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Promoting urban carpooling: a total social cost approach based on the Lyon case study (Working Paper)

Alix Le Goff¹, Martin Koning², Guillaume Monchambert¹, Clément Marchal³ & Jean-Baptiste Ray³

Abstract

This paper investigates the impacts of several implementations of daily mobility policies and external shocks on social costs, with a particular focus on carpooling. This social cost is calculated considering consumer's cost, external costs, as well as the expenses and incomes of public authorities and private companies. Four transport modes are considered: solo driver, carpool driver, carpool passenger and public transport. A modal choice model is then applied to trips with 6,287 different origin-destination of the eastern Lyon area. Simulations of time-gain and monetary scenarios are then realized to observe impacts on demand and consequently on the other parameters affecting the social costs. Our results show that consumer's costs explain the majority of the total social cost. Values commonly used for externalities barely impact the social cost in the simulations and traffic reduction measures impact more public and private revenues than they reduce externalities, leading to higher total social costs. Moreover, results illustrate significant variations at the geographical scale, depending on the ODs where the policies are applied. These results suggest implementing daily-carpooling incentives should be decided conscientiously considering the local context.

JEL Codes: D61, D62, L92, L98

Keywords: Social cost analysis, Transport policies, Carpooling, Daily mobility

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1. Introduction

In contemporary society, the sustainability and efficiency of transportation systems have become critical concerns due to the predominance of individual vehicles' usage. Solo driving represents a substantial majority of car use for commuting trips nowadays. In France, the last national survey (SDES, 2021) shows that 88% of car commuting trips⁴ are made alone.

Promoting carpooling is often cited as a solution to reduce traffic nuisances in daily mobility, such as pollution or greenhouse gas emission (Shaheen et al. 2018). Particularly, it could mitigate congestion and parking problems considering space savings that could be achieved with a better allocation of travelers in the cars.

However, it is now well-known that promoting carpooling has some limitations, such as some undesirable rebounds effects (Coulombel et al., 2019). Indeed, promoting carpooling could decrease car kilometric cost and increase its attractiveness. Consequently, it could lead to an undesired modal shift from public transportation, to higher trip distances or to an induced demand that could increase the number of car-kilometers and hence, increase car external costs.

The main objective of this paper is to evaluate how incentive policies to encourage carpooling or external shocks impact the collectivity. We will therefore test how consumer costs, external costs, public and private profits vary across several scenarios; such as time gain for carpoolers, raise of fuel prices or variations in prices paid or received by carpoolers. To measure differences between scenarios tested, we use a cost-benefit analysis method which have been widely used in transport economics literature, whether to estimate efficiency of policy measures – e.g. Wang et al. (2015) for cordon toll and higher bus frequency in the case of Madrid – of an infrastructure – e.g. Sisiopiku et al. (2010) for HOV-lanes – or of a transportation mode – e.g. Litman, (2015) for public transport or Becker et al. (2020) for MaaS. In our case study, we estimate the total social cost of transport considering four main components: consumers' costs, external costs, public authorities costs, and private operator costs.

These components are determined through the transport supplies and flows obtained for 6,287 different origin-destination (O-D) in the eastern Lyon area, France. We then estimated modal shares thanks to a modal choice model calibrated on a stated preference survey realized in 2019 among 2,151 commuters of the Lyon area. Once modal shares obtained, we are able to

⁴ Trips shorter than 80 kilometers for professional purposes.

infer for any O-D costs and/or revenues of the four components of social cost for each scenario. This allows us to compare scenarios through the total social cost calculated across the whole considered zoning. Another result of interest of this study is to consider the impact of one measure on several O-Ds and analyze its spatial heterogeneity.

First results indicate consumer's cost constitutes the main component of the social cost. External costs seem to have a very low impact on the social cost in the simulations. Traffic reduction measures also appear to impact more public and private revenues than they reduce external costs, leading to higher total social costs. Moreover, results indicate significant variations depending on the trips where the policies are applied.

Next section presents the study background. Section 3 introduces the method while section 4 describes the data used. Section 5 present the scenarios tested. Results are displayed in section 6, discussed in section 7 with their limitations and section 8 concludes.

2. Background

2.1. Historical and local context

France is not exempt from the congestion problems common to all large cities in urbanized countries. As an example, Paris is one of the most congested cities in the world with 138 hours lost in congestion in 2022 according to INRIX (2022). Furthermore, car traffic also causes parking congestion. As pointed out by Héran & Ravallet (2008), a car requires an average of 40m² for parking. Carpool for commuting trips has the potential to reduce these problems by enabling better allocation of people in cars, which can also potentially reduce the number of cars – and hence space – needed.

Carpooling in France is now very popular, thanks to the success of the BlaBlaCar platform, which is widely used for long-distance travel. However, carpool is far less popular for short-distance trips, which can be explained by several factors. Indeed, detours or waiting for a carpooler account for a much larger proportion of travel time for short trips. Furthermore, this effect is accentuated because individuals' time constraints are potentially stronger for short trips. The optimal spatial matching between carpool drivers and passengers can also be easily missed (Furuhata et al., 2013). Last but not least, public transport is much more competitive for short than for long distances in France, which makes carpooling for commuting trips less attractive than it is for long distances.

In recent years, French public authorities have been trying to democratize the practice for commuting trips. For example, a law was passed in 2015 to enable companies to facilitate carpooling for their employees⁵. This is coupled with a tax exemption for employees who organize carpooling to work⁶. Locally, public authorities are also setting up reserved parking lots or matchmaking platforms, as well as partial or total reductions in motorway tolls for carpoolers. In the case of Lyon and a few other cities in France, a new infrastructure has just been introduced. A High-Occupancy-Vehicle (HOV) lane has been implemented on the city's main north-south route in 2021. One of the three (or four) existing traffic lanes has therefore been reserved for carpool defined as vehicles with two or more occupants. While this system of reserved lanes is common in North America, the only reserved lanes in France prior to 2020 were bus lanes.

2.2. The Ecov supply (LANE)

Since the French are more accustomed to public transport than carpooling, a start-up named Ecov had the idea of creating a carpooling service similar to public transport. Carpooling lines are created, with predefined stops and station commodities where passengers can check in and wait for their carpooler as they would do with a high frequency public transportation.

One of these routes – called LANE – links Lyon, 1.4M inhabitants, to Bourgoin, a town of around 50,000 inhabitants, 50 kilometers away to the south-east. The two towns are directly linked by a highway, as shown on Figure 3.1.

With this service, passengers are guaranteed to find a driver within 20 minutes⁷. Drivers are informed that a passenger is waiting by a traffic sign upstream of the stop. Each passenger transported earns them €2, whatever the traveled distance.

The idea here is to analyze the impact of the introduction of the service and new incentives or price levels for carpooling, both on individuals and on the local community, by using the method presented in the next section.

⁵ https://www.legifrance.gouv.fr/jorf/article_jo/JORFARTI000031044948

⁶ <https://www.ecologie.gouv.fr/covoiturage-en-france-avantages-et-reglementation-en-vigueur>

⁷ If the 20-minute delay is exceeded, the start-up will pay a taxi to get them to their destination.

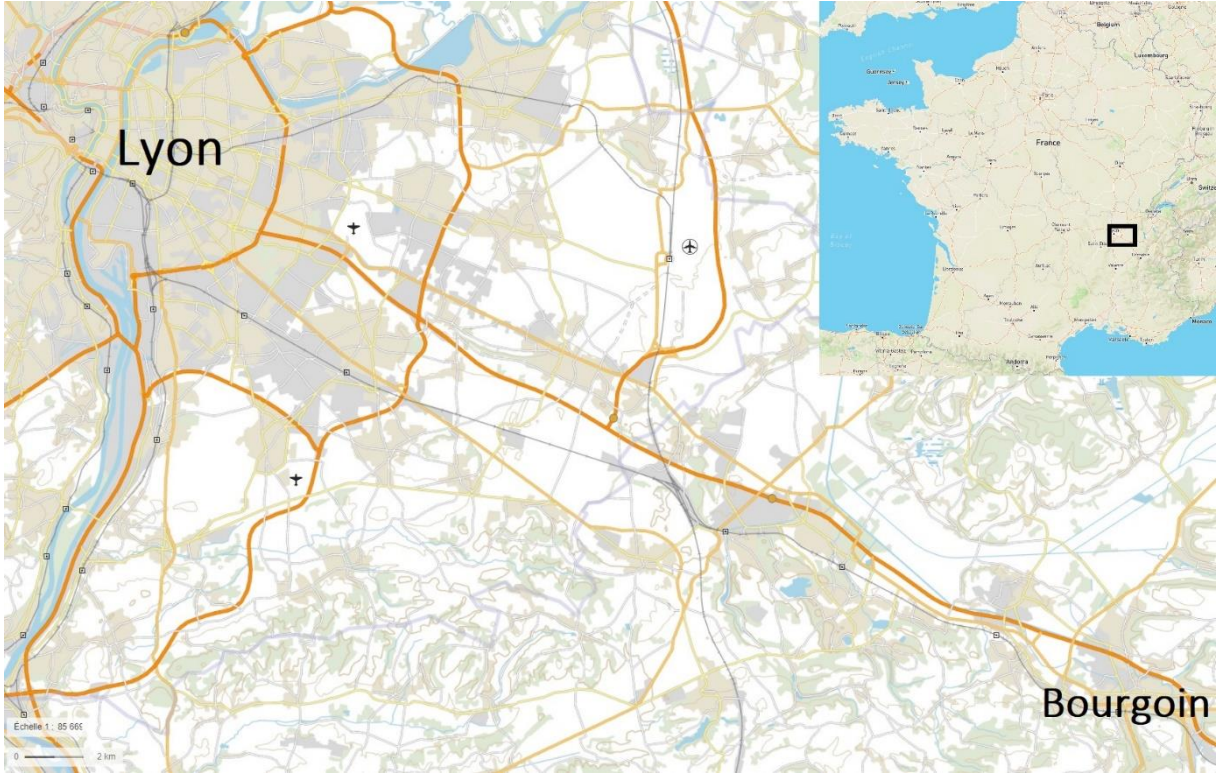


Figure 3.1 : The south-eastern Lyon region

3. Method

The objective in this paper is to estimate the total social cost of people's travel and its variations according to different policies. To obtain this total social cost, we first define its different components and detail the method used to sum them up for a given zoning and scenario. In this section, we only mention the method used. The details concerning numbers selected are provided in Data

3.1. Social cost components

The total social cost is here made of four main aggregates: the trip generalized cost for consumers, the cost of the different externalities caused by the transportation modes, the public authorities' deficit and finally the deficit of the private companies. In most of the cases, public or private deficits are negative (i.e. their revenues are superior to their expenses) and the social cost is consequently reduced. This composition of the social cost is illustrated by the following equation:

$$\begin{aligned}
 \text{Social Cost} = & \sum_k \sum_j \text{Consumers' cost}_{kj} + \text{External costs}_{kj} + \text{Public Deficit}_{kj} \\
 & + \text{Private Deficit}_{kj}
 \end{aligned} \quad (1)$$

Where k stands for the origin-destination (O-D) and j for the transport mode. The social cost estimated for an area is hence the sum, for every mode and for every O-D in the area, of four components that are detailed in following subsections. To determine the social cost, we must first define the transport supplies. In this study, we will consider four modes: solo driver, carpool driver, carpool passenger and public transport. These supplies are defined for several origin-destinations (O-D) in the eastern Lyon area.

3.1.1. Consumers' cost

The cost of the trip for consumers includes two main categories. The first one is the monetary cost of the trip. This includes gasoline, possible toll pricing and fees or payment for the carpool.

The second part of the cost supported by consumer is the time spent. The detail of the consumer's cost in O-D k for mode j is provided by the following equation:

$$\text{Consumers' cost}_{kj} = \text{Time costs}_{kj} + \text{Toll}_{kj} + \text{Fuel}_{kj} + \text{CPprice}_{kj} + \text{Ticket}_{kj} \quad (2)$$

Where *Toll* and *Fuel* represents respectively the monetary prices paid for tolls and fuel for the trip. *CPprice* represents the amount paid (or received if negative) to access or offer the carpool service. *Ticket* represents the price paid to access to public transport.

Time costs are the costs associated to the different stages of the trip. They respectively stand for free flow travel time, congested travel time, waiting time, detour time, access time, egress time and connection time. According to Wardman et al. (2016) meta-analysis on the topic, the value of time (VoT) varies depending on the stage of the trip. As an example, they found waiting time is valued around twice higher than time spent in the vehicle. In this paper, we will follow the valuation of the different stages of the trip recommended by French public authorities for cost-benefit analysis (Quinet, 2014) for France.

The on-board values of time recommended vary depending on the distance travelled. Therefore, the value of time is adjusted according to the distance of the trip for each O-D pair in the database. The value of time for the carpool driver is considered identical to the one of driver alone in its car. Therefore, the time spent alone on the trip (before the carpooler is picked up), during the detour and the time effectively carpooled (i.e. when both driver and passenger share the car) are grouped together and multiplied by the value of time on board. The value of time on board for the carpool passenger will also be considered equal to the one of car drivers. This value is then multiplied only by the time effectively carpooled, i.e. without considering

waiting, access or egress times. When considering other stages of the trip, Quinet (2014) recommends formulas that directly depends on the on-board VoT for each mode. These formulas are detailed in the data section. Moreover, sensitivity tests based on VoTs deduced from our own stated preference experiment will be presented in section 6.6.

Consumer's cost is hence calculated for each mode depending on its associated times and cost (e.g. *Ticket* is null for all alternatives except public transport). The sum of different time spent on the trip multiplied by their respective values allow us to estimate the time cost supported by a consumer, for each mode and every O-D pair.

3.1.2. *External cost*

The costs due to externalities in O-D k for mode j contain several elements presented in the equation 3 below:

$$Externalities_{kj} = Local\ Pollutants_{kj} + Noise_{kj} + Accidents_{kj} + Climate\ Change_{kj} \quad (3)$$

At first, we focus on the costs related to local pollution. The local pollutants (NOX, PM10, NH3, SO2) valuation is given in the handbook on the external costs of transport (European Commission, 2020) which gives values in €/kg.

We will therefore consider the quantity of these pollutant emitted according to the Computer Program to calculate Emissions from Road Transport (COPERT, see EMEP/EEA 2019) data. To apply these values to our data, we first need to know the vehicle speed since according to the COPERT calculations it is an input of the quantity of pollutants emitted.

The emissions of local pollutants can also vary depending on the vehicle fleet. To take this parameter into account, we use the values of the French vehicle fleet in 2020, excluding hybrid vehicles because they are not included in the EU Commission handbook values. We therefore use a car fleet differentiated by two euro-norms (euro-3 and euro-6) and by type of fuel used (gasoline, diesel and electric), leading to five categories.

Once speeds and vehicle fleet obtained, COPERT estimates the kilometric emissions (in g/vkm). These values are then multiplied by the number of vehicle-kilometers (i.e. distances travelled as solo or carpool drivers) to obtain the quantity of pollutants emitted.

For the case of NOx, the EU Commission handbook gives two different values depending on whether they are emitted in or outside the city. As a consequence, we need to know the distance driven on the different road categories. Since most of our trips in this case

study connect urban centers, we assume that 75% of the non-highway distances are on "urban" roads and 25% on "non-urban" roads. For the valuation of NOx, we consider distances travelled on highways, approximated on toll prices (see 4.3.2), are "non-urban" roads.

The sum of all these components gives the value of the local pollutant emissions for one vehicle, which must be multiplied by the flows, considering both solo drivers and carpool drivers, to obtain the total local emission cost.

The climate change cost is similarly obtained by calculating the total volume of CO2 emitted thanks to COPERT. This value is then multiplied by the climate change avoidance cost defined by the European Commission (2020).

Finally, regarding noise and accidents, we will consider values found in the EU Commission handbook and in Bergerot et al. (2021) where values are given in vkm⁸.

3.1.3. Public Deficit

Public authorities' budget in O-D k for mode j is affected in this study by the elements in the equation below, presented in a cost perspective as public expenses.

$$Public\ Deficit_{kj} = OCPF \times (Road\ Wear_{kj} + Ptfm\ Subv_{kj} - PT_{kj} - Fuel\ Tax_{kj} - Corp\ Tax_{kj}) \quad (4)$$

The opportunity cost of public funds, $OCPF$, expresses a loss in individuals' satisfaction due to the fact that taxes must be raised to fund public expenditures when money is invested by public authorities.

Public authorities are responsible for compensating wear and tear on public (non-tolled) roads, which we will consider to be the entire non-highway network in this study. Public finances are also assumed to have several sources of income through fuel taxes and corporate income taxes. Public transport finance, PT , is also here presented negatively – i.e. as an income – because only their revenues will vary across the scenarios tested. Indeed, we will consider the public transport supply will remain constant. Consequently, the public transport operating costs included in PT are considered invariant between scenarios and hence, only the differences in revenues from tickets will be observed. Finally, another potential expense is added to the public

⁸ When values in literature are given in passenger-kilometer (pkm) and not in vehicle-kilometer (vkm), we will assume a 1.2 car occupation rate, and apply this factor when necessary to do the conversion.

budget. Some scenarios, developed in section 5, provide subsidies to implement and operate a carpool platform. These subsidies are therefore included in the public authorities' budget.

3.1.4. Private Deficit

$$\begin{aligned} \text{Private Deficit}_{kj} & \\ &= \text{Highway Road Wear}_{kj} - \text{Highway Tolls}_{kj} - \text{Platform Profits}_{kj} \end{aligned} \quad (5)$$

Profit of the highway companies

In the same way as before, we calculate the deficit of private companies in O-D k for mode j . As we reason in terms of deficit, revenues are considered negatively and expenses positively. In our case, highways earnings come from tolls, and expenses from the road wear. We will consider here only the number of car-kilometers on the highway to make the road wear cost calculation.

To calculate distances travelled on highways, we base ourselves on the toll prices. Thanks to the available highway tariff grids, we have at our disposal the prices paid and the freeway distance used for this price. These values allow us, after regression, to obtain an average price for each kilometer travelled on the highway. We then use the toll price paid by individuals for each O-D to approximate the distance driven on the highway.

Profit of the carpooling platform

For the profit of the carpooling platform, we consider only the prices paid and received by the carpoolers, multiplied by their respective flows. In the reference situation, drivers receive money for agreeing to let individuals ride at the carpooling stations located on their route and passengers pay exactly the same amount. The platform will therefore have no income in the reference situation. In this paper, in each scenario where the profit of the carpooling platform is negative, it is assumed that public authorities compensate this loss with subsidies. The carpooling platform's profit is therefore always positive or equal to zero in our results. Furthermore, it is considered that the transactions are carried out as soon as the carpooling is effective.

3.2. Empirical approach

In this paper, we will consider total social cost as the sum of social costs of each trip realized in the zoning studied for each scenario.

We first define transport supplies in terms of flows, distances, travel times and costs for every O-D in the zoning. They are then used as input to a modal choice model to estimate the

flows for each mode. These modal shares will then allow us to obtain – given the transport supplies and the values found in literature – the different components of the social cost that we just described. The details of models and values used for the calculations are provided in the following section.

The method used is summarized in Figure 3.2 below.

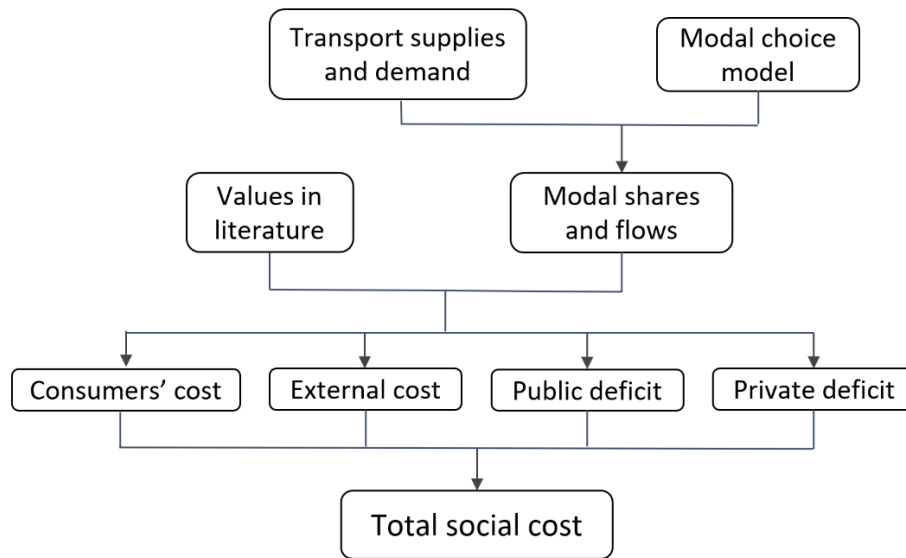


Figure 3.2 : Method summary to obtain total social cost

4. Data

4.1. Transport supplies

The transport supplies and flows on each O-D are based on the MOBPRO database, a national census that aim to survey the professional mobility over territories (INSEE, 2019). Only home-work trips originating in or going to the département of Rhône⁹ were selected. Some city territories are disaggregated according to a 1-km grid to gain precision. In cities divided in 1-km squares, the population distribution on the squares of trips origin is based on the population distribution and the distribution on the squares of trips destination is based on the job distribution. The zoning considered in this study is presented in Figure 3.3.

⁹ Lyon's département

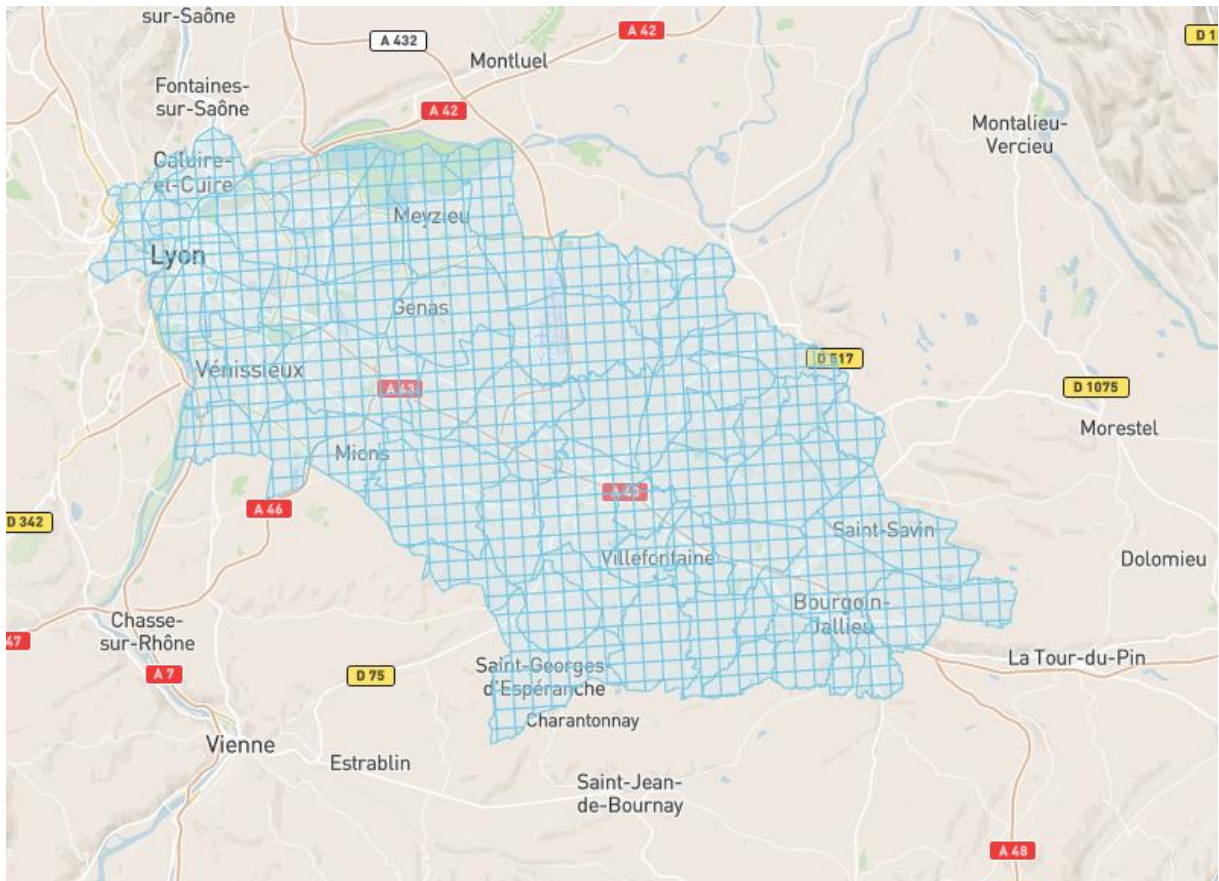


Figure 3.3 : Zoning considered in the survey

Distances are calculated following the car trip from origin to destination, considering the potential detour to a carpool station in the associated modes.

Toll costs, free flow and congested travel times are not directly available in open data or via open-source API calls. Therefore, we estimated the congested travel times and mapped the toll costs. An approximate of time lost in congestion was assigned on some sections of the road network to simulate a morning peak hour travel time. These time-lost approximates are derived from averages over Tuesdays in December 2021, excluding school vacations (Google maps API). Waiting times are assumed depending on the mode:

- 5 minutes for public transports, assuming travelers arrange to arrive at the stop shortly before their bus or train
- 7 minutes for carpool passengers, as it is the current average waiting time during peak hours.

Fuel prices are calculated from the distance via an average ratio (MTE, 2019)¹⁰.

4.2. Modal choices

Once transport supplies are defined, we use a stated preference model calibrated through a survey conducted in 2019 on 2,515 commuters (see Le Goff et al., 2022 for more details) to estimate modal shares. Individuals are assumed to make their modal choice by choosing the alternative that provides them the highest utility. Each alternative therefore has its own utility, composed with a systematic and a random part like in the random utility model (Walker & Ben Akiva, 2002). The utility functions of the four modes are defined as follows:

$$U_{ik} = ASC_k + \beta_{tt_k} * TT_{ik} + \beta_{tv_k} * TV_{ik} + \beta_{at_k} * AT_{ik} + \beta_{wt_k} * WT_{ik} + \beta_{dt_k} * DT_{ik} + \beta_{cost} * Cost_{ik} + \beta_{connect_k} * Connection_{ik} \quad (6)$$

Where U_{ik} represents the deterministic part of the individual utility in O-D i for mode k . Each mode is considered to have its own value for alternative specific constant (ASC), in vehicle travel time (TT) and travel time variability (TV), which is considered in this study as the difference between the "empty-road" travel time and the peak hour travel time. AT , WT and DT stand respectively for access, egress, waiting and detour times. $Cost$ represents the monetary cost (net of earnings for carpool drivers) of the alternative and $Connections$ the number of connections in the trip.

Once the modal shares obtained, the flows for each mode can then be estimated for every O-D. Following the results from the modal choice model, the number of carpool drivers often exceed the number of carpool passengers due to individual preferences for the driver mode. The hypothesis we made is that the effective carpool driver share is limited by passengers and that the surplus of drivers (those who do not find a passenger) finish their trip as solo drivers. The ASC and β values are displayed in Table 1 below.

¹⁰ We use values from the French Ministry of Ecological Transition (MTE). The kilometric value is calculated with the cost and the average vehicle fleet of the year 2021, by extrapolation of the 2015 and 2030 values. The value obtained is 0.0878 €/km.

Table 1: Estimate values for the stated preferences model

Modes	Solo Driver	Carpool Driver	Carpool Passenger	Public Transport
ASC	0 (reference)	0.3575	-0.3488	0.1345
Hitchhike		-0.2441	-0.4299	
Times				
In-vehicle	-0.0349	-0.0457	-0.0411	-0.0322
Variability	-0.0140	-0.0267	-0.0330	-0.0336
Access			-0.0551	-0.0551
Wait			-0.0532	-0.0532
Detour		-0.0538		
Connect_acc			-0.0684	-0.0684
Connect_egr			-0.5364	
Platform effect		0.2441	0.4299	
Cost				-0.0895 (all modes)

Notes: Hitchhike represents the difference in utility between a hitchhiking situation (i.e. no platform) and a situation with a carpooling platform. Time parameters are estimated as the disutility of one minute. The cost parameter is independent from mode.

We will consider the number of individuals and flows remain unchanged between the scenarios. These flows and the supplies from the four modes will allow the monetarization of the different components of the total social cost thanks to values found in the literature, as presented in the following subsection.

4.3. Cost structures

4.3.1. Values of Time

We will now detail the values of time used to calculate the social cost. For cars and public transports, Quinet (2014) recommends values that vary depending on the distance as follows.

Table 2 : Values of time in €₂₀₁₆/h depending on the trip distance

distance	d ≤ 20 km	20 km < d ≤ 80 km	80 km < d ≤ 400 km	d > 400km
Mode				
Private car	8.4	$6.5 + 0.096 * d$	$13.6 + 0.006 * d$	16.2
Public Transports	8.4	$4.9 + 0.177 * d$	$20.5 - 0.02 * d$	12.7

*Notes: As an example, the value of time considered for a 50-km trip made in private car will be $6.5 + 0.096 * 50 = 11.3 \text{€}/h$.*

For variability, Quinet proposes considering the gap between the median travel time and the 9th decile and multiplying this gap by 2.5 for constrained trips. This requires knowledge of the distribution of travel times. Here, we only have the "empty" travel time and a peak hour travel time. For the valuation of this travel time variability, we will consider that they are uniformly distributed between the empty travel time and the travel time in peak hour. We will therefore take 40% of the difference between these two times (9th decile - median = 40% for a uniform function) and multiply it by 2.5, since we are dealing with daily trips, mainly to work, that we will therefore consider constrained. This means that this variability can be considered as the difference between the travel time in peak hours and the empty travel time ($40\% * 2.5 = 1$). This time is then multiplied by the value of time of the associated trip.

For the connections, Quinet recommends using twice the value of the travel time. It will be considered that each of the connections of a trip by passenger carpooling or by public transport will last 5 minutes.

In terms of waiting, access and egress times, Quinet (2014) considers that they should be valued the same way as connection times, i.e. twice the value of the time of the associated mode. Detour time is not mentioned in the report and will be valued the same as the value of in-vehicle travel time.

4.3.2. Externalities

To calculate costs due to local pollutants, we need to know the vehicle fleet. In this survey we will consider that vehicle fleet is split into five main categories: petrol eu3 which represent 2% of the fleet, petrol eu6 (21%), diesel eu3 (6%), diesel eu6 (70%) and finally electric vehicles that represent 1% of the total fleet.

The type of road also must be calculated to estimate the local pollutant cost. Depending on where they are emitted, NOx have a different valuation. For instance, we estimate the distance covered on highways. Thanks to the toll grid of the highway company, we estimate by regression that the average toll is 0.11€ for each kilometer driven on the freeway. Giving this number and the level of toll in the transport supply, we can approximate the distance on highways (i.e. 9.1 km driven per € paid on average).

Values for local pollutants are given in the table 14 of the EU Commission handbook in €/kg. The values for pollutants considered in this study are considered in Table 3 below.

Table 3: cost of local pollutant and CO2 in France in €₂₀₁₆/kg

	NOx (rural)	NOx (city)	PM10	SO2	NH3	CO2
Cost	14.8	27.2	24.7	13.9	15.4	0.1

Noise and accidents are valued both thanks to Bergerot et al. (2021). The value for highways is 0.006€/vkm and 0.034€/vkm for urban roads. Accidents are valued on average on all roads at 0.031€/vkm.

Finally, we also want to consider the climate change cost due to CO2 emissions. Considering the table 24 of the EU commission handbook, we obtain a cost of 100€/tCO2 equivalent as specified in Table 3.

4.3.3. *Public and private deficits*

The main expense for public finances and the highway company in this survey will be the cost of road wear. This cost is valued at 0.008€₂₀₁₅/vkm by Bergerot et al. (2021).

Public finances also benefit from revenues, like fuel taxes, approximated to 60% of the fuel cost, which is defined in the transport supply. The corporate income tax also has to be considered. Its value will be assumed at a 25% rate on private profit benefits.

Moreover, we assume a 0.8€ average revenue per public transport user as this represents the average cost per travel for a subscriber in Lyon.¹¹

The operation of the carpool platform has a cost that will be approximated at 200.000€ per year. As we reason in terms of average cost per trip, we consider the total number of trips to approximate this fixed cost per trip made in the zoning. In 2019, there were approximately

¹¹ Considering the €64 subscription fee for working people, halved by the employer, and 40 monthly trips.

80.000 cars per day on the Lyon-Bourgoin main axis¹². Assuming there are potentially several individuals in these vehicles and adding people using public transports, we can reasonably estimate there are 100.000 trips a day on the O-D corresponding to the axis. Considering only work-related journeys, we retain only 42% of traffic according to national data (SDES, 2021). It represents 42.000 trips a day or 9.2 million trips a year in our case. Considering these values, the average operating cost of the platform per trip is around 0.022€.

We do not analyze public transport costs or private fixed costs in this study. This topic is deemed to be outside this study's scope since the transport supply will remain the same across the scenarios tested and hence evolutions will be null.

Furthermore, all expenses and revenues for public finances will be multiplied by 1.2 considering the opportunity cost of public funds, as recommended by Quinet (2014).

4.4. Model calibration and data filtering

To calibrate the modal choice model, we used data from MOBPRO (INSEE, 2019). We compared modal shares observed between private cars and public transport for some O-D in the database to those given by our stated preferences model. The latter globally underestimated public transport modal shares. This led us to test by regression if the values of the different components of the trip were correctly estimated by our model. The result of this regression showed a higher impact of number of transfers on public transport modal share than our model suggested. Furthermore, public transport time variability was certainly overestimated for trips to the city center. Indeed, this time variability was calibrated on route modes whereas most of these trips were done by train. Hence, we raised the impact of a transfer on our utilities, lowered the travel time variability for trips to city center and adjusted the public transport constant to obtain modal shares very close those observed in the MOBPRO census.

The initial database contained slightly less than 300,000 different origin-destinations (O-Ds). We first removed the O-Ds in which the number of flows was critically low – such as 1-km squares with no habitations and/or jobs. We then removed two thirds of the O-Ds conserving for 98% of the total flows in the database. In a second data filtering, we decided to remove any O-D in which the carpool supplies could not be estimated. Thus, we can apply our

¹² According to government data, map of road traffic in Lyon's region - 2019: <https://www.rhone.gouv.fr/contenu/telechargement/50676/279489/file/Carte%202019%20des%20trafics%20routiers%20dans%20le%20Rh%C3%B4ne.pdf>

model, calibrated to estimated modal choice in presence of carpool alternatives, on the remaining O-Ds. The final database we use contains 6,287 O-Ds.

4.5. Descriptive statistics

Descriptive statistics of the transport supplies for an average O-D are presented in Table 4 below. These descriptive statistics underline how heterogeneous the public transport supply is across the O-Ds in our data, with important standard deviations. This heterogeneity across O-Ds is also analyzed and illustrated through three selected O-Ds in the next section (see Table 11).

Table 4: descriptive statistics of an average trip

	Mean	sd
Road distance	35 km	5.5
Of which highways	25 km	5.9
Car travel time	28 min	4.9
PT travel time	37 min	13.8
#PT transfers	0.8	0.5
Access Carpool station	5 min	2.6
Access PT station	13 min	5.9

Notes: Values are weighted by flows and rounded.

5. Scenarios

The idea of building scenarios is to compare results after a supply change to results from the initial point. In our case, we create a LANE situation (i.e. with the implementation of a new carpool platform) which is then affected by time or monetary changes. The supply changes applied in each scenario are detailed in the next subsections.

5.1. Baseline situation and LANE supply

The baseline situation that will be considered in this study will consider both transport supplies and model calibrations described above. It is supposed carpooling trips are done in real-time, without monetary exchange and without a platform to connect carpoolers, i.e., hitchhiking. Meeting points for hitchhikers will be considered at the exact same place as

carpooling stations in other scenarios. This baseline situation will be used to compare the potential gain from the implementation of the LANE service in from the social cost perspective.

In the LANE scenario, a carpooling platform is created, thus improving the carpooling offer perceived by users that are no longer obliged to hitchhike (see “platform effect” estimate in Table 1), without changing travel times. However, from a monetary point of view, the offer is changed since passengers pay their driver 2€ for their journey. This LANE situation will then serve as a reference that the following scenarios will modify.

5.2. Time-savings incentive scenarios

First, we describe scenarios that affect travel times:

- The "HOV" scenario simulates the implementation of an HOV-lane. It affects the travel times and the travel time variability of the three car modes. It is considered here that the HOV-lane is implemented on every highway section of the trip. It creates a time gain for carpoolers (equivalent to a speed-gain of around 10km/h) and a time loss for solo drivers (equivalent to a speed-loss of around 5km/h)¹³. Their respective travel time variabilities are also reduced – for carpoolers – or raised – for solo drivers – by the same amount.
- The "Easier access to stations" scenario will simulate the presence of nearby carpooling stations for each O-D in the database. The time spent by carpoolers to access the station is reduced for both drivers and passengers. For drivers, detour time is bounded to 2 minutes. For passengers, access time is bounded to 5 minutes, by walk. In this scenario, the demand for each carpool station is assumed to remain constant, without any increase in carpoolers' waiting times.

5.3. Monetary variations scenarios

We also simulate several scenarios that affect the monetary components of the trips:

- The "Fuel Price +" scenario simulates an increase in fuel prices from €1.7/L to €2.5/L. It will be assumed here that public transport prices are not affected by this fuel price

¹³ The time gain is proportional to distance covered on highways. The difference between travel times (and variability) for carpoolers and solo driver is estimated to 15 seconds per kilometer. These 15 seconds are split such as solo driver spend more time on road than in the reference situation for 30% of that amount, and carpoolers spend less time on road than in the reference situation for 70% of that amount (i.e. solo drivers lose $0.3 \cdot 15s/km$ on highways and carpoolers gain $0.7 \cdot 15s/km$ on highways).

increase. It is therefore an indirect incentive to become a passenger in a carpool or in public transports.

-For the "Free of charge passengers" scenario, everything is in the title. Carpool drivers still earn 2€ when they carry a passenger, in every O-D. For passengers, the ride becomes free. Drivers payment would be made by the carpooling platform. Since it would not have any source of income in this scenario, public authorities would subsidize to compensate for the platform loss. The carpool platform profit in this scenario is hence equal to 0.

-In the "Private LANE" scenario, the carpooling drivers still earn 2€ as in the previous scenarios. This time, passengers pay 2.5€ for their trip. Therefore, the carpooling platform can this time pay the driver without being subsidized. It even makes profit for each carpooling trip realized.

6. Results

In this section, we compare the total social cost of the baseline and the LANE situation, and then compare the reference situation (i.e. LANE), with scenarios described previously. Consequently, we can evaluate the impact of each scenario on the social cost and its components, considering the number of travelers in the zoning remains unchanged. Results at the individual level, and hence average social cost, are presented in the following tables.

6.1. LANE service

Table 5 displays the main components of social cost and their variations between the baseline and the LANE situation. These first results indicate that the social cost is mainly driven by the level of the consumers' costs. Indeed, its absolute value is way larger than the other components of the social cost. A detail of each social cost component is provided in Table 8 to Table 10 to understand better the displayed results. Another important result to underline in this table is the negative sign of public and private deficits, meaning public authorities and private companies earn more than they spend in our simulations.

Table 5 : LANE service

	Baseline (Hitchhiking)	LANE (reference)
Average social cost (in €/trip)	14.92	14.85
Consumer's cost	16.84	16.75
External costs	1.64	1.69
Public deficit	-2.22	-2.22
Private deficit	-1.33	-1.37
Modal Shares		
Solo Driver	61.4% (40.5%)	62.3% (33.8%)
Carpool Driver	9.3% (30.2%)	10.0% (38.5%)
Carpool Passenger	9.3%	10.0%
Public Transport	19.9%	17.7%
CO2 abatement cost (in €/t)	855	(ref)
Nb of car.km per capita	25.4	26.1
Occupation rate	1.13	1.14

Notes: Modal shares between parentheses are those calculated by our modal choice model. Effective modal shares are displayed in the table considering the surplus of carpool drivers (which is limited by the carpool passenger modal share) become solo drivers. E.g. the solo driver effective modal share in the LANE scenario is $33.8\% + (38.5\% - 10.0\%) = 62.3\%$.

The social costs and its components are displayed in €/trip.

CO2 abatement cost is the monetary value that should be given to a ton of CO2 to obtain the same total social cost in the given scenario and the reference situation, ceteris paribus.

Considering the modal shares, it should be noted that the low number of carpool passengers limits the number of carpool drivers. In the LANE case, the model predicts a carpool driver modal share of 38.5% which is limited by the lower carpool passenger's share of 10%. The 28.5% of carpool drivers "in excess" is then assumed to make their trip as solo drivers. We consider that the surplus of carpool drivers becomes solo drivers, who consequently become the predominant transport mode, used by over 60% of individuals.

When we compare the two situations, the LANE service improves the utilities of carpoolers by offering a carpooling offer preferred to hitchhiking proposed in our baseline situation. This improvement in the carpooling offer has a positive impact on consumer costs. However, this is not the case for externalities. Indeed, the improvement in this offer creates a

modal shift from public transport to the car.¹⁴ This creates a higher number of car-kilometers and therefore higher externalities. On the other hand, this higher number of vehicles has a positive effect on freeway revenues, as well as on fuel tax revenues. However, the introduction of the LANE service is subsidized by the public authorities. These positive and negative effects of LANE on public finances appear to offset each other between the two situations.

6.2. Time saving incentives

Table 6 below shows how the LANE (reference) scenario is affected by the time-related changes described in the previous section.

Table 6: Time saving incentives

	LANE (ref)	HOV	Closer Stations
Average social cost (in €/trip)	14.85	15.00	14.70
Consumer's cost	16.75	16.83	16.57
External costs	1.69	1.65	1.66
Public deficit	-2.22	-2.15	-2.18
Private deficit	-1.37	-1.33	-1.34
Modal Shares			
Solo Driver	62.3% (33.8%)	57.7% (28.6%)	59.7% (33.2%)
Carpool Driv.	10.0% (38.5%)	12.8% (41.9%)	11.4% (37.9%)
Carpool Pass.	10.0%	12.8%	11.4%
Public Transport	17.7%	16.7%	17.5%
CO2 abatement cost (in €/t)	/	2739	-2191
Nb of car.km	26.1	25.5	25.7
Occupation rate	1.14	1.18	1.16

Notes: Modal shares between parentheses are those calculated by our modal choice model. Effective modal shares are displayed in the table considering the surplus of carpool drivers (which is limited by the carpool passenger modal share) become solo drivers.

The social costs and its components are displayed in €/trip. Toll and fuel costs are expressed in average cost for drivers.

CO2 abatement cost is the monetary value that should be given to a ton of CO2 to obtain the same total social cost in the given scenario and the reference situation. If we assume that the CO2 valuation is higher than the abatement cost, then we should prefer the low-emission scenario, else the high-emission scenario should have

¹⁴ These results are consistent with a simulation realized in Le Goff et al. (2023), where the welfare is also found superior in the “private platform” scenario than in the “hitchhiking” scenario, even though the monetary exchange effect seems not to be positive on welfare.

inferior total social cost. If an abatement cost is negative, it indicates that the low-emission scenario is also the least expensive one.

In our "HOV" scenario, the time saved by carpoolers and lost by solo drivers respectively result in an increase and a decrease of their associated modal shares as expected. This results in a reduced number of car-kilometer – 0.6 per trip made – which leads to reduce externalities. In the same time, it produces a lower private profit, which is here entirely carried by highways' profit. Indeed, the number of cars on highways is lower in this scenario. Moreover, this reduced traffic also negatively affects the revenues from fuel taxes which leads to the observed decrease in public finances balance. Unexpectedly, the consumers' costs seem barely affected by the changes of the HOV scenario. This result is due to the opposite effect that positively affect carpoolers and negatively solo drivers. Furthermore, even though the time loss by solo drivers is smaller than the time gain by carpoolers, the global effect on consumers is negative. The explanation comes from the solo driver modal share which is way higher than the carpoolers' one. The detailed consumers' cost table give more details to explain this phenomenon (see Table 8). The total social cost of this measure is slightly superior to the one of the LANE scenario. This increase is also mainly due to the reduction of both private companies and public authorities' revenue. This indicates that the externalities caused by traffic are more than offset by the various revenues it generates – here mainly through fuel taxes and highway tolls. This counter-intuitive result, which increases the social cost when lowering the externalities, may be explained by their low values. This is what indicates the 2,739€ CO₂ abatement cost, which is the cost of a ton of CO₂ that would make both HOV and LANE scenarios equal in terms of total social. Costs of externalities are also detailed in Table 9.

The second scenario simulates the presence of a station easily accessible for every O-D. As the modal shares indicate, the gain in utility is substantially higher for carpool passengers than for drivers.¹⁵ The carpool passenger modal share increases less than in the HOV scenario. Thus, externalities are less reduced and public and private profits are also slightly lower. From this perspective, this scenario with closer carpool stations is kind of an intermediate between the reference situation and the "HOV" scenario. The incentive to induce more carpooling seems lower than the HOV-lane situation. However, in this scenario, the utility of consumers is only positively affected, in contrast to the "HOV" which degrades the utility of solo drivers.

¹⁵ In the equivalent scenario without a gain in detour time for carpool drivers, their associated modal share is 30.5%, 0.1 percentage point lower. This indicates detour times were already small and hence the gain for carpool drivers is minor.

Consequently, consumers' costs are reduced, which makes the total social cost lower. As both externalities and total social cost are reduced, the abatement cost of CO2 becomes negative, indicating the low-CO2-emission scenario is more economically efficient. Nonetheless, this result does not necessarily imply that this scenario is the best of the three presented. Indeed, it assumes that waiting times would not be increased. This hypothesis would only be possible if the carpooling market share were to increase significantly compared to its current state. Furthermore, the costs of creating and maintaining carpool stations are not included. This scenario therefore favors carpooling offers – and reduce carpoolers' costs – compared to a situation where the number of carpoolers remains unchanged.

6.3. Monetary incentives

Table 7 below indicates the results obtained from the simulations of our monetary variations scenarios. These results confirm first observations made in the previous Table 6. The link between the carpool shares, number of car-kilometer, externalities and private profits is still observable. However, as these scenarios may directly affect public finances, it is not obvious that a higher number of car-kilometer implies reduced public expenses through higher revenues from fuel taxes, but this link should be kept in mind.

Table 7: Monetary incentives

	LANE (ref)	Fuel Price +	FOC Passengers	Private LANE
Average social cost	14.85	15.32	15.03	14.80
Consumer's cost	16.75	17.90	16.60	16.77
Externalities	1.69	1.63	1.65	1.69
Public deficit	-2.22	-2.90	-1.89	-2.26
Private deficit	-1.37	-1.32	-1.34	-1.39
Modal Shares				
Solo Driver	62.3% (33.8%)	59.1% (32.8%)	59.2% (33.2%)	63.1% (34.0%)
Carpool Driv.	10.0% (38.5%)	11.0% (37.3%)	11.7% (37.7%)	9.6% (38.7%)
Carpool Pass.	10.0%	11.0%	11.7%	9.6%
Public Transport	17.7%	18.9%	17.4%	17.7%
CO2 abatement cost	/	4019	2480	1991
Nb of car.km	26.1	25.3	25.6	26.2
Occupation rate	1.14	1.16	1.16	1.13

Notes: Modal shares between parentheses are those calculated by our modal choice model. Effective modal shares are displayed in the table considering the surplus of carpool drivers (which is limited by the carpool passenger modal share) become solo drivers.

The social costs and its components are displayed in €/trip. Toll and fuel costs are expressed in average cost for drivers.

CO₂ abatement cost is the monetary value that should be given to a ton of CO₂ to obtain the same total social cost in the given scenario and the reference situation.

The first scenario assumes an increase in fuel prices. This increase induces higher modal shares for passenger modes than in the LANE situation. There is no surprise in the increase in consumers' cost since this scenario only raises drivers' cost. It should be noted that this scenario leads to the largest decrease in car-kilometers and externalities from all scenarios tested. As a consequence, private profits are also lower. However, public authorities' revenues become higher than in the reference situation. Even though the drivers' modal shares are slightly lower, public authorities' revenues are increased for each car remaining on the road since fuel is still taxed at the same rate, which consequently increases revenues per car km.

The second scenario presented assumes that the carpooling platform still pays 2€ to the carpooling drivers, but passengers are free of charge. As a consequence, the carpooling platform is subsidized by public authorities to be able to pay this amount, in addition of the operational costs of 200k€. This is similar to an incentive distributed to carpool passengers. This results in a lower consumer's cost, but higher public expenses. As the passengers' modal share is limiting the total carpool share, this incentive results in a lower number of car-kilometers and a higher occupation rate than the LANE scenario. Externalities and private profits are hence slightly reduced. Nonetheless, the increase in public expenses outweigh the gain from the reduce in consumers' cost which lead to a higher total social cost than in the LANE scenario.

In the last scenario, the drivers' gain remains the same but the passengers pay a price slightly higher than this gain. The platform can therefore directly pay the amount due to the drivers without requiring a subsidy and even make a small profit. This profit can therefore finance the introduction of the LANE service, which does not need any subsidy. Thus, public expenses are lower than in the reference situation. The increase in the cost of carpooling for passengers directly induces an increase in consumers costs, but also a decrease in its modal share and an increase in car-kilometers, again increasing public and private revenues and externalities. The total social cost is here lower than in the previous situation. This scenario shows that it seems more desirable – from the total social cost perspective – to have a private carpooling platform. And this is despite a lower carpooling market share and thus a higher number of car-kilometers than in the latter two situations. This counter-intuitive result shows

that promoting carpooling and reducing the number of vehicles on the road does not reduce - with the values used - the total social cost.

In these scenarios, CO2 abatement costs are very high, underlining the difficulty to make these scenarios economically efficient and with low emissions objectives, as discussed in section 6.6.

6.4. Total social cost component details

Next tables detail the four main components of the social cost. Table 8 displays details of the consumer's costs, mainly through time components.

We can observe that the "HOV" scenario offers a reduced cost for carpoolers but an increased cost for solo drivers. Two main reasons explain why the overall consumers cost is slightly higher in HOV scenario. First, the cost of the mode with the highest modal share, solo driver, is increased. Second, the HOV-lane is an incentive to switch to carpool, which is a costlier mode than solo driver, despite the time gain for travelers. Furthermore, this very low modal share of carpool passengers implies the same modal share for carpool drivers, despite a very attractive time cost. In the scenario with closer stations, the entire gain for consumers is based on the gain granted to carpool passengers. Other phenomena can be observed on the costs related to travel time. The "Fuel Price +" scenario increases the time costs of passenger modes. This is explained because carpool modes, despite being more time consuming, are more attractive after an increase in fuel costs. The opposite effect is also found when we observe the evolution of the cost of individuals choosing public transport in the "HOV" and "closer stations" scenarios. Indeed, since the carpooling modes have better supplies than in the reference situation, users can more easily find an alternative to public transport and thus, use this mode only when its cost is low. Finally, the "Private LANE" scenario appears to be similar in every aspect to the reference situation. Here, the difference between the consumer costs is explained because the passengers have to pay for their carpooling trip. This payment is not fully given to the driver, which should worsen the consumer cost. However, this payment is also the reason why the modal share of the carpooling passenger decreases in this scenario. This decrease in the carpool passenger modal share leads to a modal shift towards the least expensive mode for consumers: solo driver. This shift explains a lower average consumer's cost in the " Private LANE" scenario.

Table 8: Consumer's cost detailed

	LANE (ref)	HOV	Closer Stations	Fuel Price +	Private LANE
Consumer's cost	14.82	14.97	14.67	15.29	14.79
Time components					
Solo Driver	9.43	10.00	9.42	9.42	9.42
Carpool Driver	6.35	4.94	6.33	6.34	6.35
Carpool Pass.	24.09	22.69	22.05	24.14	24.58
Public Transport	20.87	20.80	20.84	20.94	20.87
Toll cost	2.71	2.71	2.71	2.71	2.71
Fuel cost	3.09	3.09	3.08	4.54	3.09

Notes: Consumer's cost is the average individual cost. Time, toll and fuel costs are expressed in average cost for the mode user, e.g. a solo driver has on average 9.43€, 2.71€ and 3.09€ costs due respectively to time spent during its trip, tolls and fuel in the reference situation.

The analysis of Table 9 below is very straightforward as all externalities are linearly dependent from the number of car-kilometers. External costs are mainly driven by accidents, which represent around half of the total. Valuation for CO2 emitted and noise each account for around 20% of the externalities' costs. Finally, the valuation of local pollutants only represents 10% of the total external costs.

Table 9: Externalities cost detailed

	LANE	HOV	Fuel Price +
Total Externalities	1.69	1.65	1.63
Local pollutants	0.18	0.17	0.17
Noise	0.33	0.32	0.32
Accidents	0.81	0.79	0.78
Climate change	0.37	0.37	0.36

Notes: This table presents average values at the individual level, in € per trip.

Table 10: Public expenses and private profit detailed

	LANE	HOV	Fuel Price	FOC Passengers	Private LANE
Public Deficit	-2.22	-2.15	-2.90	-1.89	-2.26
Road Wear	0.08	0.08	0.08	0.08	0.08
Fuel Tax	-1.61	-1.57	-2.29	-1.58	-1.62
Corporate Tax	-0.55	-0.53	-0.53	-0.53	-0.56
PT revenues	-0.17	-0.16	-0.18	-0.17	-0.17
Ptfm Subsidy	0.03	0.03	0.03	0.31	0.00
Private Deficit	-1.37	-1.33	-1.32	-1.34	-1.39
Platform	0.00	0.00	0.00	0.00	0.02
Highway	-1.37	-1.33	-1.32	-1.34	-1.37

Notes: This table presents average values at the individual leve. Results for public finances are here presented as expenses, so the public revenues are displayed as negative values and expenses as positive values.

Table 10 displays details of public and private expenses and revenues. Fuel tax and highway profits are directly correlated with the number of car-kilometer. This higher profit also benefits to public finances through corporate tax. This table also illustrate how fuel prices raise impacts fuel tax and how impactful the platform subsidy is on public finances in the “Free of charge passengers” scenario. The “Private LANE” scenario reveals that public finances benefits both from the withdrawal of the subsidy and from higher taxes because private profits are higher in this scenario. Furthermore, as the number of car-kilometer is also higher, public finances also benefits from more fuel taxes.

6.5. Spatial heterogeneity

First, we will focus on the spatial diversity of our data. Indeed, all O-Ds can be affected differently by the measures we simulated. Table 11 and Figure 3.4 below present three O-Ds with very different characteristics that illustrate this phenomenon. The first O-D selected (O-D#1) connects the center of Bourgoin to the center of Lyon. The public transport supply is excellent and its market share is therefore important. The O-D#2 connects a village in the North of Bourgoin to Lyon. In this O-D, access to public transports is more complicated and the trip requires a connection. A significant part of the trip by car is made off the highway and the market share of carpooling is low. Finally, the O-D#3, which connects Bourgoin to the southeastern suburbs of Lyon, has a public transportation offer requiring two connections with a very high travel time, and its market share is almost zero. On the other hand, access to the carpooling stations is easy and almost the entire trip is made on the highway. The dedicated lane will therefore have its full effect on an O-D like this one.

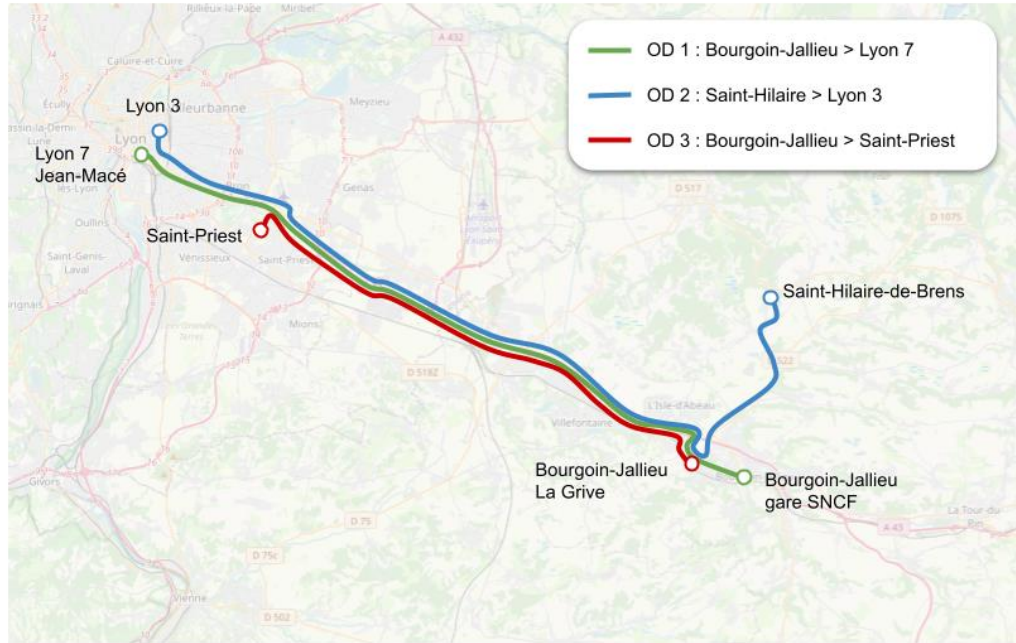


Figure 3.4 : The three O-Ds selected

Table 11: descriptive statistics of the 3 selected O-Ds

	O-D#1	O-D#2	O-D#3
Road distance	44 km	45 km	31 km
Of which highways	35 km	19 km	30 km
Car travel time	33 min	45 min	19 min
PT travel time	27 min	95 min	71 min
#PT transfers	0	1	2
Access Carpool station	8 min	16 min	1 min
Access PT station	12 min	16 min	2 min

Notes: Values are weighted by flows and rounded.

Table 12: HOV and FP+ scenarios applied to the three selected O-Ds

	HOV			FP+		
	OD#1	OD#2	OD#3	OD#1	OD#2	OD#3
Average social cost	+0,05	+0,14	-0,19	+0,10	+0,70	+0,39
Consumer's cost	+0,06	+0,10	-0,33	+0,22	+1,79	+1,04
Externalities	+0,02	-0,04	-0,11	-0,05	-0,08	-0,03
Public deficit	-0,01	+0,06	+0,14	-0,11	-1,05	-0,66
Private deficit	-0,02	+0,03	+0,11	+0,05	+0,03	+0,04
Modal Shares						
Solo Driver	-1.1 p.p.	-4.9 p.p.	-8.9 p.p.	-1.0 p.p.	-1.1 p.p.	-0.9 p.p.
Carpool Driver	+1.7 p.p.	+3.1 p.p.	+4.1 p.p.	-0.9 p.p.	-1.2 p.p.	-1.0 p.p.
Carpool Passenger	+1.1 p.p.	+2.1 p.p.	+4.9 p.p.	+0.0 p.p.	+1.5 p.p.	+1.8 p.p.
Public Transport	-1.7 p.p.	-0.3 p.p.	-0.1 p.p.	+1.9 p.p.	+0.8 p.p.	+0.1 p.p.

Notes: Social cost values in this table display the differences at the individual level between the scenario and the reference situation. E. g. the HOV-lane scenario increases the average social cost for an average individual in O-D#1 by €0.05.

Modal shares values indicate the evolution of modal shares in percentage point compared to the reference situation in each O-D. The sum of the four modal shifts may be different from 0 due to rounded values.

Table 12 displays results of the HOV-lane and the fuel price increase scenarios for the three chosen O-Ds. It shows a lot of heterogeneity in the simulations' impact. The HOV-lane scenario is a clear gain from the total social cost perspective in O-D#3. As the trip is almost entirely done on highways, time savings make carpooling alternatives very attractive. It provides gains from both externalities and consumers costs perspective that outweigh the lower revenues for public authorities and private companies. This HOV-lane scenario is inefficient for both O-D#1 and 2 for different reasons. In O-D#2, the HOV-lane degrades the solo driver supply which represents a large majority of the modal share on this O-D. The incentive towards carpool does not compensate for this loss. It allows for externalities reduction but the loss for public authorities and private companies due to the decrease in car-kilometer outweighs it. In the O-D#1, the HOV-lane encourage people to switch to carpool whereas they are mostly using public transport. This measure results in a loss even from the externalities' perspective, considering the public transport supply remains constant. Only public authorities and private companies benefit from this measure due to more people using their car and the highway.

Concerning the fuel price increase scenario, here again the three O-Ds are impacted in different ways. O-D#1 is barely affected as the majority of the demand use public transport and

we assume public authorities do not raise the ticket price. O-D#2 is the most impacted O-D as a large majority of the population use their car and the carpool alternatives are not attractive. This is the contrary in O-D#3 in which the carpool alternative offers an alternative to solo driving, so the increase in car cost can be mitigated.

6.6. Sensibility tests

Results presented above are dependent on some of the values chosen to estimate the total social cost. In this subsection, we will present several alternative ways to reconsider some of our results.

6.6.1. Reassessing externalities and public action

As mentioned previously, social costs obtained by our simulations will be different if one uses other values for our parameters. The first example of this case is when we consider a different value for CO₂ emissions, as presented in Table 13. The "CO₂+" scenario gives the valuation of externalities if one considers the high valuation of CO₂ proposed by the EU commission (2020) for the long-term projects. This value is five times superior to the value for current projects (€498/tCO₂ vs €100/tCO₂ currently). Even considering this value, the total value of externalities would be slightly less than doubled. This valuation would still consider the HOV-lane scenario as less desirable, from the total social cost perspective, than the reference situation, *ceteris paribus*. In order to make the total social cost of the HOV-lane scenario smaller than in the reference situation, the ton of CO₂ emitted should be valued at around €2,739 (cf. CO₂ abatement cost in Table 6) if one wants to obtain a smaller social cost than the reference (LANE) scenario. This valuation of CO₂ would be more than an order of magnitude larger than the current one. Therefore, considering the low weight of externalities in the social costs, it seems unlikely that scenarios requiring some effort to reduce externalities would be interesting from a cost benefit analysis perspective.

Table 13: CO2 valuation sensibility test

	CO2 current value (100€/t)		CO2+ (498€/t)	
	LANE	HOV	LANE	HOV
Average social cost	14.85	15.00	16.32	16.45
Consumer's cost	16.75	16.83	16.75	16.83
Externalities	1.69	1.65	3.16	3.10
Of which CO2	0.37	0.37	1.85	1.82
Public deficit	-2.22	-2.15	-2.22	-2.15
Private deficit	-1.37	-1.33	-1.37	-1.33

Notes: This table presents average values at the individual level, in € per trip.

Another important value that could make scenarios ranking different is the OCPF (see 3.1.3). The OCPF affects both revenues and expenses of public authorities. It is valued in this paper at 1.2. As an example, if one wants to compare the “HOV” scenario to “FOC Passengers” (see Table 6 & Table 7), the total social cost is slightly higher for the second (+0.03 in “FOC passengers”). This result would be different if one does not consider the OCPF (or OCPF=1, see Table 14). In this case, this reduces the absolute value of public deficit, dividing it by 1.2. This would result in a -1.79 value for “HOV” scenario and a -1.58 value for “FOC Passengers”. These new values would result in a social cost of 15.36 for “HOV” and 15.33 for “FOC Passengers”. Without considering the OCPF, the “HOV” scenario would have a higher social cost than the “FOC Passengers” one.

Table 14: OCPF sensibility test

	OCPF = 1.2		OCPF = 1	
	HOV	FOC Passengers	HOV	FOC Passengers
Average social cost	15.00	15.03	15.36	15.33
Consumer's cost	16.83	16.60	16.83	16.60
Externalities	1.65	1.65	1.65	1.65
Public deficit	-2.15	-1.89	-1.79	-1.58
Private deficit	-1.33	-1.34	-1.33	-1.34

Notes: This table presents average values at the individual level, in € per trip.

6.6.2. Reassessing values of time (VoTs)

Another way to value differently the scenarios is to consider different VoTs than those described in the data section. Table 15 below displays results equivalent to Table 8 considering VoTs obtained through our stated preference survey carried out in the Lyon area in 2019 (see Le Goff et al., 2022 for more details).

Table 15: Consumers costs considering our VoTs

	Reference	HOV	Closer Stations	Fuel Price +	Private LANE
Consumer's cost	26.33	26.22	26.30	27.82	26.32
Time components					
Solo Driver	15.42	16.40	15.41	15.41	15.42
Carpool Driver	17.61	14.16	17.53	17.58	17.61
Carpool Pass.	35.17	31.62	33.63	35.22	35.66
Public Transport	41.33	41.08	41.27	41.66	41.35
Toll cost	2.71	2.71	2.71	2.71	2.71
Fuel cost	3.09	3.09	3.08	4.54	3.09

Notes: Consumer's cost is the average individual cost. Time, toll and fuel costs are expressed in average cost for the mode user, e.g. a solo driver has on average 15.42€, 2.71€ and 3.09€ costs due respectively to time spent during its trip, tolls and fuel in the reference situation.

Our values of time are overall higher and this affect even more carpooling trips as our carpool values are higher than solo driver values for in-vehicle travel time. Consequently, the impact of time gain incentives is stronger with our values. As the reduction of travel time for carpoolers is more impactful on consumer's cost with our values, the HOV scenario has a lower consumer's cost than the reference situation, whereas it was the opposite with values from the literature used previously. As our values give a smaller valuation of connection and access to a carpool station, the gain for carpool passenger is also lowered in the « closer stations » scenario. This reduced gain is illustrated by the carpool passenger cost, that is now only €1.54 lower compared to the reference situation (€2.04 with values from literature, see Table 8).

To summarize, we find with values from the literature that the total social cost is mainly driven by consumers' costs. The values given to externalities seems too low to have an impact on the total social cost and outweigh the public and private revenues from traffic. Private LANE scenario is one of the scenarios with the lowest total social cost, even though it is the scenario with the lowest car occupation rate and the highest number of car-kilometer. However, these results can vary depending on assumptions made. This concerns values used for the OCPF, or

those for the externalities, although they would have to be increased substantially if one wants climate impact of the transport supplies to be reduced. This also concerns the values of travel times which can have a significant impact on the consumers' costs, which themselves play a serious role in the total social cost. Finally, scenarios tested show an important spatial heterogeneity in their respective impacts. Carpooling incentives should consequently be applied, or not, according to the local context.

7. Limitations

Several hypotheses have been made in the calculations of this paper. Examples include the distribution of the vehicle fleet, the distribution of road types used (city/rural/highway), which may not perfectly reflect characteristics of trips made on each O-D, which could lead to unprecise estimation of the social cost. We also did not consider the equity dimension in our analysis, which could affect our results in understanding the potential of carpooling as a solution for more equitable mobility. As any hypothesis, these can be criticized and changed, which would of course affect values found in the results.

The main limitation of this paper comes from the use of a logit model without nested structure or other forms taking into account individual heterogeneity for the individuals' modal choice. Furthermore, we did not consider the potential impact of our scenarios on congestion, which could also affect modal shares differently. The demand for trips from outside to inside the zoning studied was not considered, and could also affect traffic conditions. Therefore, the external validity of some of our results and conclusions may be biased. The results should rather be put in perspective with each other than considered for the exact values found for each scenario.

8. Conclusion

This paper presents an analysis of social cost changes simulating in several scenarios. The implementation of carpooling incentives or external shocks affecting the demand have been tested. The social costs are composed of four main components: consumer's cost, externalities, public authorities' deficit and private profits.

The results show that consumer's cost constitutes the majority of the total social cost with values commonly used. Values given to externalities seems too low to have an impact on the total social cost and outweigh the public and private revenues from traffic. Hence, public authorities have diverging interests. One could expect them to implement measures to reduce

negative externalities, and consequently to reduce traffic in this case. However, they also have an interest in keeping a high number of cars on the road to benefit from more revenues from taxes.

Consequently, the private platform scenario is one of the best scenarios tested – from the total social cost perspective – whereas it is the one with the lowest car occupation rate and the highest number of car-kilometer. This result underlines the difficulty to make low-emission scenarios economically efficient considering the current values of externalities.

Moreover, our results show a substantial spatial heterogeneity of policy impacts. As an example, incentive measures towards carpooling alternatives should not be implemented where public transport supply is already a good alternative to car. On the other hand, deploying a carpooling alternative when public transport alternative does not exist is an excellent measure to mitigate consumer's cost when a negative exogenous shock happens, such as a fuel price increase.

This study tends to show promoting carpooling for daily trips should be made conscientiously considering local context. If one wants to reduce car traffic and externalities, carpool incentives can even lead to the opposite of the intended effects. However, improving carpooling supply can be interesting to provide an additional transport solution for travelers and potentially greater resilience to external shocks. This is particularly the case where public transport supply is non-existent or inefficient. These results raise the question of potential impacts on demand outside the policy area which could be explored in future research.

Appendix

Table: Total social cost composition detail (in €/capita)

Scenario		Baseline	LANE	HOV	FP+	Priv LANE	
Modal Shares							
	DS	41% (62%)	34% (63%)	29% (58%)	33% (59%)	34% (63%)	
	DCP	30% (9%)	39% (10%)	42% (13%)	37% (11%)	39% (10%)	
	PCP	9%	10%	13%	11%	10%	
	PT	20%	18%	17%	19%	18%	
Total social cost		14,92	14,85	15,00	15,32	14,81	
Consumer's cost							
	TOTAL	16,84	16,75	16,83	17,90	16,77	
Per mode	Solo Driv	9,29	9,44	9,08	9,78	9,55	
	Cp Driv	1,32	1,22	1,37	1,50	1,17	
	Cp Pass	2,06	2,41	2,89	2,66	2,36	
	Pub T	4,18	3,69	3,48	3,96	3,70	
At individual level							
	Solo Driv	Total	15,19	15,23	15,80	16,67	15,23
		Travel Time	4,65	4,66	4,96	4,65	4,66
		TT Variability	4,72	4,74	5,05	4,73	4,74
		Cost	5,82	5,83	5,79	7,28	5,83
	Cp Driv	Total	14,13	12,16	10,74	13,58	12,15
		Travel Time	3,44	3,45	2,72	3,45	3,45
		TT Variability	4,66	4,68	3,95	4,69	4,68

	Detour Time	0,25	0,25	0,27	0,22	0,25
	Cost	5,77	3,78	3,80	5,22	3,78
Cp	Total	22,05	24,09	22,69	24,14	24,58
Pass	Travel Time	3,44	3,45	2,72	3,45	3,45
	TT Variability	4,66	4,68	3,95	4,69	4,68
	Wait Time	1,75	1,76	1,76	1,76	1,76
	Access Time	1,90	1,90	1,92	1,91	1,90
	Egress Time	6,78	6,79	6,81	6,80	6,78
	Connections	2,91	2,92	2,93	2,93	2,92
	Cost	0,60	2,60	2,61	2,60	3,10
Pub T	Total	20,96	20,87	20,80	20,94	20,87
	Travel Time	6,90	6,84	6,80	6,89	6,84
	TT Variability	1,96	1,93	1,91	1,94	1,93
	Wait Time	1,41	1,41	1,41	1,41	1,41
	Access Time	4,73	4,75	4,74	4,75	4,75
	Egress Time	3,73	3,75	3,75	3,75	3,75
	Connections	1,43	1,40	1,38	1,42	1,40
	Cost	0,80	0,80	0,80	0,80	0,80
Externalities						
	TOTAL	1,64	1,69	1,65	1,63	1,69
	Local pollutants	0,17	0,18	0,17	0,17	0,18
	Noise	0,32	0,33	0,32	0,32	0,33
	Accidents	0,79	0,81	0,79	0,78	0,81
	Climate change	0,36	0,37	0,37	0,36	0,37
	CO2 (g)	3607	3708	3651	3589	3726
Public Deficit						
	Total	-2,22	-2,22	-2,15	-2,90	-2,25

Fuel Taxes	-1,57	-1,61	-1,57	-2,29	-1,62
Corporate Taxes	-0,53	-0,55	-0,53	-0,53	-0,56
Road wear	0,08	0,08	0,08	0,08	0,08
Income Pub Trprt	-0,19	-0,17	-0,16	-0,18	-0,17
Ptfm Subsidy	0,00	0,03	0,03	0,03	0,02
<hr/>					
Private deficit					
Total	-1,33	-1,37	-1,33	-1,32	-1,41
Highway profit	-1,33	-1,37	-1,33	-1,32	-1,37
Platform profit	0,00	0,00	0,00	0,00	-0,04
<hr/>					
Number of Veh.km	25,41	26,13	25,52	25,28	26,25
Occupancy rate	1,13	1,14	1,18	1,16	1,13

Notes: Modal shares between parenthesis are effective modal shares considering carpool drivers who cannot find a carpool passenger become solo drivers. Values of consumer's cost are detailed by mode at the global level by multiplying effective modal share by consumer's cost at individual level.

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