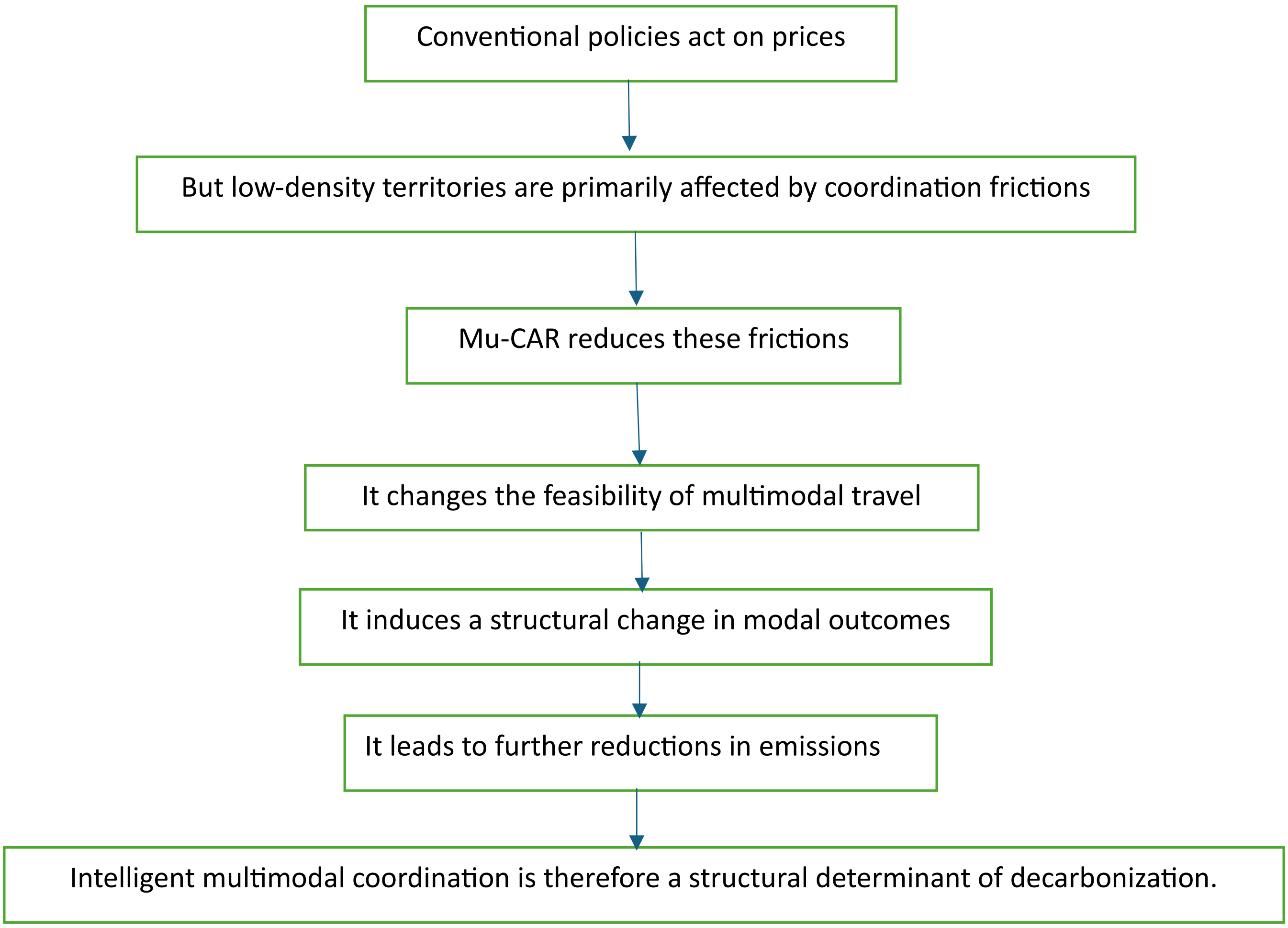

Figure 1. Conceptual Framework

The remainder of the paper is organized as follows. Section 2 presents the theoretical framework and develops the main mechanisms underlying the relationship between multimodal coordination, spatial structure, and decarbonization. Section 3 describes the empirical strategy used to assess these mechanisms. Section 4 presents the simulation framework and data. Section 5 reports the main results, while Section 6 examines the sensitivity of these results to alternative assumptions and parameter values. Section 7 concludes and discusses the broader implications of the findings for the design of decarbonization policies in low-density territories.

2. Theoretical Framework

A large body of literature examines public policies aimed at reducing CO_2 emissions from passenger transport. A widely used framework to structure these interventions is the Avoid–Shift–Improve (ASI) model (Bakker et al., 2014). Originally promoted by the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) (*Deutsche Gesellschaft für Internationale Zusammenarbeit, 2012*), this framework distinguishes three complementary levers: (i) reducing travel demand (Avoid), (ii) promoting a modal shift toward lower-carbon alternatives (Shift), and (iii) improving the energy and environmental efficiency of transport technologies (Improve).This typology allows policies to be grouped according to their primary mechanism of action, while acknowledging that some measures may simultaneously fall into multiple categories (Zamora, 2014).

The *Avoid* pillar encompasses strategies aimed at reducing the overall volume of travel or dependence on private car use, notably by acting on the spatial and temporal organization of activities (Bakker et al., 2017). Among the most widely studied instruments are road mobility pricing policies, such as fuel taxes, urban tolls, congestion pricing schemes, cordon pricing, and vehicle access restrictions in designated areas. These instruments seek to modify the generalized cost of car use and to internalize part of the environmental and congestion externalities associated with private vehicle travel. Other measures within this dimension include policies aimed at reducing commuting demand, for instance through teleworking or the adjustment of working hours, which can contribute to lowering motorized travel demand and peak-hour congestion (Bakker et al., 2014).

The *Shift* pillar refers to policies aimed at reorienting mobility behavior away from high-emission modes, particularly private cars, toward more sustainable alternatives such as public transport, walking, and cycling. The literature emphasizes that such modal shifts depend on a range of determinants related to service attributes (travel time, reliability, comfort), information availability, as well as individual preferences and social norms (IPCC, 2022). Associated policies include, in particular, improvements in public transport supply, the development of cycling infrastructure, and incentive schemes promoting shared mobility.

Finally, the *Improve* pillar encompasses strategies focused on enhancing the environmental performance of vehicles and transport infrastructure, notably through the diffusion of cleaner technologies, the adoption of alternative fuels (electricity, hydrogen, advanced biofuels), and improvements in the energy efficiency of powertrains and transport systems (IPCC, 2022). These policies are typically associated with technology standards, innovation and purchase subsidies, as well as public investment in charging and energy distribution infrastructure.

Taken together, the three pillars of the ASI framework provide a structured lens for understanding the range of available policy instruments for decarbonizing passenger transport, combining both demand-side and supply-side interventions. The literature broadly converges on the view that no single measure is sufficient to achieve the required emission reductions in the short to medium terms, and that policy portfolios combining economic instruments, infrastructure investments, and behavioral incentives are necessary (Bakker et al., 2014; IPCC, 2022).

The ASI literature primarily focuses on mode-specific attributes but tends to under-specify intermodal coordination costs. The Mu-CAR approach extends the ASI framework by introducing a coordination layer that operates on generalized costs across modes, rather than on the attributes of each mode in isolation. From this perspective, policies promoting shared and multimodal mobility can act as a complementary lever, alongside pricing instruments and technological policies, to reduce emissions while limiting the transition costs for users. More specifically, Mu-CAR acts as a multimodal coordination infrastructure that enables the operational integration of carpooling, public transport, and travel synchronization mechanisms within a unified mobility system. By reducing coordination frictions, it effectively alters the structure of generalized travel costs and thereby reshapes equilibrium mobility choices.

3. Empirical Strategy

The model is calibrated such that variations in λ_m[1] across scenarios capture aggregate behavioral responses consistent with policy-induced changes in generalized costs and utility differentials.

The framework is designed as a structural simulation model to explore how changes in coordination costs affect modal choices and emissions. Each scenario defines a specific cost structure, and the resulting modal shares are calibrated to be consistent with these costs. The model is static and compares mobility and emission outcomes across alternative policy scenarios, without explicitly modeling the transition between scenarios. It is structured into three layers: (i) a baseline multimodal allocation, (ii) structural extensions capturing spatial and policy heterogeneity, and (iii) a simulation layer used for welfare analysis and robustness checks. This structure allows us to assess how changes in coordination frictions affect mobility choices, emissions, and welfare across different spatial and policy contexts.

3.1. Emission Reductions

We define CO_2 emission reductions associated with Mu-CAR as the difference between emissions in the baseline scenario, representing the mobility system in the absence of any carpooling system, and emissions in each carpooling scenario, which incorporates the corresponding behavioral and modal changes (either with regular carpooling or Mu-CAR). The baseline therefore reflects the pre-project mobility configuration without any carpooling involved, while each carpooling scenario (either with regular carpooling or Mu-CAR) represents a specific configuration defined by a given set of calibrated parameters. Emission reductions are then calculated for each scenario separately.

The calculation follows the Global Carbon Council (GCC, 2025) methodology, originally developed for carpooling projects and adapted here to a multimodal transport setting, with limited reference to the Verra (2025) framework.

For the baseline scenario, emissions are calculated as:

$$BE = \sum_m \lambda_{b,m} \times D_b \times EF_{b,m}, \tag{1}$$

[1] denotes the modal share associated with transport mode (m), i.e., the share of total trips allocated to that mode within a given scenario.

where:

- BE denotes baseline emissions;
- b denotes the baseline scenario;
- $m$denotes the transport mode;
- $\lambda_{b,m}$ is the share of mode $m$in the total number of trips;
- D_b is the total travel distance in the baseline scenario;
- $EF_{b,m}$ is the passenger/kilometer emission factor of mode m.

To express emission factors on a passenger/kilometer basis, the vehicle emission factor is adjusted according to vehicle occupancy:

$$EF = \frac{EF_{vkm}}{VO}, \tag{2}$$

where $EF_{vkm}$is the vehicle emission factor on a vehicle/kilometre basis and VO is the vehicle occupancy rate.

For each project scenario, the same calculation is applied using the corresponding scenario-specific parameters:

$$PE = \sum_m \lambda_{p,m} \times D_p \times EF_{p,m}, \tag{3}$$

where:

- PE denotes project emissions;
- p denotes the project scenario;
- m denotes the transport mode;
- $\lambda_{p,m}$ is the share of mode $m$in the project scenario;
- D_p is the total travel distance in the project scenario;
- $EF_{p,m}$ is the corresponding passenger/kilometer emission factor.

The modal shares, travel distances, and emission factors may therefore differ across scenarios depending on the calibrated parameters defining each configuration. The functional form of the emissions calculation remains unchanged. Emission reductions are subsequently calculated as:

$$ER = BE - PE, \tag{4}$$

where ER denotes the CO_2 emission reductions associated with the project scenario.

3.2. Modal choice

3.2.1. Utility function

Given that the emission equations are identical across scenarios, differences between the baseline and project scenarios arise primarily from changes in modal shares and emission factors. Modal shift is captured through variations in modal shares across scenarios and is encouraged by Mu-CAR through three incentive channels: carbon rewards, fuel taxes, and peer effects. These mechanisms are consistent with the literature, which highlights the central role of financial incentives and social influence in the adoption of carpooling in France (Delhomme and Gheorghiu, 2016), as well as the effectiveness of fuel taxation as a pricing instrument for reducing CO_2 emissions (Hammadou and Papaix, 2015).

The project also affects emission factors (EF) through two complementary channels: substitution toward lower-emission transport modes and changes in the composition of the vehicle fleet. Because carbon rewards are indexed to fuel type and vehicle age, owners of older and more polluting vehicles face stronger incentives to switch to public transport or carpooling. This mechanism contributes to reducing the average emission factor associated with both carpooling and solo driving. Carbon rewards are defined here as monetary incentives linked to individual emission reduction efforts.

These modal decisions are represented through utility functions defined as the sum of perceived costs and benefits associated with each transport mode. Generalized trip costs, including the monetary valuation of travel time, fuel expenditures, carpooling charges, and public transport fares (Le Goff et al., 2025), enter the utility functions with a negative sign ($\Gamma_m < 0$), following Fielbaum and Pudāne (2024). The utility functions for the different transport modes are therefore specified as follows:

Solo driver:

$$U_{sd} = \Gamma_{sd} + B, \quad (5)$$

Public transport:

$$U_{pt} = \Gamma_{pt} + fB, \quad (6)$$

Carpooling**:**

$$U_{cp} = \Gamma_{cp} + eB \quad (7)$$

Accordingly, the utility specification and the modal-share calibration should be interpreted as complementary components of the framework. The formulation is operationalized in the multimodal chain utility specification (Equation 8), where utility depends on the share of each transport mode m within the trip:

$$U_{mm} = \sum_m \lambda_m U_m + \Delta_{mm}, \tag{8}$$

where:

- m denotes the transport mode and includes *sd*, *pt*, and *cp*, corresponding respectively to solo driving, public transport, and carpooling, as well as the multimodal case;
- U_m represents the utility function of mode m, interpreted as utility per kilometre or per segment;
- B corresponds to the benefits associated with private vehicle travel;
- f is a decreasing function of vehicle occupancy rate (see Fielbaum and Pudāne (2024) for further details on $B$and f);
- e is the coefficient capturing the extent to which this benefit applies to carpooling,
- λ_m represents the fraction of distance travelled using mode m within a multimodal trip, with $\sum_m \lambda_m = 1$;
- Δ_{mm} represents transfer costs (thus <0) specific to multimodal trips (Cascajo et al., 2017).

Although the decision unit is defined as a mobility chain, the modal shares λ_m are interpreted as the disaggregated shares of total distance allocated to each mode within that chain. This allows multimodal trajectories to be represented while maintaining a consistent accounting of mode-specific emissions. By introducing an incentive $I_{mm} > 0$, the multimodal utility becomes:

$$U_{mm} = \sum_m \lambda_m U_m + \Delta_{mm} + I_{mm}. \tag{9}$$

Where λ_m[2] denotes the exogenous share of distance travelled using mode m within the multimodal trip. Let $U_j^* = \max\{U_{sd}, U_{pt}, U_{cp}\}$ denote the best alternative mode (excluding multimodality). The switching condition is then:

$$U_{mm} > U_j^* + \tau \quad (10)$$

where $\tau > 0$ represents an indifference or perception threshold (Zhang et al., 2019). Substituting the expression of U_{mm}:

$$\sum_m \lambda_m U_m + \Delta_{mm} + I_{mm} > U_j^* + \tau \quad (11)$$

we obtain the minimum required incentive:

$$I_{mm} > U_j^* - \sum_m \lambda_m U_m - \Delta_{mm} + \tau. \quad (12)$$

Since I_{mm} depends positively on fuel type and vehicle age, individuals owning older and more polluting vehicles receive a stronger incentive to adopt multimodal trips. Moreover, a reduction in Δ_{mm} decreases the disutility associated with multimodality and thereby makes it more attractive. This can be achieved, for instance, through improvements in infrastructure along travel corridors, such as the development of active travel routes through green spaces (Yu et al., 2024). Finally, it is important to note that the impact of modal shift on emission reductions is not limited to modal shares and emission factors, although these constitute its primary channels. Fielbaum and Pudāne (2024), in the context of automated shared vehicles, also show that modal shift can affect trip distances. We take this into account in the present study, through an extension of our methodology that allows varying the modal shares with different parameters (see section 3.2.2.1). Hence, the modal shares can vary across policy scenarios and spatial conditions according to the assumed behavioral response to generalized travel costs and coordination conditions.

3.2.2. *Modal report*

To evaluate the effectiveness of integrating carpooling into the public transport system, we develop a simple formulation of distance-based modal choice dynamics. This framework

[2] At this stage, the modal shares λ_m are treated as exogenous and fixed within each scenario. Section 3.2.2.1 subsequently introduces a method to endogenize these shares, allowing them to vary with other model parameters and generating the scenarios considered in the simulations.

models how users are distributed between carpooling and public transport as a function of their distance to the urban center, which in turn influences local population density. We compare two scenarios: a conventional carpooling system and the Mu-CAR project, based on a Mobility as a Service (MaaS) platform enabling the coordination of multimodal trips. In this framework, modal shares vary with distance to the urban center through its effect on population density and, consequently, on the feasibility of carpooling and access to public transport. Spatial heterogeneity acts as an exogenous structuring factor, which is used in our framework to compute the direct allocation of modal shares that are associated to this. The objective is to capture how spatial context and incentives jointly shape the distribution of transport modes and, ultimately, CO_2 emissions.

3.2.2.1. Distance–density relationship

We adopt a population density function that gradually decreases toward a minimum rural density as distance increases. This specification avoids unrealistic predictions of zero density and captures the empirically observed plateau in very low-density areas. We define:

- d: distance to the city centre (in km), with $d \geq d_{\min}$
- $\rho(d)$: population density at distance d
- $\rho_{\min}$: asymptotic minimum density (e.g., rural threshold)
- $\rho_{\max}$: maximum density at $d_{\min}$
- $d_{\min}$: minimum distance to the city centre below which the carpooling share may decline[3]
- $k > 0$: a parameter

The distance–density function is defined as:

$$\rho(d) = \rho_{\min} + (\rho_{\max} - \rho_{\min})e^{-k(d-d_{\min})} \quad (13)$$

which satisfies:

$$\rho(d_{\min}) = \rho_{\max}, \lim_{d\to\infty} \rho(d) = \rho_{\min}. \quad (14)$$

[3] Ferguson (1995) noted that the carpooling rate begins to increase beyond a certain distance, but may decrease below this range

This specification implies an exponential decay in population density as distance to the urban center increases, asymptotically converging toward a minimum rural threshold $\rho_{\min}$. It thus captures the gradual decline in carpooling feasibility in low-density areas without predicting zero density. We define:

$$L(\rho) = \begin{cases} 0 & \text{if } \rho \geq \rho_{\max} \\ \theta \frac{\rho_{\max}-\rho}{\rho_{\max}-\rho^*} & \text{if } \rho^* < \rho < \rho_{\max} \\ \theta & \text{if } \rho \leq \rho^* \end{cases} \tag{15}$$

where ρ^*denotes a critical density threshold below which regular carpooling becomes non-viable. $\theta \in [0,1]$represents the maximum reduction in regular carpooling induced by declining density, and is independent of the modal share parameters λ_m used elsewhere in the model. Accounting for these adjustments in modal shares, the revised shares of regular carpooling and solo driving are given by:

$$\lambda_{cp}^{reg}(\rho) = \lambda - L(\rho) \tag{16}$$
$$\lambda_{sd}^{reg}(\rho) = \lambda_{sd} + L(\rho) \tag{17}$$

where “reg” denotes regular carpooling.

3.2.2.2. Modal shares in Mu-CAR

We define:

- $\beta \in [0,1]$: share of regular carpooling loss that persists under Mu-CAR
- $\varepsilon(\rho) = \beta \cdot L(\rho)$: reduced carpooling loss thanks to platform coordination
- $\delta(\rho) \geq 0$: potential reduction in solo driving induced by the Mu-CAR platform itself

The function $\delta(\rho)$ represents the potential reduction in solo driving induced by the Mu-CAR platform through improved coordination. Since coordination difficulties are expected to increase as population density decreases, the potential contribution of Mu-CAR is assumed to increase when density decreases. Accordingly, $\delta(\rho)$is a non-increasing function of population density ρ: lower values of ρ correspond to greater potential coordination gains. In the present calibration, however, $\delta(\rho)$is set to zero, so that the simulations focus on the effect of Mu-CAR in mitigating the loss of carpooling through the $\beta L(\rho)$ mechanism. The $\delta(\rho)$ term is retained in the general formulation to represent an additional coordination effect that can be activated and calibrated in future extensions of the model.

- $\alpha \in [0,1]$: share of $\delta(\rho)$ directed toward carpooling
- $(1-\alpha)$: share of $\delta(\rho)$ directed toward public transport

$$\lambda_{cp}^{mucar}(\rho) = \lambda_{cp} - \beta L(\rho) + \alpha\delta(\rho) \tag{18}$$
$$\lambda_{pt}^{mucar}(\rho) = \lambda_{pt} + \beta \cdot L(\rho) + (1-\alpha) \cdot \delta(\rho) \tag{19}$$
$$\lambda_{sd}^{mucar}(\rho) = \lambda_{sd} - \delta(\rho) \tag{20}$$

where λ_m^{mucar} denotes the share of mode m in the Mu-CAR project. To ensure accounting consistency within the model, we assume that the initial modal shares satisfy $\lambda_{cp}^{reg} + \lambda_{pt}^{reg} + \lambda_{sd}^{reg} = 1 - \lambda_{sm}$ and $\lambda_{cp}^{mucar} + \lambda_{pt}^{mucar} + \lambda_{sd}^{mucar} = 1 - \lambda_{sm}$, where λ_{sm} is the share of soft mobility, held exogenous. Moreover, the functions $L(\rho)$ and $\delta(\rho)$ are constrained to preserve non-negative modal shares, implying in particular $0 \leq \delta(\rho) \leq \lambda_{sd}$and $0 \leq \beta L(\rho) \leq \lambda_{cp}$. These equations describe the evolution of modal shares with distance to the city centre under two scenarios: regular carpooling and the Mu-CAR platform. As density decreases, regular carpooling declines, leading to a shift toward solo driving. In contrast, Mu-CAR mitigates this loss by integrating carpooling with public transport and introducing incentives, thereby reallocating users between carpooling and public transport. The model preserves total modal share and captures behavioural changes with distance through its link to spatial population density.

3.2.2.3. Weight of modal shift per vehicle and average subsidy

We consider a population of car drivers partitioned according to vehicle registration year $y \in Y$. Let:

- $f_y \geq 0$ denote the share of drivers owning a vehicle from cohort y, with $\sum_{y \in Y} f_y = 1$;
- y^{ref} denote the reference year corresponding to the most recent vehicle cohort;
- S_y denote the per-trip subsidy associated with shifting a driver from solo driving to carpooling.

Age-dependent subsidy :

The subsidy is defined as a function of vehicle age:

$$S_y = S_0 + \alpha(y^{ref} - y) \tag{21}$$

where:

- $S_0 > 0$ is the baseline per-trip subsidy for a modal shift to carpooling;
- $\alpha \geq 0$ is the increase in the subsidy per additional year of vehicle age;
- $y^{ref} - y$ represents vehicle age relative to the most recent vehicle cohort.

Allocation rule for modal shift :

We consider an aggregate rate of modal shift from solo driving to carpooling, denoted $w \in [0,1]$. This aggregate shift rate is distributed across vehicle cohorts according to a weighting rule proportional to both incentive intensity and the prevalence of each cohort in the driver population. We define the normalized weight:

$$w_y = \frac{S_y f_y}{\sum_{y \in Y} S_y f_y} \tag{22}$$

with:

$$w_y \geq 0, \ \sum_{y \in Y} w_y = 1. \tag{23}$$

Here, w_y represents the share of the aggregate modal shift attributable to vehicle cohort y.

Implicit average subsidy per shifted trip

The average subsidy associated with a trip shifted toward carpooling is given by:

$$\bar{S} = \sum_{y \in Y} w_y S_y \tag{24}$$

Substituting (22), we obtain:

$$\bar{S} = \frac{\sum_{y \in Y} S_y^2 f_y}{\sum_{y \in Y} S_y f_y}. \tag{25}$$

3.2.2.4.Abatement cost

Abatement cost corresponds to the expense required to avoid emitting one metric ton of CO_2 (France Stratégie, 2021). In this study, following Le Goff et al. (2025), we adopt a total social cost approach. This means that the cost is computed as the sum of private and public costs:

$$SC = CC + PC \tag{26}$$

where:

- SC= social cost;
- CC= consumer cost;
- PC= public cost.

As previously noted, consumer cost is defined as the sum of time costs, fuel expenditures, carpooling fees, and bus fares. The new cost component corresponds to incentives, or, as specified here, subsidies. Subsidies and taxes are treated as transfer payments between agents and the public sector. Their net contribution to social cost is accounted for through the opportunity cost of public funds, ensuring that transfers neither artificially increase nor decrease total social costs.

$$CC_m = TimeCost_m + Fuel_m + PT_m - Subsidies_m \tag{27}$$

where:

- $CC_m$is the consumer cost for mode m;
- $TimeCost_m$is the monetary valuation of time spent in mode m;
- PT_m denotes the public transport fare associated with mode m, and is equal to zero for non-public-transport modes.
- $Subsidies_m$are subsidies allocated to mode m, which may be positive (e.g., carbon revenue transfers) or negative (e.g., fuel taxation).

In the case of carpooling, fuel cost is divided by the vehicle occupancy rate:

$$Fuel_{cp} = \frac{Fuel_{sd}}{VO} \tag{28}$$

The public cost is composed of road infrastructure wear, subsidies to platforms, and public transport revenues, all weighted by the opportunity cost of public funds (OCPF):

$$PC = OCPF \times (RoadWear + Subsidies - PT) \tag{29}$$

Public transport fare revenues PT_m are accounted for as a private cost in $CC_m$and as public revenue PT[4] in PC, consistent with a net social cost approach that properly integrates transfers.

To compute the abatement cost (AC), we proceed as follows:

$$AC = \frac{\Delta SC}{ER} \tag{30}$$

where:

$$\Delta SC = SC_{project} - SC_{baseline} \tag{31}$$

4. Simulation and Data

The Mu-CAR scenario should be interpreted as a stylized representation for a fully integrated multimodal coordination system. Although calibrated to the Nord Franche-Comté region, the analysis is intended as a stylized representation of coordination frictions in low-density territories more generally. The mechanisms identified are interpreted as structurally informative rather than region-specific, and may plausibly extend to other contexts characterized by similar spatial dispersion, low multimodal integration, and limited coordination capacity in transport systems.

It is not intended to represent a specific policy implementation, but rather to serve as a reference case illustrating the potential magnitude of emission reductions achievable under conditions of near-complete coordination across mobility services. The simulation reports emission reductions and abatement costs at the population level. To estimate multimodal CO_2 emissions, calculations were first performed separately for each transport mode and subsequently weighted according to modal shares within the population[5]. The following seven scenarios were examined:

[4] For the sake of notational consistency, we note PT to represent the aggregated value for all modes m (which is consistent with the logic of PC), even though the PT_m associated with public transports is the only one that is non-negative (see equation (27)).

[5] This approach was adopted because, although it yields results comparable to those obtained from individual-level calculations, it is more consistent with the empirical literature, which typically evaluates travel behavior and emissions at the population level within specific urban contexts

Table 1. Description of the Scenarios Tested

Scenario	Description
Baseline	Reference scenario without any additional policy measures.
Regular Carpooling (RC)	Carpooling plays a more prominent role than in the baseline scenario.
Regular Carpooling + Carbon Dividend (RC + CD)	Carpooling is promoted and combined with a carbon dividend scheme, an approach that has been tested in several European cities, including Montpellier through the Carpool with BlaBlaCar Daily initiative (Montpellier Méditerranée Métropole, 2024).
Regular Carpooling + Carbon Dividend + Fuel Tax (RC + CD + FT)	Regular carpooling combined with a carbon dividend and a fuel tax.
MuCAR Project (MC)	Scenario corresponding to the MuCAR project.
MuCAR Project + Carbon Dividend (MC + CD)	MuCAR project combined with a carbon dividend scheme.
MuCAR Project + Carbon Dividend + Fuel Tax (MC + CD + FT)	MuCAR project combined with a carbon dividend and a fuel tax.

The simulated population is set at 100,000 individuals and is divided into two groups that differ in their responsiveness to incentives. The first group, characterized by a high degree of responsiveness, accounts for 25% of the population. The remaining 75% belong to a second group that is less responsive to incentives. This distribution is adopted for simulation purposes and will be further explored through sensitivity analyses to assess how alternative group proportions affect the results. The emission factors (EFs) used in the scenarios are primarily derived from ADEME (2025). Average values are applied in the baseline scenario, whereas emission factors vary by year and fuel type in the project scenarios. Vehicle occupancy rates (VORs) are based on BlaBlaCar (2019), assuming an average occupancy of 3.4 persons per vehicle for carpooling. For public transport, an occupancy rate of 60% is assumed, corresponding to a vehicle capacity of 30 passengers.

Regarding costs, the consumer cost component is estimated using values of travel time derived from Le Goff et al. (2022) and Wardman et al. (2016). Public transport fares are set at €1.20 per trip, based on the fare structure currently applied in the Nord Franche-Comté region[6]. A

[6]The monthly fares in Belfort and Montbéliard were €36 and €41, respectively, corresponding to approximately €1.20 and €1.36 per day, assuming 30 days per month. In the Pays d'Héricourt, the fare was €1 per trip at the time of data collection in 2025. These values were obtained from the official websites of the respective local public transport services, as consulted in 2025. The overall average fare used in the analysis is approximately €1.19, rounded to €1.20.

minimum subsidy of €1 per trip is assumed to encourage modal shifts toward multimodal transportation. To further incentivize participation among owners of older vehicles, the subsidy increases with vehicle age. The age gradient is calibrated over the range of vehicle registration years considered in the dataset (1995–2020). Specifically, the subsidy is set at €1 for vehicles registered in 2020 and €1.50 for vehicles registered in 1995. Given the 25-year age difference between these two cohorts, the resulting annual increment is:

$$\alpha = \frac{1.50-1.00}{2020-1995} = 0.02\ €/year \quad (32)$$

Thus, the value α=0.02 is a calibration parameter rather than an externally observed subsidy rate. It ensures a total subsidy differential of €0.50 between the most recent and oldest vehicle cohorts considered in the analysis. This linear specification provides a simple and transparent way to introduce greater incentives for owners of older vehicles while remaining consistent with the age range of the vehicle fleet in the dataset.

Within this framework, the subsidy functions as a carbon dividend, increasing with vehicle age to reflect the greater emissions-abatement potential associated with replacing or reducing the use of more polluting vehicles. For each trip shifted away from solo driving, an additional €0.02 is therefore granted for every additional year of vehicle age. Assuming 230 trips per year, this corresponds to an additional annual subsidy of €46.00 for a vehicle registered in 2010 (10 years older than a 2020 vehicle) and €115.00 for a vehicle registered in 1995 (25 years older than a 2020 vehicle). The total subsidy is therefore €1.20 per trip for a 2010 vehicle and €1.50 per trip for a 1995 vehicle.

The fuel tax is calculated as the average of projected fuel price increases associated with the implementation of ETS2, based on estimates reported by Hernández (2025) in a publication of the European Parliament.

Private benefits and behavioral disutilities associated with multimodal travel are not modeled as separate aggregate components. However, they are indirectly captured through the Γ parameters in the utility functions, which influence the propensity to switch to Mu-CAR. All scenarios are modeled at the group level, with modal shifts represented through changes in aggregate travel behavior. Consequently, differences across scenarios are primarily reflected in variations in modal shares. Regarding public costs, following the study conducted by Le Goff (2023) in a French region, road infrastructure wear and tear is valued at €0.008 per kilometer, while the marginal cost of public funds (MCPF) is assumed to be equal to 20% of total public expenditure. Finally, the modal distribution of trips in the baseline scenario is derived from an ongoing study conducted by CEREMA (2024) for the Nord Franche-Comté region[7].

The initial modal shares used in the model are calibrated based on the modal distribution of the reference situation, informed by the CEREMA (2024) study for the Nord Franche-Comté region, and correspond to the three transport modes involved in the modal redistribution mechanism. The initial share of regular carpooling is set to $\lambda_{cp} = 0.05$, the share of public transport to $\lambda_{pt} = 0.07$, and the share of solo driving to $\lambda_{sd} = 0.60$. The remaining 0.28 of the population corresponds to soft mobility, denoted by $\lambda_{sm} = 0.28$, which is treated as exogenous and is not affected by the modal redistribution mechanism. Thus, the initial modal shares satisfy:

$$\lambda_{cp} + \lambda_{pt} + \lambda_{sd} + \lambda_{sm} = 1, \tag{33}$$

with:

$$\lambda_{cp} = 0.05,\ \lambda_{pt} = 0.07,\ \lambda_{sd} = 0.60,\ \lambda_{sm} = 0.28. \tag{34}$$

The three parameters λ_{cp}, λ_{pt}, and λ_{sd} are subsequently used as the initial modal shares in equations (18)–(20) to derive the endogenous modal shares under the Mu-CAR scenario.

Several limitations of the simulation should be noted. One of the most important concerns the estimation of modal shift behavior. Although the simulation provides useful insights into the potential effects of multimodal coordination policies, a field experiment conducted prior to the simulation would have strengthened the empirical basis of the analysis. Such an experiment could have generated more accurate information on the behavioral responses of the target population, including actual modal shift patterns, preferences regarding incentive mechanisms, and the incentive levels required to induce behavioral change. Consequently, the simulation results should be interpreted as indicative estimates rather than precise predictions of real-world outcomes.

[7] For the project scenarios, changes in modal shares resulting from the introduction of subsidies are based on the findings of Le Goff et al. (2022), whereas the effects of fuel taxation on modal shares are derived from Hammadou and Papaix (2015).

5. Results

5.1. Effects of Policy Measures on Modal Distribution

The heatmap results (Figure 2) reveal a clear hierarchy in the effects of policy measures on the modal equilibrium. In the baseline scenario, mobility is largely dominated by private car use, accounting for approximately 65% of trips, while carpooling remains virtually absent. Policies relying solely on price-based instruments—namely subsidies and fuel taxes—produce only marginal adjustments in modal shares. The share of solo driving decreases only slightly, remaining around 64.0–64.2%, while carpooling accounts for less than 1% of total trips. Public transport exhibits a modest increase, reaching approximately 7.4%, whereas active mobility remains essentially unchanged at around 28%. These findings suggest a relatively low aggregate responsiveness of modal choice to monetary incentives when the underlying coordination mechanisms remain unchanged.

By contrast, the scenarios incorporating Mu-CAR reveal a structural shift in the modal equilibrium. The share of solo driving declines substantially, falling from approximately 65% to around 60%, while carpooling exceeds 4% of total trips. This reallocation is accompanied by a moderate increase in public transport use, whose share rises to approximately 7.9–8.3% (and 7.2-7.4% under regular carpooling), whereas soft mobility remains broadly stable. The magnitude of these changes contrasts sharply with the limited effects observed under stand-alone pricing policies, indicating that Mu-CAR generates more than an incremental adjustment and instead induces a deeper transformation in travel organization.

The results also reveal heterogeneous effects across transport modes. Carpooling emerges as the mode most responsive to the policies considered, with its share increasing from virtually 0% in the baseline scenario to more than 4% under Mu-CAR. Public transport also experiences a more pronounced increase under Mu-CAR than under regular carpooling combined with incentives, rising from 7.0% in the baseline to approximately 7.9–8.3%. By contrast, soft mobility remains broadly unchanged across the scenarios. These results suggest that the structural effect of Mu-CAR should be understood primarily as a reallocation between solo driving, carpooling, and public transport, rather than as a general transformation of all mobility modes. Mu-CAR therefore appears to enhance the interaction between carpooling and public transport, generating a broader modal reallocation than stand-alone pricing instruments.

Although the precise magnitude of these changes remains dependent on the simulation assumptions, the objective of the analysis is primarily to illustrate the structural differences between the scenarios rather than to provide precise forecasts of future modal shares.

Furthermore, the hybrid scenarios indicate that pricing instruments become more effective when combined with Mu-CAR. The share of solo driving continues to decline gradually in the combined scenarios, reaching approximately 59.4–59.8%, while carpooling remains at a high level (approximately 4.3–4.5%) and public transport increases slightly to around 8.3%. These findings point to non-linear complementarities between multimodal coordination mechanisms and pricing instruments, suggesting that financial incentives generate larger effects when deployed within an integrated mobility system.

Overall, the results indicate that the effectiveness of carpooling policies depends primarily on their integration within multimodal transport systems rather than on the expansion of carpooling as a stand-alone mode. The potential environmental benefits therefore arise not only from modal substitution but also from the capacity of the transport system to structure integrated travel chains and facilitate coordination across transport modes.

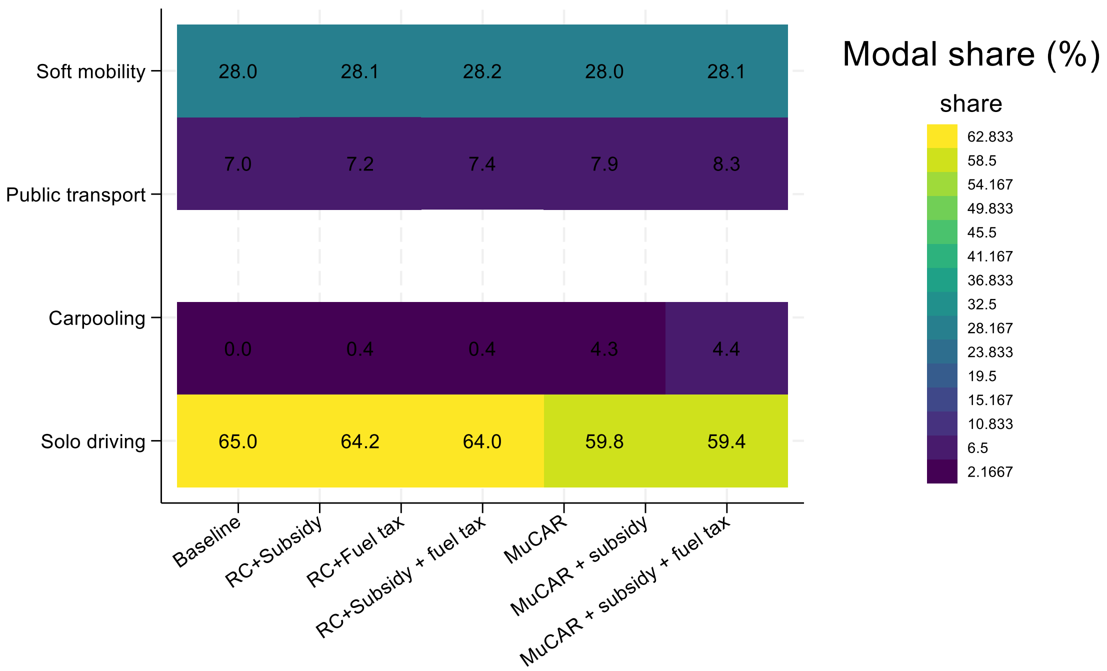

Figure 2 . Modal shares across policy scenarios

Figure 3 reports the changes in modal shares relative to the baseline scenario under three policy regimes: (i) pricing instruments alone, (ii) Mu-CAR, and (iii) hybrid policies combining Mu-CAR with pricing instruments.

Under pricing policies alone, including fuel taxation and subsidies, changes in modal shares remain limited. The share of solo driving decreases by approximately 0.5 to 1 percentage point, while carpooling remains virtually unchanged. Public transport use increases modestly, by around 0.2 to 0.5 percentage points, whereas soft mobility remains stable. These findings suggest a limited degree of modal substitution in response to price signals alone. Behavioral adjustments appear to occur primarily within existing travel patterns rather than through substantial reallocation across transport modes.

In contrast, the introduction of Mu-CAR produces a pronounced shift in modal shares. The share of solo driving declines by approximately 5 percentage points, while carpooling increases by about 4 percentage points. Public transport use rises by roughly 1 percentage point, whereas soft mobility remains largely unchanged. The reduction in solo driving is therefore largely offset by the increase in carpooling. This adjustment pattern is consistent with a direct substitution effect between solo driving and carpooling resulting from improved coordination mechanisms and enhanced multimodal integration.

When Mu-CAR is combined with pricing instruments, the modal shift becomes even more pronounced. The share of solo driving decreases by approximately 5.5 to 6 percentage points, while carpooling increases by between 4 and 4.5 percentage points. Public transport use also rises slightly relative to the Mu-CAR-only scenario. Notably, the combined effect differs from the simple sum of the individual policy effects. Pricing instruments appear to exert a stronger influence when implemented within the Mu-CAR framework than when applied in isolation.

Three main findings emerge from these results. First, pricing policies alone generate only limited modal reallocation. Second, Mu-CAR without additional pricing incentives produces a more substantial shift away from solo driving than pricing policies implemented without Mu-CAR. Third, combining Mu-CAR with pricing instruments generates the largest modal changes, suggesting that economic incentives are more effective when embedded within a multimodal coordination framework.

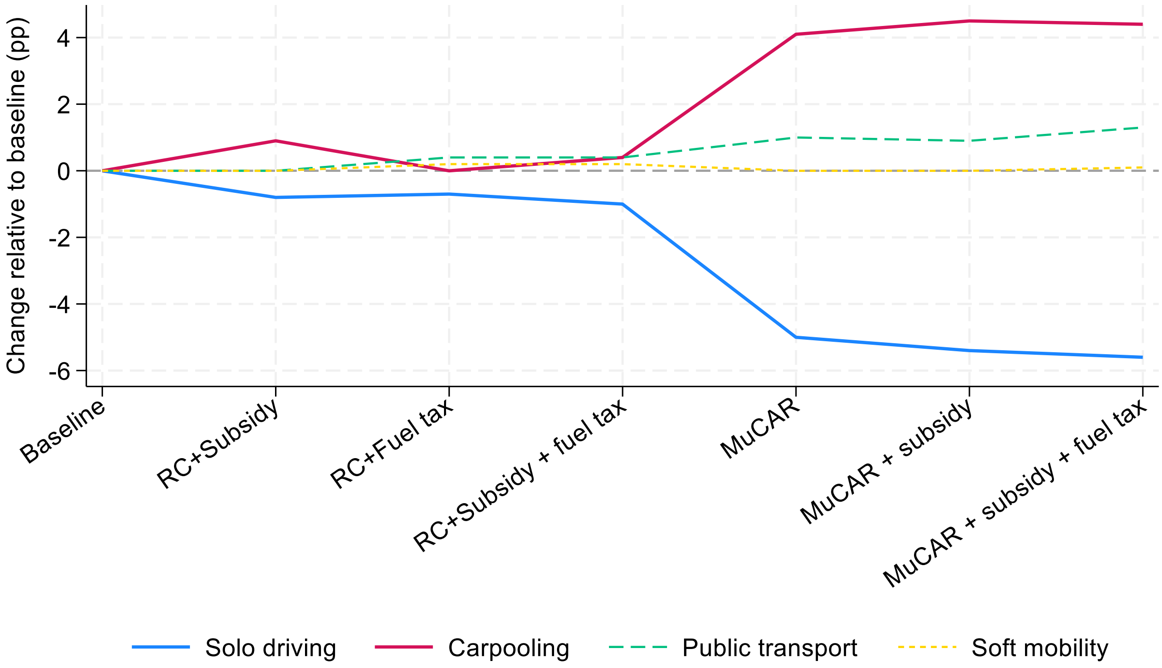

Figure 3. Δ parts modales vs baseline

5.2.*Emissions reduction*

Figure 4 compares annual CO_2 emission reductions across the different policy scenarios and reveals a pronounced asymmetry between conventional policies and multimodal coordination mechanisms. Conventional policies generate relatively modest emission reductions, with the regular carpooling scenario achieving 222.62 tCO_2/year. The introduction of the carbon dividend (CR) increases the reduction to 388.29 tCO_2/year, while the fuel tax leads to 527.76 tCO_2/year. When both pricing instruments are combined with regular carpooling, the reduction reaches 693.42 tCO_2/year**.** These results indicate that pricing-based policies can contribute to emissions abatement, but their effects remain comparatively limited when the underlying coordination of mobility options is unchanged.

In contrast, multimodal coordination is associated with substantially larger emission reductions. The Mu-CAR scenario achieves 2,429.96 tCO_2/year, representing a markedly greater abatement effect than any of the conventional policy scenarios. Adding the carbon dividend further increases the reduction to 2,595.30 tCO_2/year, while the combination of Mu-CAR, the carbon dividend, and the fuel tax reaches 2,619.30 tCO_2/year**.** The relatively small additional differences between these multimodal scenarios indicate that most of the emission reduction is associated with the introduction of multimodal coordination, while pricing instruments provide comparatively smaller incremental gains once coordination mechanisms are already in place.

This pattern is consistent with the modal reallocation effects discussed in the previous section. In particular, the substantially greater abatement associated with Mu-CAR suggests that emission reductions are primarily linked to a reduction in solo driving and a greater use of shared and intermodal travel options. By contrast, pricing instruments implemented without multimodal coordination appear less capable of modifying travel behaviour at the same scale. The limited additional gains obtained from combining pricing instruments with Mu-CAR further suggest that the marginal contribution of pricing policies decreases once major coordination barriers have already been reduced.

The magnitude of these estimated reductions is also broadly consistent with the range reported in the literature on ridesharing and shared mobility, although direct comparisons should be made cautiously because existing studies differ in terms of geographical scale, population covered, baseline definition, travel demand, and behavioural assumptions. For example, Jalali et al. (2017), in their study of ridesharing potential in Changsha, China, analysed mobility patterns from approximately 8,900 privately owned vehicles. Under a conservative ridesharing scenario, they estimated a reduction of approximately 4.0 tCO_2 per day, equivalent to roughly 1,460 tCO_2 per year when annualized. In the present study, the simulation covers a substantially larger population of 100,000 individuals, which provides an important contextual basis for interpreting the estimated 2,619.30 tCO_2/year reduction under the combined Mu-CAR + CR + FT scenario. Expressed per simulated individual, this corresponds to approximately 26.2 $kgCO_2$ of avoided emissions per individual per year.

This per-capita magnitude provides an additional perspective on the estimated abatement and indicates that the reported total partly reflects the scale of the simulated population and the aggregate travel demand represented in the model, rather than an unusually large reduction per individual. The magnitude of the estimated reduction is therefore plausible given the scale of the simulated population and the broader multimodal coordination mechanism considered. Nevertheless, comparisons with previous studies should be interpreted with caution because differences in population size, travel demand, system boundaries, baseline emissions, and behavioural assumptions can substantially affect the absolute magnitude of estimated emission reductions.

Overall, the results indicate that multimodal coordination constitutes the primary structural driver of emissions abatement, while pricing instruments play a complementary role by reinforcing an already integrated mobility system. In low-density territories, the decarbonization potential of transport therefore appears to depend not only on the strength of price signals but, more fundamentally, on the capacity of the mobility system to coordinate travel across modes and make shared and intermodal alternatives more accessible and attractive.

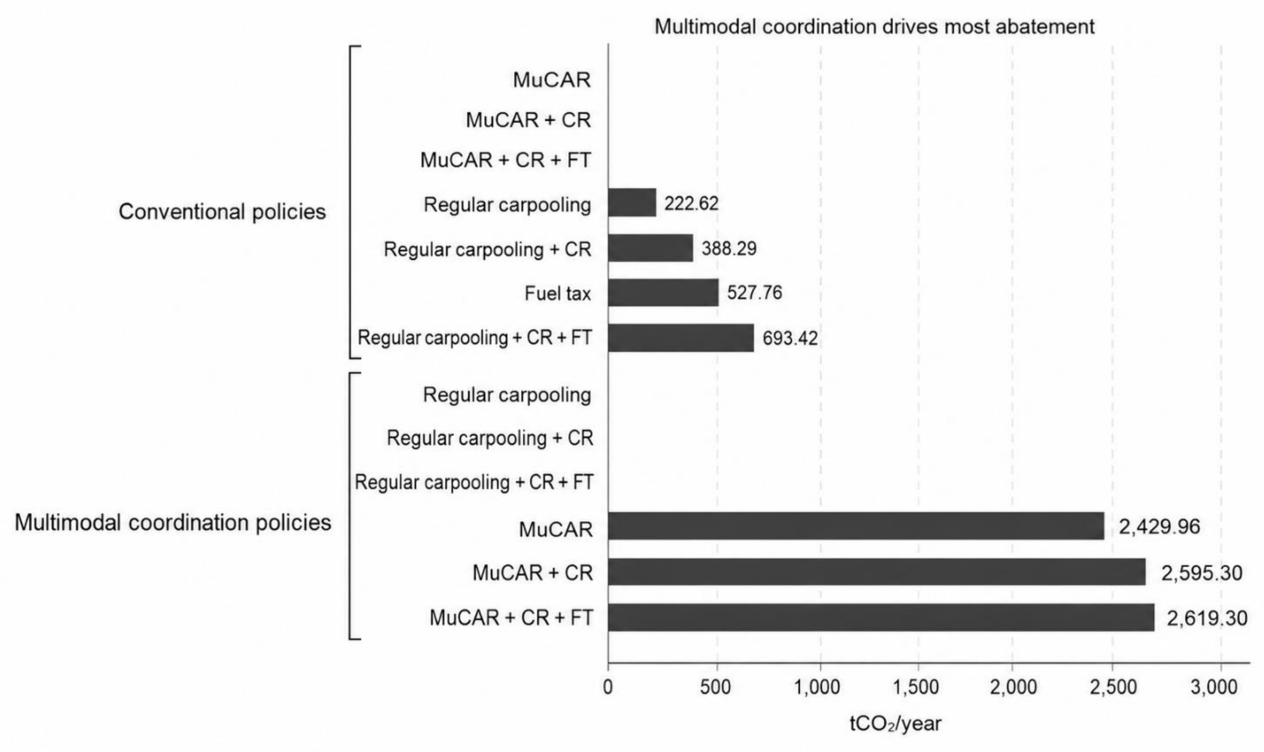

Figure 4. Annual CO_2 emission reductions under conventional and multimodal coordination policy scenarios

5.3. Welfare and abatement cost comparison

We assess the welfare implications of transport decarbonization policies by calculating: (i) changes in users' generalized travel costs, (ii) budgetary impacts on the public sector, and (iii) the total social cost associated with emissions reductions. The average abatement cost is defined as:

$$AC = \frac{\Delta \text{Total Cost}}{\Delta E}$$

and is expressed in €/tCO_2. Table 2 also reports the public and private cost components separately, allowing the distributive effects of each policy to be identified. The results reveal substantial heterogeneity across policy configurations. Regular carpooling generates 222.62 tCO_2/year of emissions abatement, while the addition of carbon pricing (CR) and fuel taxation (FT) increases the reduction to 388.29 and 527.76 tCO_2/year, respectively. The combined Regular carpooling + CR + FT scenario achieves 693.42 tCO_2/year of abatement but is associated with a positive total cost of €1.35 million per year, corresponding to an abatement cost of €1,944.01/tCO_2. This indicates a substantial economic burden relative to the additional environmental gains achieved by combining the three instruments.

By contrast, the MuCAR scenarios achieve substantially larger emissions reductions, ranging from 2,429.96 tCO_2/year for MuCAR alone to 2,619.30 tCO_2/year under the combined MuCAR + CR + FT configuration. Importantly, all three MuCAR-based configurations generate net welfare gains, with total costs of −€7.43 million, −€6.54 million, and −€2.63 million per year, respectively. Their corresponding abatement costs are −€3,058.57/tCO_2, −€2,519.93/tCO_2, and −€1,004.93/tCO_2. The negative abatement costs indicate that these emissions reductions are achieved alongside net reductions in total social costs rather than requiring additional resources.

Table 2. Welfare and abatement cost comparison across scenarios

Scenario	Annual abatement (tCO_2)	Δ Consumer cost (€ / year)	Δ Public cost (€ / year)	Δ Total cost (€ / year)	Abatement cost (€/tCO_2)
Regular carpooling	222.62	-626,4	-52,518	-678,918	-3,049.67
Regular carpooling + CR	388.29	-1,092,533	160,783	-931,75	-2,399.62
Regular carpooling + FT	527.76	46,308	-39,403	6,905	13.08
Regular carpooling + CR + FT	693.42	9,285,959	-7,937,946	1,348,013	1,944.01
MuCAR	2,429.96	-6,663,297	-768,896	-7,432,193	-3,058.57
MuCAR + CR	2,595.30	-7,129,430	589,468	-6,539,962	-2,519.93
MuCAR + CR + FT	2,619.30	4,142,245	-6,774,449	-2,632,203	-1,004.93

Notes: Negative values indicate welfare gains. Public costs include fiscal impacts adjusted by the opportunity cost of public funds.

Conversely, as illustrated in Figure 5, the Mu-CAR scenarios occupy the most favourable region of the efficiency–welfare space, combining substantially higher emissions reductions with large net welfare gains. This performance reflects significant reductions in generalized travel costs and suggests that the main benefits arise from reducing coordination frictions and improving the integration of multimodal transport options, rather than from stronger price signals alone. The comparison between Mu-CAR and its extensions with pricing instruments is particularly informative: adding CR increases annual abatement only marginally, from 2,429.96 to 2,595.30 tCO_2, while reducing the net welfare gain from €7.43 million to €6.54 million per year. Adding FT on top of Mu-CAR + CR further increases abatement only slightly, to 2,619.30 tCO_2/year, while substantially reducing the net welfare gain to €2.63 million per year. This pattern suggests diminishing returns from additional pricing instruments once coordination frictions have already been substantially reduced through Mu-CAR.

Overall, the results indicate that, in low-density areas, the effectiveness of transport decarbonization policies depends not only on the strength of monetary incentives but, importantly, on the ability to coordinate mobility options and reduce the frictions associated with multimodal travel. In this respect, Mu-CAR achieves substantially greater emissions reductions while simultaneously generating net welfare gains, whereas conventional carpooling and pricing combinations tend to deliver smaller environmental benefits and, in some configurations, impose significant net social costs.

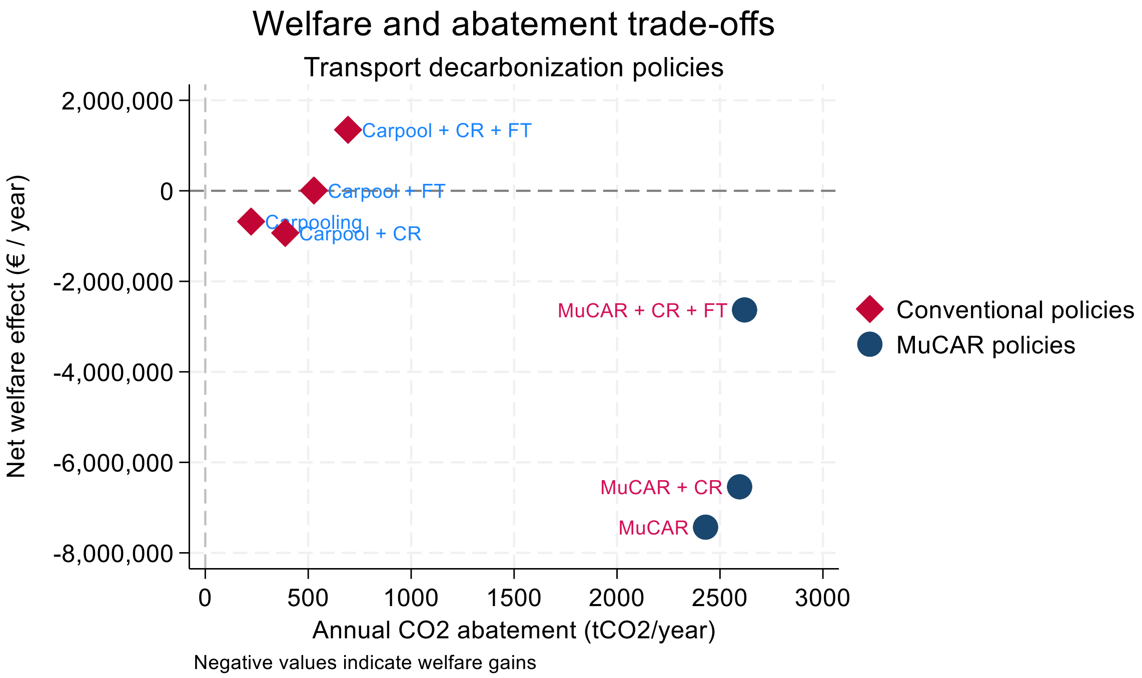

Figure 5 . Coordination-Driven Mobility Regimes Shift the Welfare–Abatement Frontier

6. Sensitivity analysis

While the preceding results indicate a clear aggregate advantage of Mu-CAR-based scenarios in terms of emissions reductions and welfare outcomes, these average results do not reveal the extent to which policy performance depends on key model assumptions. A one-at-a-time (OAT) sensitivity analysis was conducted to assess the relative influence of the main model parameters on both environmental and economic outcomes. Under this approach, each parameter was independently varied across its predefined range while all other parameters were held constant at their baseline values. The sensitivity of each model output to parameter p_i was quantified as the absolute range of variation in the resulting outcome:

$$S_i = \max(Y_{p_i}) - \min(Y_{p_i})$$

where Y_{p_i} denotes the model outcome obtained by varying parameter p_i over its specified range while keeping all other parameters constant. A larger sensitivity range indicates a greater influence of the corresponding parameter on the model outcome.

The sensitivity analysis reveals distinct patterns for CO_2 emissions avoided and abatement costs across policy scenarios (Table 3 and Fig.6). For CO_2 emissions avoided, distance is consistently the dominant parameter, with sensitivity values ranging from 872.97 under RC + CR to 2,465.34 under Mu-CAR + CR + FT, and exceeding 2,287 across all Mu-CAR-based scenarios. As illustrated in Fig. 6(a), increasing travel distance leads to opposite trends between the RC- and Mu-CAR-based scenarios: CO_2 emissions avoided increase substantially under Mu-CAR policies, whereas they decline under RC scenarios. In contrast, G1[8] and vehicle year have comparatively limited effects on CO_2 emissions avoided. G1 has no influence in the standalone RC and Mu-CAR scenarios but reaches 36.60–41.85 when CR and FT are introduced, while vehicle year ranges from only 0.64 to 7.45. Overall, uncertainty in estimated CO_2 reductions is therefore driven primarily by travel distance rather than by vehicle characteristics or G1.

The sensitivity pattern differs markedly for abatement costs. Distance remains influential, but its effect is highly scenario-dependent, peaking at 19,367.49 under RC + CR + FT. This pronounced sensitivity is clearly illustrated in Fig. 6(b), where abatement costs under this scenario decrease sharply as travel distance increases, unlike the comparatively moderate variations observed for the other policy configurations. Other parameters also become more

[8] The percentage of individuals in group G1 (those sensitive to incentives)

relevant: vehicle year reaches sensitivities of 79.89 under RC + CR and 73.07 under Mu-CAR + CR + FT, while G1 is generally negligible but reaches 735.55 under RC + CR + FT. Thus, whereas environmental outcomes are overwhelmingly determined by travel distance, abatement costs depend on a broader and more scenario-specific combination of mobility-related, vehicle, and policy parameters.

The particularly strong distance sensitivity observed under RC + CR + FT warrants further interpretation. Figure 6(b) shows that abatement costs decline sharply as travel distance increases in this configuration, which may be misleading and should therefore be interpreted with a lot of caution. Indeed, both the cost component entering the numerator and the amount of avoided CO_2 in the denominator decline with distance, but the numerator decreases much more rapidly, resulting in the observed strong decline in the abatement-cost ratio. This pattern is consistent with the progressive weakening of regular carpooling as travel distance increases, which reduces the environmental performance of the RC-based configuration (see Figure 6(a), which illustrates that CO_2 abatement declines under RC-based configurations but increases under Mu-CAR-based configurations). Hence, the lower abatement cost at longer distances should not be interpreted as an improvement in policy effectiveness, meaning that RC configuration would allow delivering more CO_2 abatements at lower cost. On the contrary, this result illustrates the strong reduction in carpooling under regular configuration (whereas carpooling still rises under Mu-CAR configuration, as distance increases), which explains the sharp decline in the cost (numerator). Accordingly, the lower carpooling leads to a decline in the cost that it is even faster than the observed abatement reduction (denominator), which explains the downward effect in the abatement cost. That is why the downward trend in the abatement cost should not be interpreted as an evidence of improved policy performance, but, rather, this demonstrates that the environmental performance of regular carpooling weakens as travel distance increases.This divergence highlights an important implication for policy evaluation: environmental performance and abatement-cost efficiency can respond differently to the same underlying parameter, particularly when policy instruments interact with alternative mobility structures.

***Table 3**. Sensitivity ranges of CO_2 emissions avoided and abatement costs under alternative policy scenarios*

CO_2 emissions avoided under policy scenarios						
Parameter	**RC**	**RC + CR**	**RC + CR + FT**	**Mu-CAR**	**Mu-CAR + CR**	**Mu-CAR + CR + FT**
Distance	1028,71	872,97	2152,63	2287,29	2443,01	2465,34
G1	0	36,6	41,78	0	36,6	41,85
Vehicle year	0,64	1,12	1,43	6,73	7,17	7,45
Abatement cost under policy scenarios						
Parameter	**RC**	**RC + CR**	**RC + CR + FT**	**Mu-CAR**	**Mu-CAR + CR**	**Mu-CAR + CR + FT**
Distance	0,013	1741,87	19367,49	377,59	2429,99	2120,28
G1	0	0,0002	735,55	0	2,65	49,07
Vehicle year	0,68	79,89	43,03	0,88	66,52	73,07

Note : Sensitivity values represent the absolute range of variation in the corresponding model outcome resulting from changes in each parameter over its predefined range, while all other parameters are held constant at their baseline values

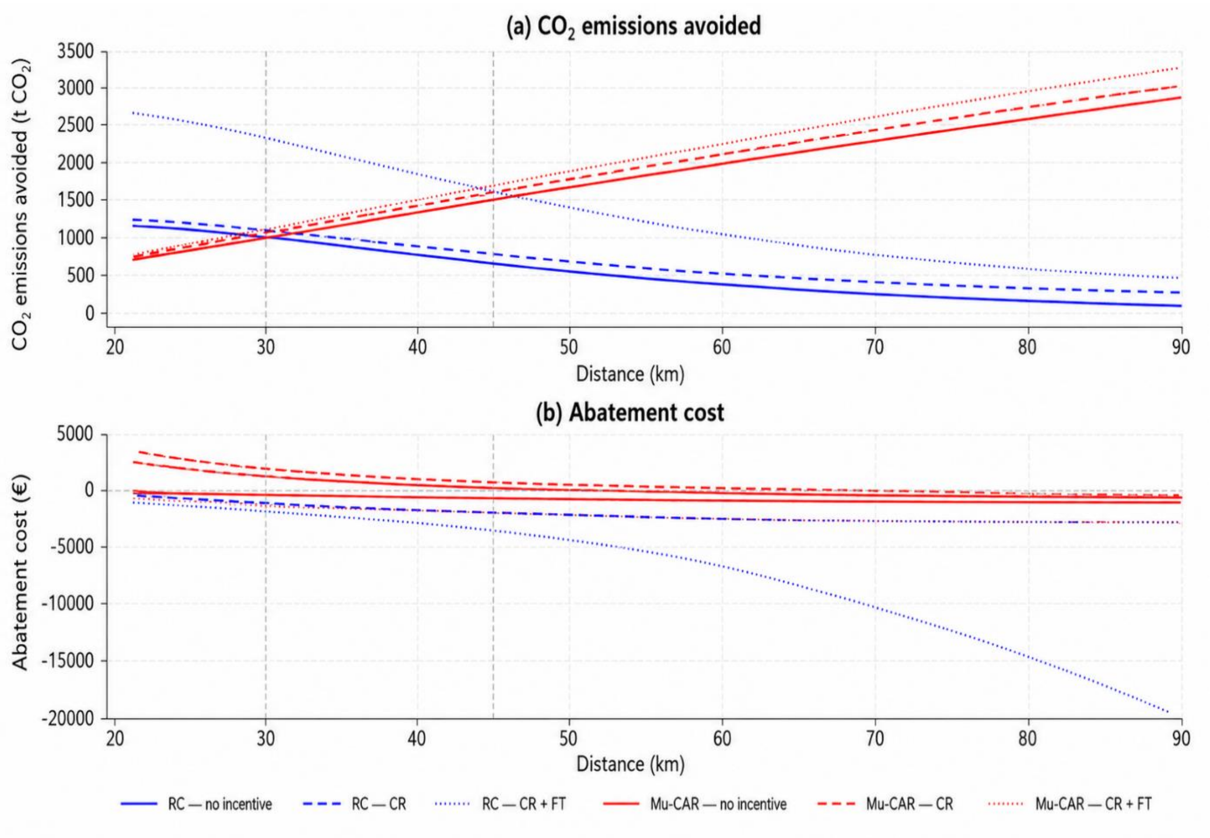

***Figure 6**. Effects of travel distance on (a) CO_2 emissions avoided and (b) abatement costs under alternative RC and MuCAR policy scenarios.*

7. Conclusion

This study examined the roles of pricing instruments and multimodal coordination in transport decarbonization in low-density territories. While pricing policies and regular carpooling produce limited changes in modal shares and CO_2 emissions, Mu-CAR induces a structural shift from solo driving towards carpooling and public transport, achieving 2,429.96 tCO_2 of annual abatement compared with 222.62 tCO_2 under regular carpooling. Mu-CAR-based scenarios also generate net welfare gains and negative abatement costs, whereas additional pricing instruments provide limited incremental emission reductions while reducing welfare gains.

Sensitivity and break-even analyses further show that travel distance is the main driver of environmental performance and that Mu-CAR's economic and environmental advantages do not necessarily occur over the same distance ranges. Overall, transport decarbonization in low-density territories depends not only on price signals but fundamentally on the coordination architecture of mobility systems. By reducing intermodal frictions, intelligent multimodal coordination can reshape mobility equilibria and facilitate lower-carbon travel. Conceptually, the study extends the Avoid–Shift–Improve framework by identifying multimodal coordination as an enabling mechanism for environmental and welfare improvements.

Acknowledgements

This work has been supported by the EIPHI&TRANSBIO Graduate Schools (contracts ANR-17-EURE-0002&ANR-20-SFRI-0008) and Bourgogne-Franche-Comté Region. The authors have benefited from the support of the REEL.i chair and Réseau EDEN.i, under the aegis of the FC'INNOV Foundation of University Marie et Louis Pasteur.

Reference

ADEME (2025). Évolution du taux moyen d'émissions de CO2 en France. Accessed: 2025-06-26.

Astier, N., Bouquet, P.-F., Lambin, X., 2023. Riding together: eliciting travelers' preferences for long-distance carpooling. Available at SSRN 4360029.

Bakker, S., Dematera Contreras, K., Kappiantari, M., Tuan, N.A., Guillen, M.D., Gunthawong, G., Zuidgeest, M., Liefferink, D., Van Maarseveen, M., 2017. Low-carbon transport policy in four ASEAN countries: Developments in Indonesia, the Philippines, Thailand and Vietnam. Sustainability 9, 1217.

Bakker, S., Zuidgeest, M., De Coninck, H., Huizenga, C., 2014. Transport, Development and Climate Change Mitigation: Towards an Integrated Approach. Transport Reviews 34, 335–355.

Banister, D., 2011. The trilogy of distance, speed and time. Journal of Transport Geography 19, 950–959.

BlaBlaCar (2019). Zero empty seats: A study into BlaBlaCar's environmental contribution. Accessed: 2025-06-26.

Cascajo, R., Garcia-Martinez, A., Monzon, A., 2017. Stated preference survey for estimating passenger transfer penalties: design and application to Madrid. Eur. Transp. Res. Rev. 9, 42.

Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (CEREMA) (2024, December). Nord Franche-Comté: la voiture toujours reine malgré un recul des déplacements. Le Trois. Accessed June 26, 2025.

Delhomme, P., Gheorghiu, A., 2016. Comparing French carpoolers and non-carpoolers: Which factors contribute the most to carpooling? Transportation Research Part D: Transport and Environment 42, 1–15.

Ferguson, E., 1995. Demographics of carpooling. Transportation Research Record 142–150.

Fielbaum, A., Pudāne, B., 2024. Are shared automated vehicles good for public-or private-transport-oriented cities (or neither)? Transportation Research Part D: Transport and Environment 136, 104373.

France Stratégie (2021). Les coûts d'abattement – Partie 2 : Transports. Rapport, France Stratégie

Gaspoz Frédéric , Canalda Philippe. "Problème de Covoiturage Flexible et sa Résolution avec l'Algorithme GbFCA à base gloutonne Gaspoz, 26ème congrès annuel de la société française de recherche opérationnelle et d'aide à la décision (ROADEF) ENPC, Institut Polytechnique de Paris, Marne-la-Vallée, France 26-28 février 2025, 2 pages,

Gesellschaft für Internationale Zusammenarbeit (2012). Sustainable Urban Transport: Avoid-Shift-Improve (A-S-I). Accessed: 2025-06-18.

Global Carbon Council (2025). Methodology for Private Carpooling for Long-Distance Inter-Urban Travel. Methodology Report GCCM007

Hammadou, H., Papaix, C., 2015. Policy packages for modal shift and CO2 reduction in Lille, France. Transportation Research Part D: Transport and Environment 38, 105–116.

Hernández, J. F. L. (2025, May). EU Emissions Trading System for buildings, road transport and additional sectors (ETS2). EPRS Briefing PE 772.878, European Parliamentary Research Service, European Parliament.

IPCC (2022). Climate Change 2022: Mitigation of Climate Change, Chapter 10: Transport. Cambridge, UK and New York, NY, USA: Cambridge University Press. Accessed 2025-06-27

Jalali, R., Koohi-Fayegh, S., El-Khatib, K., Hoornweg, D., & Li, H. (2017). Investigating the Potential of Ridesharing to Reduce Vehicle Emissions. Urban Planning, 2(2), 26–40

Joliot Anna, Philippe Canalda, Hakim Mabed, Gérard Cécé. "Premières Résolutions PLNE du Covoiturage Flexible", 26ème congrès annuel de la société française de recherche opérationnelle et d'aide à la décision (ROADEF) ENPC, Institut Polytechnique de Paris, Marne-la-Vallée, France 26-28 février 2025, 2 pages

Julagasigorn, P., Banomyong, R., Grant, D.B., Varadejsatitwong, P., 2021. What encourages people to carpool? A conceptual framework of carpooling psychological factors and research propositions. Transportation Research Interdisciplinary Perspectives 12, 100493.

Konishi, H., Mun, S., 2010. Carpooling and congestion pricing: HOV and HOT lanes. Regional Science and Urban Economics 40, 173–186.

Lah, O., 2015. The barriers to low-carbon land-transport and policies to overcome them. Eur. Transp. Res. Rev. 7, 5.

Laroche, F., 2022. The effect of COVID-19 on long-distance transport services in France. Regional Science Policy & Practice 14, 41–61.

Laroche, F., Schemeleva, K., 2026. Exploratory study of long-distance carpooling supply and public financial incentives: The case of France. Research in Transportation Economics 116, 101734.

Le Goff, A., Koning, M., Monchambert, G., Marchal, C., Ray, J.-B., 2025. Promoting urban carpooling: a social cost approach based on the Lyon case study. Les Cahiers Scientifiques du Transport/Scientific Papers in Transportation 84.

Le Goff, A., Monchambert, G., Raux, C., 2022. Are solo driving commuters ready to switch to carpool? Heterogeneity of preferences in Lyon's urban area. Transport Policy 115, 27–39.

Le Goff, A.-D. (2023). Carpooling for daily trips: individual behavior and challenges for public policies. Ph. D. thesis, Université Lumière-Lyon II

Montpellier Méditerranée Métropole (2024). Carpool with BlaBlaCar Daily. Accessed: 2025-06-26

Morris, M.D., 1991. Factorial Sampling Plans for Preliminary Computational Experiments. Technometrics 33, 161–174.

Salihou, F., Bulteau, J., Le Boennec, R., Berrada, J., Da Costa, P., 2026. The impacts of combining incentives on carpooling for commuting in the Paris region. Journal of Environmental Planning and Management 69, 649–675.

Saltelli, A., Ratto, M., Tarantola, S., Campolongo, F., 2005. Sensitivity Analysis for Chemical Models. Chem. Rev. 105, 2811–2828.

Schäfer, A.W., Yeh, S., 2020. A holistic analysis of passenger travel energy and greenhouse gas intensities. Nature Sustainability 3, 459–462.

Shaheen, S.A., Cohen, A.P., 2013. Carsharing and Personal Vehicle Services: Worldwide Market Developments and Emerging Trends. International Journal of Sustainable Transportation 7, 5–34.

Tønnesen, A., Knapskog, M., Rynning, M.K., Groven, K., 2022. Planning for climate-friendly transport in Norwegian rural areas. Transportation Research Part D: Transport and Environment 102, 103156.

Wadud, Z., Adeel, M., Anable, J., 2024. Understanding the large role of long-distance travel in carbon emissions from passenger travel. Nature Energy 9, 1129–1138.

Wang, Y., Monchambert, G., 2026. Does subsidy increase the use of carpooling via platforms? The case of short-distance carpooling in France. Transportation Research Part A: Policy and Practice 203, 104767.

Wardman, M., Chintakayala, V.P.K., de Jong, G., 2016. Values of travel time in Europe: Review and meta-analysis. Transportation Research Part A: Policy and Practice 94, 93–111.

Verra, V. C. S. (2025). Methodology for Carpooling. Methodology Report VM0028.
Yu, J., Zhang, H., Dong, X., Shen, J., 2024. The impact of street greenery on active travel: A narrative systematic review. Frontiers in public health 12, 1337804.
Zamora, J.C.P., 2014. The “avoid-shift-improve” model: A powerful planning tool for transportation schemes with low GHG emissions. MIPALCON 141.
Zhang, X., Guan, H., Zhu, H., Zhu, J., 2019. Analysis of travel mode choice behavior considering the indifference threshold. Sustainability 11, 5495.

CHAIR REEL.i

Renewable
Energy
Economics and
Law
for .industry

The **REEL.i Chair** is hosted by **Université Marie et Louis Pasteur** under the auspice of the **FC'INNOV Foundation** and with the support of **Origo**.

Associated to the **Réseau EDEN.i** research network, REEL.i adopts a multidisciplinary approach to analyze the economic and legal questions related to renewable energy, with a special interest for energy decentralization in industrial territories.