Assessing the ex-ante impacts of a low-emission zone on transport poverty and vulnerability with the VulMob indicator

Lola Blandin, Hélène Bouscasse, Sandrine Mathy

Assessing the ex-ante impacts of a low-emission zone on transport poverty and mobility vulnerability with the VulMob indicator

Lola Blandin,
Univ. Grenoble Alpes, INRAE, CNRS, Grenoble INP, GAEL, 38000, Grenoble, France

Hélène Bouscasse,
CESAER, Agrosup Dijon, INRAE, University Bourgogne Franche-Comte, Dijon, France

Sandrine Mathy,
Univ. Grenoble Alpes, INRAE, CNRS, Grenoble INP, GAEL, 38000, Grenoble, France - corresponding author, email address: sandrine.mathy@univ-grenoble-alpes.fr

Abstract

Numerous Low Emission Zones (LEZs) have been implemented across Europe to improve air quality and reduce car use. However, to date, the impact of LEZs has been widely perceived as regressive, since vehicles that meet the low emission requirements are more expensive than others. The literature assessing the impact of LEZs on vulnerable and poor households prior to their implementation is sparse, particularly if we take into account the diversity of households' capacities to adapt according to their characteristics and mobility habits, beyond the sole solution of purchasing a LEZ-compatible vehicle. However, such assessments would make it possible to define accompanying policies to improve the social justice of the LEZs. In this article, we develop a methodology to evaluate the ex-ante impacts of a LEZ on vulnerable or poor households. First, we identify households affected by the LEZ. Second, the VulMob multidimensional indicator is used to identify, among affected households, households with low transport-affordability and highly vulnerable households according to their vulnerability profiles. Third, we assess the adaptive capacity in terms of modal shift options and considering the possibility to modify the destination. We apply this methodology to the Grenoble area (France), using the Local Household Travel Survey. The results show that not only are highly vulnerable households more affected by the LEZ than other households, but also that more of them are left with no alternative but to buy a LEZ-compliant car. Nevertheless, modal shift seems an adaptation solution with great potential for all households. This could improve the environmental and health

performance of LEZs. This work can guide decision-makers in the definition of preventive and compensatory policies, considering the profiles of transport vulnerability and the specificities of the territory.

Keywords: Low-emission zone; Transport vulnerability; Ex-ante evaluation

1. Introduction

The negative externalities induced by the predominance of the private car in mobility are numerous: pollution, contribution to climate change, noise, accidents, etc. Low emission zones (LEZs) are part of the range of transport policies aimed at reducing these externalities. They prohibit the access of the most polluting vehicles (according to a categorization of the pollution level of the vehicles) within a more or less wide perimeter encompassing urban centers. LEZs have seen significant growth in Europe: 320 of them have been implemented in the EU-27, UK and Norway (Clean Cities Campaign and Transport & Environment, 2022). As of 2020, 46 of 130 large cities in 12 European countries have deployed a LEZ compared to only five major cities having implemented tolls (Fageda et al., 2020). Yet, LEZs do not follow a one-size-fits-all scheme and can differ considerably between cities (size of the perimeter, time slots, kind of prohibited vehicles, ban or fee for the most polluting vehicles…) according to the policy choices made by authorities. LEZs can also be combined with other public policies such as congestion charge zones.

Because mobility is a symbol of freedom and a condition for access to basic services and facilities that determine everyone's socioeconomic conditions, the implementation of transport policies is often accompanied by strong public opposition, one of the main components of which relates to issues of environmental and social justice. These policies can carry the risk of social exclusion (Lucas, 2012; Mattioli, 2014; De Vrij and Vanoutrive 2022) and can be perceived as favoring the most privileged social classes living in urban centers. The absence of public acceptance of a policy instrument can have other practical consequences, such as reducing the effectiveness of the measure (Jia et al., 2017) or forcing changes in the measures once implemented (Raux et al., 2004). It appears that specific beliefs in the policy in term of social justice have significant effects on acceptance (Morton et al., 2021; Rejeb et al., 2024).

Despite its importance in the implementation of LEZs, there is very little literature on the *ex-ante* evaluation of the impact of LEZs on transport poverty and vulnerability. This is therefore necessary to define policies to support households that would be particularly affected. This could lead to greater acceptance by the population and, consequently, to the implementation of more ambitious policies.

Such an evaluation should take into account households' ability to adapt to the implementation of a LEZ, and not just poverty-related issues. Indeed, it is not because a household has a low income and owns a polluting vehicle that it will necessarily be affected by the LEZ. If the people in the household only travel short distances and have quick access to alternatives to the car, they will be less affected than a household that travels long distances and is far from public transport infrastructure. The VulMob multidimensional indicator (Blandin et al., 2023) was developed precisely to take account of this capacity to adapt to the implementation of policies aimed at reducing car use.

The objective of this article is to propose an *ex-ante* evaluation of the impacts of the LEZ implementation on transport vulnerabilities and poverty. To do so, we first evaluate the potential impacts on affected households for two different LEZ perimeters and two time schedules. Second, the VulMob multidimensional indicator developed by Blandin et al., (2023) is used to identify among affected households, households with low transport-affordability and highly vulnerable households according to their vulnerability profiles. Third, we explore the potential for adaptation considering different possibilities: modal shift, modification of the trips' destination and purchase of a new car focusing on vulnerability profiles. Our field of application is the Grenoble region, located in the French Alps.

This paper is organized as follows. Section 2 presents the literature related to the social impacts of LEZs. Section 3 describes the data, the Grenoble context, low transport-affordability identification criteria and the profiles of highly vulnerable households identified with VulMob. The methodology is developed in section 4 and the LEZ impacts and potential for adaptation are exposed in Section 5. Section 6 discusses the results and section 7 concludes.

The main contribution of our article lies in the deployment of a rigorous and reproducible methodology for assessing the impact of LEZs on transport poverty and mobility vulnerabilities, taking into account the specific adaptive capacities of each household. The originality and relevance of our approach is based on several elements:

- the use of the original multidimensional vulnerability indicator VulMob, which makes it possible to assess the diversity of causes of vulnerabilities and to identify and spatialize vulnerability profiles within households;

- the identification and simulation of different solutions for adapting to environmental policy: to adapt to the LEZ, we study in particular the possibilities of modal shift;

- the approach is based on mobility data collected as part of household travel surveys, which are carried out approximately every ten years in French cities, and can therefore be replicated in other urban contexts and for other transport policies.

2. Literature on social impacts of LEZs on mobility

The literature assessing the social impact of LEZs in terms of mobility has mainly focused on the impact through the deployment of low-polluting vehicles. For example, in the OECD report entitled "Distributional effects of urban transport policies to discourage car use: A literature review", Lindsey et al. (2023) conclude that the LEZs have a regressive effect because vehicles that meet the low emission requirements are more expensive than others. This conclusion is based on the hypothesis that (i) income positively correlates with ownership of low emission vehicles and (ii) residents of low emission zones have higher incomes. Indeed, according to Parkhurst (2017), low-income drivers are more likely to own the oldest vehicles subject to charges or ban. Charleux, (2014), in a LEZ scenario in the Grenoble conurbation (France), shows that the likelihood of being affected by the LEZ is related to the social group: the less stringent is the LEZ (in terms of banned vehicles categories), the more unequal the impacts would be on mobility. Indeed, a LEZ perimeter that is restricted to a quite wealthy center where many urban resources are concentrated and only applies to old vehicles, would de facto exempt the wealthiest populations. On the contrary, a regulation that would treat all vehicles equally, regardless of their emission class (such as a congestion charge) might be more egalitarian.

However, one of the challenges to assess the social impact of LEZs also involves individual adaptability, particularly with the objective to reduce car use and to promote modal shift towards alternatives to the car, such as public transport, cycling, walking and all forms of multimodality. To date, little attention has been paid to studying the potential effects of LEZs in promoting a shift to greener modes of transport. However, it has been shown in the case of the Madrid (Gonzalez et al., 2021) and London (Aldred and Goodman, 2020) LEZs that car ownership rates are significantly lower in households located within a LEZ.

Tarriño-Ortiz et al (2022) carried out an *ex-post* evaluation of the Madrid Central LEZ based on a questionnaire and showed that it had triggered a significant modal shift towards sustainable modes (half of the respondents indicated a modal shift caused by the LEZ), with the highest modal shift rates observed among car drivers. It is therefore important to consider the potential impacts of an LEZ in terms of modal shift, especially as this could help to limit the regressive effects when only the possibility of buying a LEZ-compliant vehicle is taken into account. These impacts will depend on the location of households according to their income level and whether or not they have access to alternatives to the car. For example, implementing a LEZ in Brussels could even decrease social and environmental inequalities as low-income population predominantly reside in the city-center, and have convenient access to public transportation, which is not the case in London (Verbeek and Hincks, 2022). In a prospective approach, Liotta (2024) investigates the potential impacts of LEZs on job accessibility (opportunities of employment an individual has access to within a reasonable transport time) across different occupational categories in 8 French cities. The impact would be regressive in 6 of the 8 cities examined, as low-skilled workers bear greater burden due to the limited availability of public transportation (active mobility is not considered) near their residences and workplaces, longer commuting distances, and a higher proportion of polluting vehicles.

3. The Grenoble case study

3.1. The social argument at the heart of the difficult implementation of LEZs in France

In France, the implementation of LEZs is fraught with obstacles relating to their social impact. In 2012, it is for this reason in particular that the implementation of a priority action area for air quality (*Zone d'Actions Prioritaires pour l'Air*) was finally cancelled (Charleux, 2014). LEZ became mandatory in 2019 with the *Loi d'Orientation des Mobilités* in the eleven cities where air quality limit values are exceeded. LEZs were expected to become more widespread with the *Loi Climat et Résilience* (2021): LEZs for passenger mobility would become mandatory for the metropolitan areas with more than 150,000 inhabitants. This would have involved 42 cities by 2025. But once again, in July 2023, in the wake of a Senate report (Tabarot, 2023) calling for the mandatory introduction of LEZs to be postponed until 2030, the government reversed its position. The LEZs will only be compulsory in the five metropolitan areas where the regulatory thresholds for NO_2 are regularly

exceeded: Lyon, Paris, Rouen, Marseille and Strasbourg. The Senate report concluded that there was a risk that many users would be left by the wayside, starting with the most vulnerable and those furthest from the city centers. These conclusions are based on an online consultation only. The methodology is not based on mobility data for the different population categories that could be affected by these LEZs.

3.2. Settings and data

Grenoble Alps Metropolis (GAM) is a French metropolis that brings together 49 municipalities on a 545-km^2 area, located in the French Alps in the Auvergne Rhône-Alpes region. This conurbation (see "Métropole" in Figure 1) accounts for approximately 445,000 inhabitants and has the specificity to be in a hemmed zone, surrounded by the mountains. It has a "traditional" structure, with a monocentric organization around Grenoble, the main city, hosting more than 150,000 inhabitants. In 2022, Grenoble was elected "European Green Capital" and is often considered as a pioneer in France in terms of ecological and environmental issues. In particular, a proactive public transport and bicycle policy has been developed during the last past years. Grenoble has had a freight transport LEZ since 2019 and was one of 42 agglomerations with more than 150,000 inhabitants required to introduce a LEZ for passenger mobility under the 2021 law. Despite the government's retreat, this LEZ was implemented in July 2023.

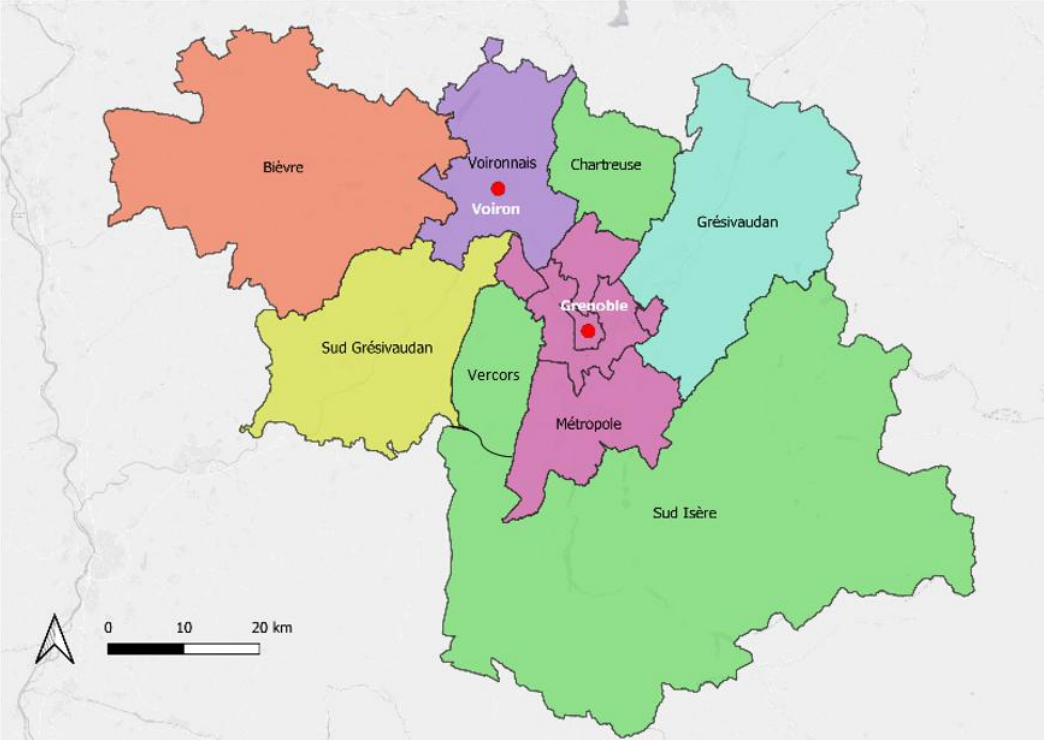


Figure 1 - Organization of the Grenoble territory by sectors

The Grenoble area (constituted by the Metropolis and the peripheral areas) hosts more than 820,000 inhabitants from 359 municipalities dispatched in eight sectors corresponding to the economic and structural organization of the region (Figure 1). Almost 55% of them live in the Grenoble Metropolis, 11% in Grésivaudan, 10.7% in Voironnais, 10% in Bièvre, 5.2% in Sud Grésivaudan, 5% in Sud Isère and less than 3% in Chartreuse and Vercors. In terms of socio-demographics, a young and active population characterizes the Metropolis: 40.5% of the inhabitants are less than 30 years old. In the global area, almost a quarter are families, 35.2% are pensioners and 12.9% are couples without children. With almost 14% of executive workers, Grenoble is one of the most attractive conurbation for highly qualified workers in France. In terms of income, Grenoble is a very heterogeneous city, where high and low income households tend to live in different boroughs. Some sectors in Voironnais and Grésivaudan, in particular close to the urban core, are wealthy in comparison to other such as Sud Isère or Bièvre (see Figure 2).

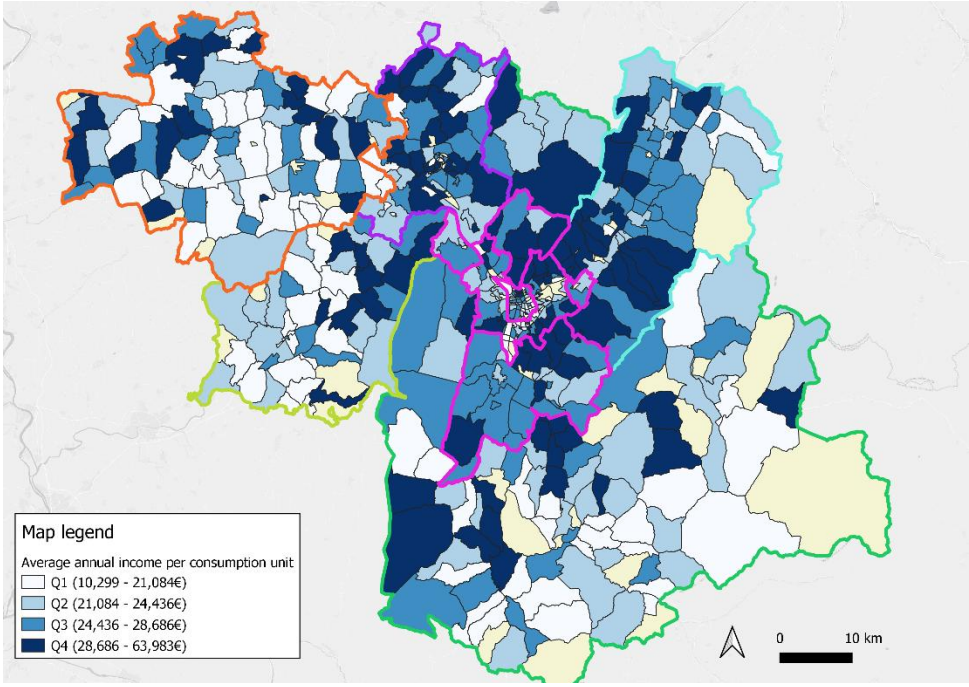


Figure 2 - Distribution of incomes per consumption unit in the Grenoble area.
NB: The areas described in the text are delimited by the colored lines and refer to the previously defined sectors.

In order to evaluate the impacts of a LEZ and the possible modal shift solutions, much information on travel habits (modes of transport, distances), on the visited places (residential location, workplace…), but also on the specific households' characteristics (housing description, habits, transport modes…) are required. In France, the Local Household Travel Surveys *(Enquête Ménages Déplacements (EMD)* in their previous version or currently *Enquête Ménage Certifiée CEREMA (EMC²))* are conducted every 10 years in the major cities. A standard procedure enabling comparisons between different cities and between successive surveys is followed (CERTU, 2008). These surveys provide a precise description of households, all the family members and associated mobility habits (information on the travel habits during a day of the week, i.e. the day prior to the survey, from Mondays to Fridays and the main characteristics of households' vehicle(s): number, age, motor type etc.). We use the data from EMC² Grenoble (2020), a survey of 7,500 typical households living in the Grenoble area. These observations are then weighted to represent the 378,275 households living in the whole area. The data processing leads to a final sample of 359,427 households because of missing cases.

Considering mobility flows, the main city of Grenoble is a prominent urban hub where the majority of travel flows converge, while the city of Voiron constitutes a secondary hub. Households mainly travel between Grenoble and the Grésivaudan or the Voironnais regions (see Appendix A). In 2010, the

residents of the area made on average 236,000 trips between the metropolis and the rest of the greater region on a weekday. People living outside from the metropolis made about 75% of these trips, which reflects its attractiveness and consequences of the suburbanization process. Significant changes in modal shares have occurred during the decade 2010-2020 in the whole perimeters (including rural areas). The modal share of bike has doubled, and walking habits increased as well, while the modal share of car decreased by 6.3 points (see Appendix B). At the metropolitan level, the attractiveness of active modes (walking and biking) is becoming even more important.

3.3. The highly vulnerable and low transport-affordability households in the Grenoble area

Blandin et al. (2023) present VulMob, a multidimensional indicator that enables to identify low transport-affordability households and highly vulnerable (HV) households and to elaborate a typology of HV profiles. VulMob is organized in four dimensions: financial resources, work constraints, heavy car use and structural constraints. All 13 factors constituting the dimensions are detailed in Table 1. It provides a multifactorial evaluation of the transport vulnerabilities at the individual level but also allows identifying low transport-affordability households who are defined as households combining low-income and high mobility costs (D1F1 and D1F2 in Table 1). Moreover, households cumulating at least six transport vulnerabilities over 13 are considered as HV. We applied this methodology to the Local Household Travel Survey to define a typology of HV households in the Grenoble area.

19,932 (5.5%) households are identified as low transport-affordability and 34,749 households (9.6%) as HV. The hierarchical clustering analysis (HCA) conducted in the six most populated sectors[1] (Grésivaudan, Sud Grésivaudan, Bièvre, Voironnais, Sud-Isère and the Metropolis) leads to a typology, composed of five main profiles of cumulated vulnerabilities (see Table 2). Households in the same profile share common vulnerability patterns.

[1] We excluded Chartreuse and Vercors sectors because of the small size of the sample for statistical analysis.

Table 1 - Dimensions and factors of the VulMob indicator
(*Source: Blandin et al. 2023)*

Dimension	**Factor**	**Variable**	**Polarity**	**Threshold** (vulnerable if…)
1 - Financial resources	D1F1 - Income per consumption unit[2]	$income$	+	< Poverty line
	D1F2 - Mobility expenses	$\frac{mobility\ expenses}{income}$	-	> 2M
2 - Work constraints	D2F1 - Share of mandatory trips	$\frac{N_{mandatory\ trips}}{N_{trips}}$	-	> 75%
	D2F2 - Nighttime job trips	$\frac{N_{night\ trips}}{N_{trips}}$	-	At least one
	D2F3 - Commuting distance	$distance_{home-work}$	-	> 10 km (SDES)
3 - Heavy car use	D3F1 - Frequency of car use	/	-	"Everyday"
	D3F2 - Share of car trips	$\frac{N_{car\ trips}}{N_{trips}}$	-	= 100%
	D3F3 - Maximum distance by car	max($distance_{car}$)	-	> Impact area (km)
	D3F4 - Car efficiency	Crit'Air sticker	-	≥ 3
4 - Structural constraints	D4F1 – Public Transport Accessibility	PTAL	+	< Level 3
	D4F2 - Service Accessibility	$\overline{distance_{services\ avg}}$	-	> Q8
	D4F3 - Car access	$\frac{N_{cars}}{N_{drivers}}$	+	Less than 1 for 2
	D4F4 - Household structure *(categorical variable – 12 categories)*	Categories of structure	/	single pensioners, single-parent families large families (3 and more children)

NB: The structural constraint dimension refers to the constraints associated to the residential location (public transport accessibility and service accessibility) and not the individual mobility habits. This dimension is therefore associated to a potential vulnerability that may be overcome with different adaptation solutions (such as modal shift, a change in destination or the purchase of a new car).

[2] Income per consumption unit (or standard of living) is equal to the disposable income of the household divided by the number of consumption units (CU). The number of CU is calculated according to the following scale: one for the household referent + 0.5 for other people over 14 years old + 0.3 for children under 14 years old (OECD).

Table 2 - Typology of the HV households in the Grenoble area

Profiles of HV households						
	Low transport-affordability	**A** monetary constrained	**B** without alternative	**C** night worker	**D** structural heavy car users	**E** costly heavy car users
Number of households	19,932	3,452	5,705	10,702	5,000	6,024
Share of the global sample	5.5%	0.96%	1.59%	2.98%	1.39%	1.68%
Share of the HV households	-	9.42%	16.42%	30.80%	14.39%	17.34%
Pattern of cumulated vulnerabilities	-Low income -High mobility expenses	- Low income - Bad public transport accessibility	- Bad service accessibility - Bad public transport accessibility	- Nighttime job trips - Living far from the work place	- Family weaknesses - Daily car use	- High mobility expenses - Exclusive car use - Bad public transport accessibility

Residential location of the HVs		
Sector	**Number of HV households in this sector**	**Share of the HVs (%)**
Métropole	13,973	41.0
Bièvre	3,765	11.1
Grésivaudan	4,971	14.6
Voironnais	3,625	10.6
Sud Grésivaudan	3,506	10.3
Vercors	691	13.4
Chartreuse	583	1.7
Sud Isère	3,635	10.7
Total	**34,749**	**100**

4. Methodology

4.1. LEZ scenarios

We focus on evaluating the impacts of the regulatory timetable in the *Loi Climat et Résilience* (Figure 3). Circulation restrictions are introduced following a standardized classification of the vehicles in six categories using Crit'Air stickers based on age and fuel type (Appendix C).

In Grenoble, policy makers studied two LEZ perimeter scenarios. The first one (A, in orange in Figure 4) is limited to the center of the Metropolis, i.e. Grenoble inner ring, while a larger perimeter (B, in yellow in Figure 4) is extended to 12 other cities from the first crown. For each perimeter, we consider two modalities for the ban time slot: either the LEZ is implemented 24 hours a day (permanent), or only between 8AM and 8PM (temporary). In both cases, we assume that the LEZ would be operational 7 days a week. In the main text of the article, we only detail the results associated to the permanent

LEZ. Impacts associated to the temporary time schedule are available in Appendix D. Table 3 provides a quick summary of the two-studied scenarios.

Figure 3 - Schedule of Crit'Air labels affected by the ban in a LEZ in France, as defined in the Loi Climat et Résilience (2021)

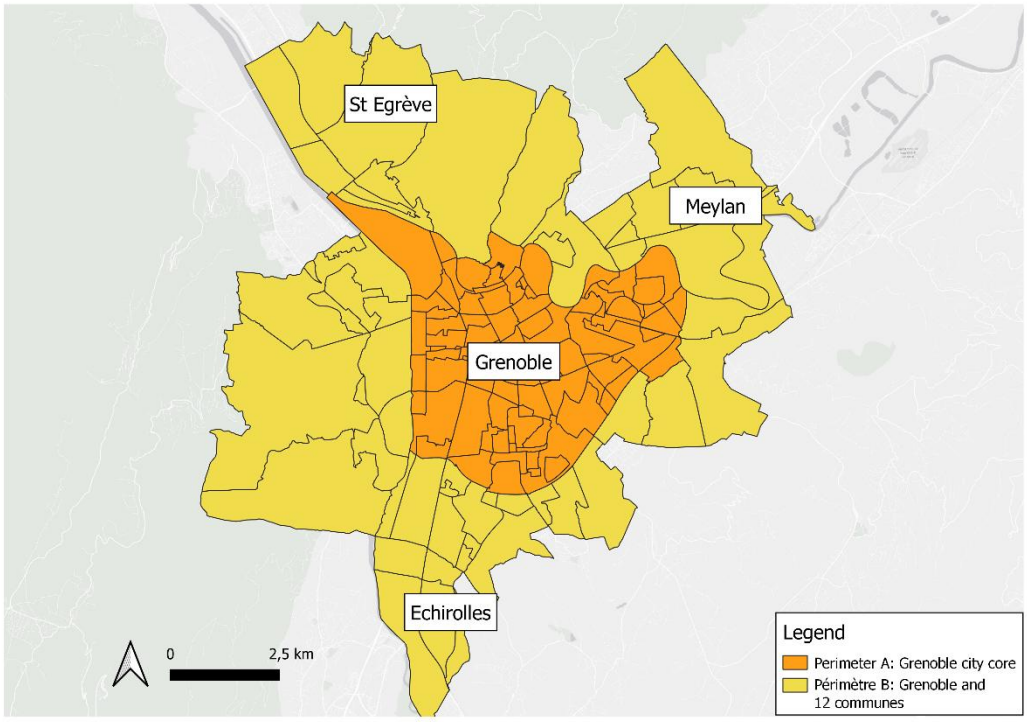


Figure 4 - Studied perimeters for the implementation of a LEZ

Table 3 - Summary of the two studied scenarios

	Scenario A	**Scenario B**
Perimeter	Grenoble	Grenoble + 12 municipalities[3]
Number of car trips for a typical day	250,000	430,000
Temporality	7/7 days a week	7/7 days a week

4.2. Adaptation hypothesis

[3] The 12 municipalities are: Échirolles, Eybens, Fontaine, Gières, La Tronche, Le Pont-de-Claix, Meylan, Saint-Égrève, Saint-Martin-d'Hères, Saint-Martin-le-Vinoux, Seyssinet-Pariset et Seyssins

We rely on the Local Household Travel Surveys. To evaluate the impacts of the LEZ, we identify the car trips that start, cross and/or arrive in the defined perimeter. We consider that the vehicle fleet is the one identified in the 2020 survey, and take into account the most efficient car of each household. For each trip made by car[4], we check whether it would be forbidden by the LEZ.

In our approach, we focus on the ability to adapt to the LEZ in terms of modal shift. We consider the purchase of a ZFE-compatible vehicle as the solution of last resort. Indeed, beyond the fact that all vehicles, even electric ones (Woo et al., 2022), continue to emit fine particles, the development of active mobility is accompanied by significant health gains and negative externalities reductions (greenhouse gases, noise…) (Bouscasse et al., 2022a) which it is important to highlight.

In order to adapt to the LEZ, we consider households have different solutions according to the following logical chain (Figure 5):

1. Is the car trip transferable to other modes of transportation?
2. If not, according to the trip purpose, can the trip be modified or cancelled?
3. If not, can the household purchase a LEZ-compatible car?

These steps are defined to explore the different possibilities for adaptation. Modal shift makes it possible to maintain the same travel pattern, while modifying the route may require more adaptation effort. Buying a new car would solve all the adaptation problems, but is considered a solution of last resort if one of the objectives of the LEZs is to reduce car use.

4.2.1. Modal shift

To evaluate the possible modal shifts solutions for households affected by the LEZ, we consider trip distances, ascending elevation, inclusion in a loop and compare the travel time by car and public transport (bus and tramway only; train options being excluded).

Distances defining a modal shift possibility are based on median behaviors observed in the EMD data (2010) for walk and bike and on Bouscasse et al., (2022a). We apply these modal shift assumptions (Table 4) to the data from the "trips" Table of the Local Travel Households Survey. For each car trip, we identify the corresponding loop, calculate the total distance and the maximum ascending elevation

[4] This study excludes motorbikes and scooters, as they account for 0.3% of the total number of trips in the survey.

of the loop, and estimate for each trip the duration time by car and by public transport using the OpenTripPlanner API[5] based on Google Maps.

Table 4 - Summary of the modal shift hypothesis

Transport mode				
Trip	<1 km	<3 km	<8 km	> 8km
Loop	<4 km	<12 km	<20 km	> 20 km
Ascending elevation	<6%	<6%	<10%	

4.2.2. Trip purposes

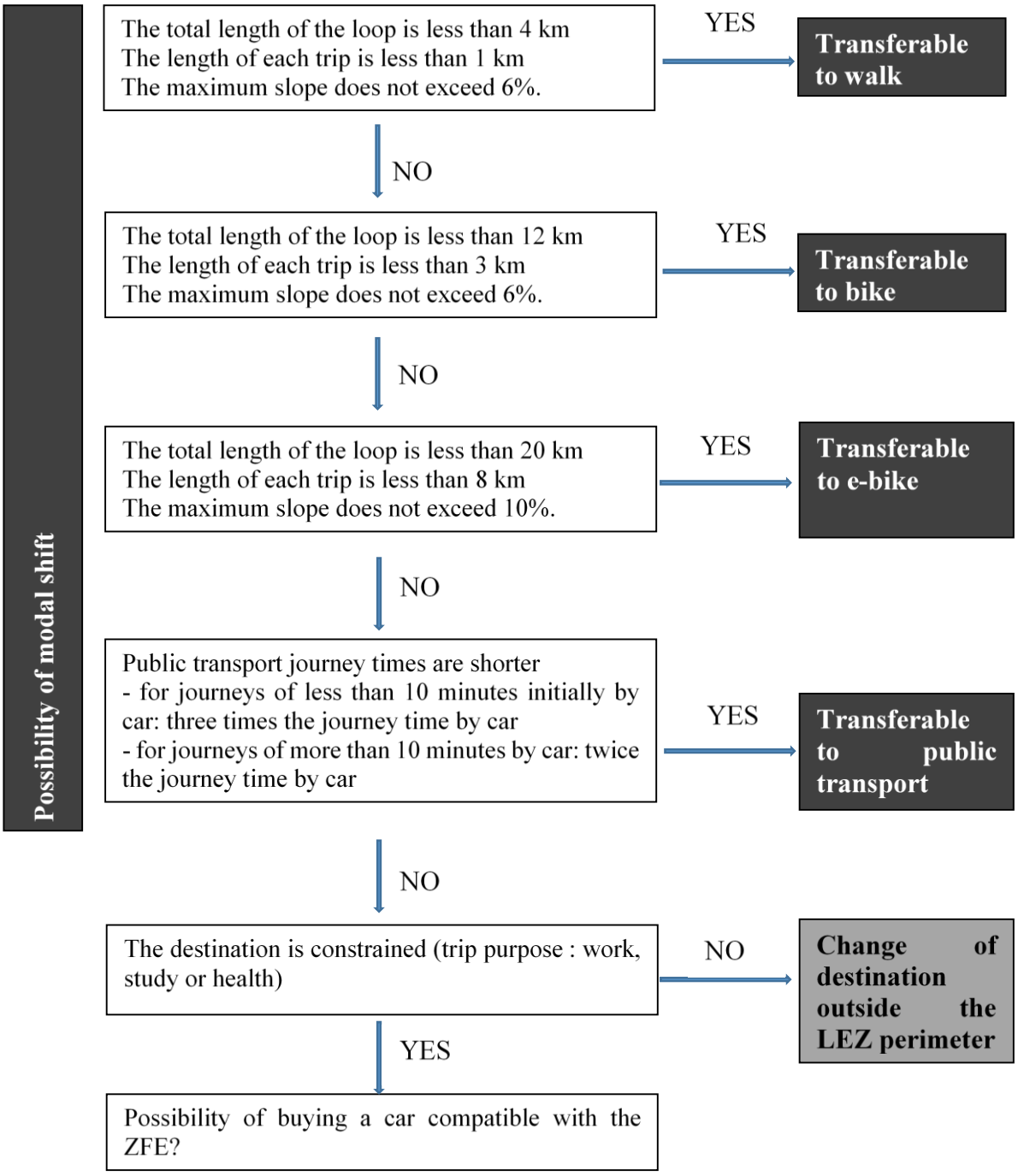
Some trips are more constrained than others: commuting trips are constrained by the destination, whereas trips for leisure or shopping activities can be modified, particularly in terms of destination. Of course, this argument raises important economic issues that deal with the attractiveness of the urban core. We assume that the only destinations that cannot be modified are places of work, study and health. If these destinations are included in a loop, the loop is therefore considered as "constrained".

4.2.3. Car purchase

While this solution can be considered without much difficulty for some households, it remains financially complicated for modest households. The challenge is to determine at what threshold of annual income per unit of consumption the purchase of such a car is a real problem. The Grenoble conurbation provides financial support to households with a tax income (which takes into account the size of the household) of less than 21.6 k€ per year. This amount is also close to the median income in the sample (21.5 k€/year/cu), that we consider for the analysis.

The possibility of purchasing a car compatible with the LEZ is discussed on the basis of income deciles to target financial support policies.

[5] See https://docs.ropensci.org/opentripplanner/articles/opentripplanner.html for more information



Note: A loop is a combination of successive trips originating and terminating at home. A trip is transferable to another mode if all the trips in the loop are transferable.

Figure 5: Assumptions for adaptation to the LEZ

5. Results

In this section, we quantify the impacts of the LEZ on households living in the Grenoble area, evaluate the potential for adaptation, with the last solution analyzed being the purchase of a LEZ compatible car.

5.1. Assessing the impacts of the LEZ implementation

In the global area, 305,494 households hold a car (80.8% of the sample). 2.2% of these cars will be prohibited by 2023 (Crit'Air 5 and non-classified vehicles), 4.8% by 2024 (Crit'Air 4) and 19.3% by 2025 (Crit'Air 3). Low-income households are more likely to hold the most polluting cars (Appendix E). Yet, the natural renewal of the vehicle fleet should decrease the share of Crit'Air 4, 5 and non-classified cars. Therefore, the ban of Crit'Air 3 vehicles appears as the main issue to face.

Focusing on the global impacts of the LEZ (Table 5), Scenario A would affect 20,225 households in total between 2023 and 2025 (5.6% of the population), while the scenario B would affect 28,854 households over the same period (8.0% of the population). Therefore, extending the perimeter to 13 municipalities would increase the number of affected households by 42.6%. Among the affected households, 10.6% are HV under Scenario A (resp. 11.6% under Scenario B) and represent 0.6% of the global population (resp. 0.9%).

The spatial impacts of the LEZ are heterogeneous. An important share of affected households lives in the perimeter of the LEZ (33% in Scenario A; see Figure 6). The LEZ also affects households living in others parts of the area of study, in particular in Voironnais and Grésivaudan. Additional affected households with the largest perimeter (Scenario B) are mainly located in the Metropolis: increasing the size of the perimeter may particularly affect households living in or close to Grenoble. More details on the residential location of impacted households according to their profiles are given in Appendix H.

Table 5 - Global impacts of the LEZ according to scenarios (*All % are expressed as a share of the global sample.*

Scenario A	**Affected by the LEZ**	**Not affected by the LEZ**	**Total**
Not HV	18,074 *(5.0%)*	306,604 *(85.4%)*	324,678 *(90.4%)*
HV	2,151 *(0.6%)*	32,598 *(9.0%)*	34,749 *(9.6%)*
Total	20,225 *(5.6%)*	339,202 *(94.4%)*	359,427 *(100.0%)*

Scenario B	**Affected by the LEZ**	**Not affected by the LEZ**	**Total**
Not HV	25,516 *(7.1%)*	299,162 *(85.8%)*	324,678 *(90.4%)*
HV	3,338 *(0.9%)*	31,411 *(8.7%)*	34,749 *(9.6%)*
Total	28,854 *(8.0%)*	330,573 *(92.0%)*	359,427 *(100.0%)*

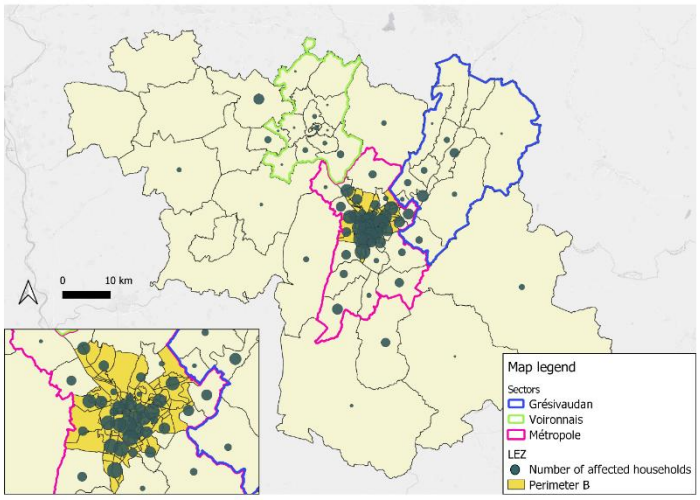


Figure 6 - Residential location of the affected households in scenario B

5.2. What capacity to adapt to the LEZ?

We evaluate the extent to which adaptation solutions exist for affected households, considering the existing vulnerability issues, the potential for modal shift and the possibility to change the trip destination. We focus on the most ambitious scenario (B), which has been adopted by the local decision-makers. Scenario A results are described in Appendix F. Tables 6 and 7 show the potential for adaptation for the households concerned by the LEZ, considering two levels of analysis: households and trips. For households, we consider that they are affected and with no adaptation if at least one trip is concerned. For trips, we analyze only the trips made by car.

8% of the households are affected by the LEZ, 7% are not HV and 0.9% are HV. Proportionally, HV households are slightly more affected, as 9.6% of them are affected by the LEZ compared with 7.9% of non-HVs. This is even more marked at trip level: 17% of HV trips are affected by the LEZ, compared with 8.9% of non-HV trips. This may be due to a relative concentration of HV people in the metropolis itself as shown in (Blandin et al., 2023) (see Table 2) and more generally HV households that are affected by the LEZ have more trips within the LEZ perimeter. Indeed, car trips in the LEZ perimeter represent 20.8% of the car trips made by households affected by the LEZ; this rises to 48.3% for HV households[6].

[6] Number of car trips made in the perimeter divided by the total number of car trips made by the same households in the global area, without considering the restrictions related to Crit'Air stickers.

Table 6 - Overview of the LEZ impacts with the adaptation solutions, by profiles. Households analysis

	Households analysis							
	Total	Non-HV	HV	A- Monetary constrained	B- Without alternative	C- Night workers	D- Structural heavy car users	E- Costly heavy car users
1- **Total** number of households	359 427	324 678	34 749	3 452	5 705	10 702	5 000	6 024
% of all households (Total - 1)	*100,00%*	*90,33%*	*9,67%*	*0,96%*	*1,59%*	*2,98%*	*1,39%*	*1,68%*
2- Households **affected by the LEZ** (by 2023)	28 854	25 516	3 338	583	527	657	535	590
% of all households (Total - 1)	*8,03%*	*7,10%*	*0,93%*	*0,16%*	*0,15%*	*0,18%*	*0,15%*	*0,16%*
%of all, non-HV and HV households (Total, non-HV, HV - 2)	*8,03%*	*7,86%*	*9,61%*	*16,89%*	*9,24%*	*6,14%*	*10,70%*	*9,79%*
3- Households affected by the LEZ + **No Modal report**	12 411	10 525	1 886	351	438	339	160	472
% of all households (Total - 1)	*3,45%*	*2,93%*	*0,52%*	*0,10%*	*0,12%*	*0,09%*	*0,04%*	*0,13%*
% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)	*43,0%*	*41,2%*	*56,5%*	*60,2%*	*83,1%*	*51,6%*	*29,9%*	*80,0%*
4- Households affected by the LEZ + No modal report + **Constrained destination**	8 710	7 180	1 530	328	140	312	160	463
% of all households (Total - 1)	*2,42%*	*2,00%*	*0,43%*	*0,09%*	*0,04%*	*0,09%*	*0,04%*	*0,13%*
% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)	*30,2%*	*28,1%*	*45,8%*	*56,3%*	*26,6%*	*47,5%*	*29,9%*	*78,5%*
5- Households affected by the LEZ + No modal report + Constrained destination + **Financially constrained (low transport affordability)**	1 607	1 312	295	112	7	21	8	140
% of all households (Total - 1)	*0,45%*	*0,37%*	*0,08%*	*0,03%*	*0,02%*	*0,61%*	*0,14%*	*1,31%*
% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)	*5,6%*	*5,1%*	*8,8%*	*19,2%*	*1,3%*	*3,2%*	*1,5%*	*23,7%*

Notes:
- 1,530 households are affected by the LEZ, highly vulnerable, without modal shift solution for at least one trip that is constrained by the destination (third column, situation 4), while they are 8,710 in the global sample (first column, situation 4). Looking at the profiles of HV households: for the profile A (Monetary constrained), 328 households are affected by the LEZ, with no modal shift for at least one trip, that is constrained by the destination (third column, situation 4).
For percentages,
- The first line is the share of the total population. For instance, 0.52% of the total households are HV households, affected by the LEZ and with no modal shift for at least one trip (third column, situation 3).
- The second line is the share of HV or non-HV households or within each profile affected by the situations 2 to 5. For instance, 56.6% of the highly vulnerable households that are affected by the LEZ remain without any modal shift solution for at least one trip (third column, situation 3).
** p-value < 0.05*

Table 7 - Overview of the LEZ impacts with the adaptation possibilities, by profiles. Trips analysis

	Car trips analysis by HV profiles and mode of transport for modal report							
	Total	Non-HV	HV	A- Monetary constrained	B- Without alternative	C- Night workers	D- Structural heavy car users	E- Costly heavy car users
1- **Total** number of car trips	956 858	885 093	71 765	9 817	13 740	19 974	10 506	11 403
% of all trips (Total - 1)	*100,0%*	*92,5%*	*7,5%*	*1,0%*	*1,4%*	*2,1%*	*1,1%*	*1,2%*
2- Trips **affected by the LEZ** (by 2025)	90 815	78 645	12 170	2 907	1 393	2 289	2 758	2 098
% of all trips (Total - 1)	*9,5%*	*8,2%*	*1,3%*	*0,3%*	*0,1%*	*0,2%*	*0,3%*	*0,2%*
% of all, HV and non-HV trips (Total, HV, Non-HV - 2)	*9,5%*	*8,9%*	*17,0%*					
% of affected trips with a modal shift solution	*60,4%*	*61,6%*	*52,9%*	*50,2%*	*22,2%*	*49,2%*	*86,3%*	*27,3%*
... by Bike	*14,8%*	*15,0%*	*13,8%*	*24,7%*	*0,0%*	*21,6%*	*8,4%*	*0,0%*
... by E-bike	*28,6%*	*28,5%*	*28,9%*	*11,2%*	*10,4%*	*11,3%*	*75,8%*	*19,9%*
... by Walking	*3,2%*	*3,6%*	*0,7%*	*0,8%*	*0,0%*	*0,0%*	*2,0%*	*0,0%*
... by Public transport	*13,8%*	*14,5%*	*9,5%*	*13,4%*	*11,8%*	*16,4%*	*0,0%*	*7,3%*
3- Trips affected by the LEZ + **No Modal report**	35 925	30 190	5 735	1 448	1 084	1 162	379	1 693
% of all trips (Total - 1)	*3,8%*	*3,2%*	*0,6%*	*0,2%*	*0,1%*	*0,1%*	*0,0%*	*0,2%*
% of all, HV and non-HV affected trips (Total, HV, Non-HV - 2)	*39,6%*	*38,4%*	*47,1%*	*49,8%*	*77,8%*	*50,8%*	*13,7%*	*80,7%*
4- Trips affected by the LEZ + No modal report + **Constrained destination**	21 816	17 838	3 978	887	262	934	379	1306
% of all households (Total - 1)	*2,3%*	*1,9%*	*0,4%*	*0,1%*	*0,0%*	*0,1%*	*0,0%*	*0,1%*
% of all, HV and non-HV households (Total, HV, Non-HV - 2)	*24,0%*	*22,7%*	*32,7%*	*30,5%*	*18,8%*	*40,8%*	*13,7%*	*62,2%*
5- Trips affected by the LEZ + No modal report + Constrained destination + **Financially constrained** (low transport affordability)	2 940	2 024	916	331	29	102	40	379
% of all households (Total - 1)	*0,3%*	*0,2%*	*0,1%*	*0,0%*	*0,0%*	*0,0%*	*0,0%*	*0,0%*
% of all, HV and non-HV households (Total, HV, Non-HV - 2)	*3,2%*	*2,6%*	*7,5%*	*11,4%*	*2,1%*	*4,5%*	*1,5%*	*18,1%*

Notes:
- 3,978 affected by the LEZ are made by highly vulnerable households, without modal shift solution and constrained by the destination (third column, situation 4), while they represent 21,816 trips in the global sample (first column, situation 4). Looking at the profiles of the HV households: for the profile A (Monetary constrained), 887 trips are affected by the LEZ, with no modal shift, constrained by the destination.
For percentages,
- The first line is the share of the total population. For instance, 0.60% of the total number of trips are made by HV households, affected by the LEZ and with no modal shift solution (third column, situation 3).
-The second line is the share of HV or non-HV (also divided by profiles) households affected by the situations 2 to 5. For instance, 47.1% of the trips made by HV households affected by the LEZ, remain without any modal shiftt solution (third column, situation 3).
** p-value < 0.05*

Analysis of the adaptation solutions

First, modal shift (line 3 in Table 6) constitutes a solution for 57% (=100%-43%) of households affected by the LEZ. However, this is more likely to be the case for non-HV households than for HV households, since 56.5% of the HV affected households remain without modal shift solution, while it is the case for only 41.2% of the non-HV affected households (Figure 7). Overall, 0.5% of the population is HV, affected by the LEZ and with no modal shift solution. Considering trips (Table 7), 60.4% of car trips have a modal shift solution. 61.6% of non-HV household trips have a modal shift solution, but it is only 52.9% for HV households.

Second, after considering the possibility of destination change for non-constrained trips, 45.8% of HV affected households remain without solution, while this amounts to 28.1% only for non-HV affected households. The gap is therefore widening between the two population categories. At the trip level, the gap remains similar to that observed after modal shift: 32.7% of affected trips by HV households are constrained in addition to having no modal shift solution, compared with 22.7% of trips by non-HV households. HVs' commuting trips (home-work) are more located within the LEZ and that they make fewer "optional" trips.

Third, among the households that remain without modal report solutions and with constrained trips, some are also low transport-affordability households (5.6% of the households affected by the LEZ; 0.4% of all households), which will further reduce their ability to adapt with alternative solutions such as buying a LEZ-compatible car (see Section 5.3). They represent 1,607 households that would require support policies. Among them, some suffer from a combination of financial vulnerability and other vulnerabilities: 0.1% of the population is HV, poor and has no solution to modal shift or change of destination.

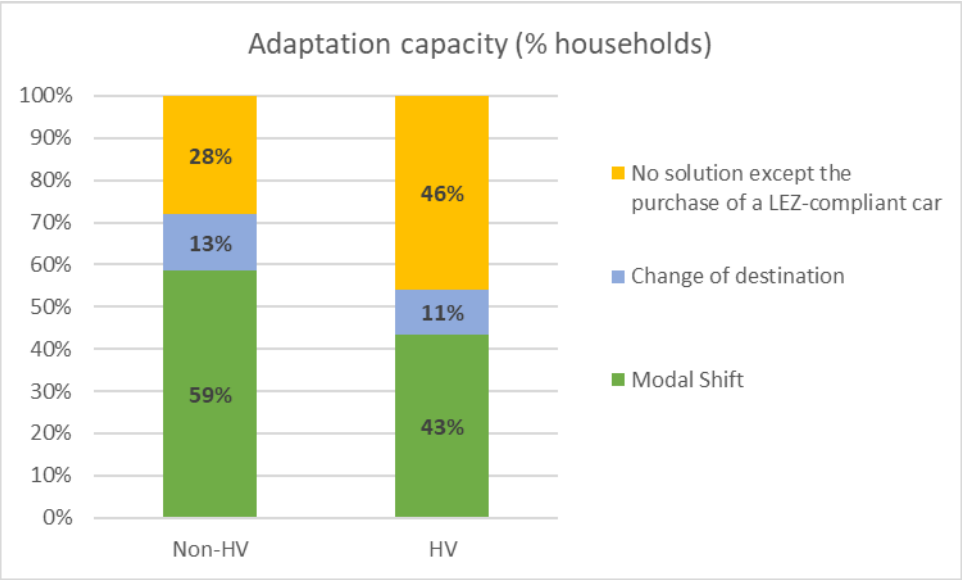


Figure 7: Non-HV and HV households' ability to adapt to the LEZ

Analysis by highly vulnerable profiles – household level

The LEZ has differentiated impacts on the different HV profiles (Table 6 and Figure 8). First, the share of households without modal shift solution significantly varies between 29.9% (Profile D *"Structural heavy car users"*) to 83.1% (Profile B *"Without alternative"*) of the affected households, while it represents 43.0% of the households in the global sample. However, profile B has fewer constrained trips than other households do and after considering the possibility to change destination, only 26.6% of them remain without solution (no modal shift and constrained trip), which is less than the general population. At the other end of the scale, 78.5% of the "*costly heavy car users*" (Profile E) remain without solution.

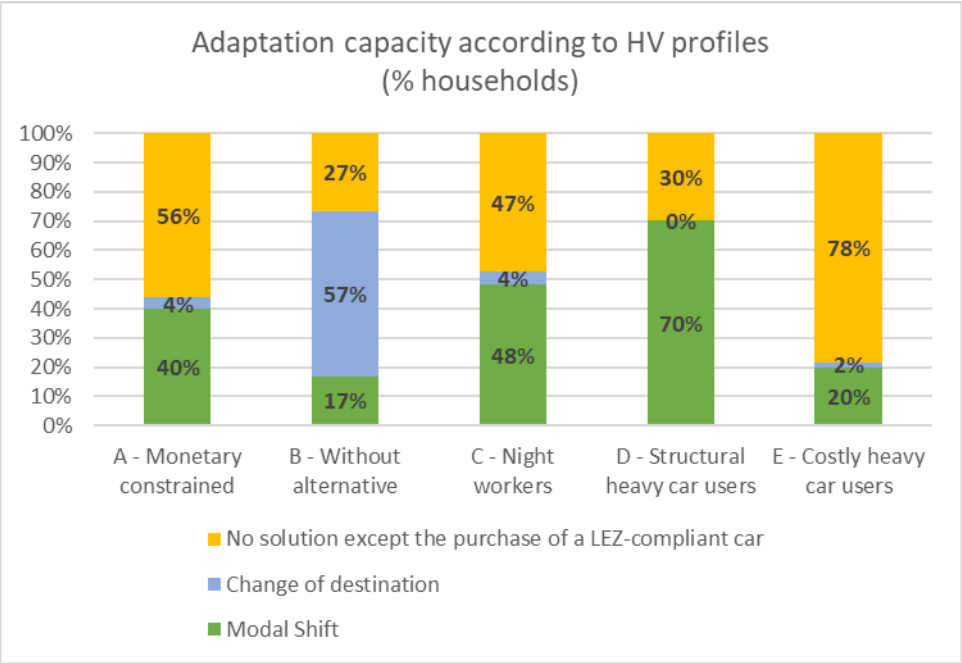


Figure 8: Adaptation capacities to the LEZ of HV households according to profiles

Analysis of the modal report, including by highly vulnerable profiles – car trips level

Table 7 and Figure 9 propose an analysis by vulnerability profile at trip level, which also makes it possible to look at the possible car alternatives for each of them.

Conventional cycling and public transport are two alternatives that allow almost one-third of the journeys affected by the LEZ to be reported (14.8% and 13.8% respectively). E-bikes would be used for almost another third of trips (28.6%), while walking remains marginal in terms of modal shift potential (3.2%). The overall potential for modal shift is lower for journeys made by HV households, as a result of a lower capacity to shift to walking and public transport. On the other hand, modal shift towards cycling, whether conventional or electric, is very similar whether the household is HV or not.

These modal shift possibilities remain contrasted according to the different profiles of HV households. In particular, conventional bikes could allow shifting almost 25% of the trips made by "*monetary constrained"* households, and e-bikes appear as a great solution for "*structural heavy car users"*. On the contrary, households "*without alternatives"* and "*costly heavy car users"* have no possibility to report their trips to conventional bikes (0%) and a low access to e-bike (respectively 10.4% and 5.7%) due to their residential location (see Appendix G). 77.8% and 85.1% of affected trips of these two profiles remain without modal shift solution. The specificity of the profile "*costly heavy car users"* is

also that 77.1% of the affected trips have a constrained destination. Although this profile only concerns 1.7% of the population, it should be noted that these journeys would be particularly affected by the LEZ, which is consistent with the fact households in this profile live mainly in the Metropolis, Voironnais and Grésivaudan (Appendix G).

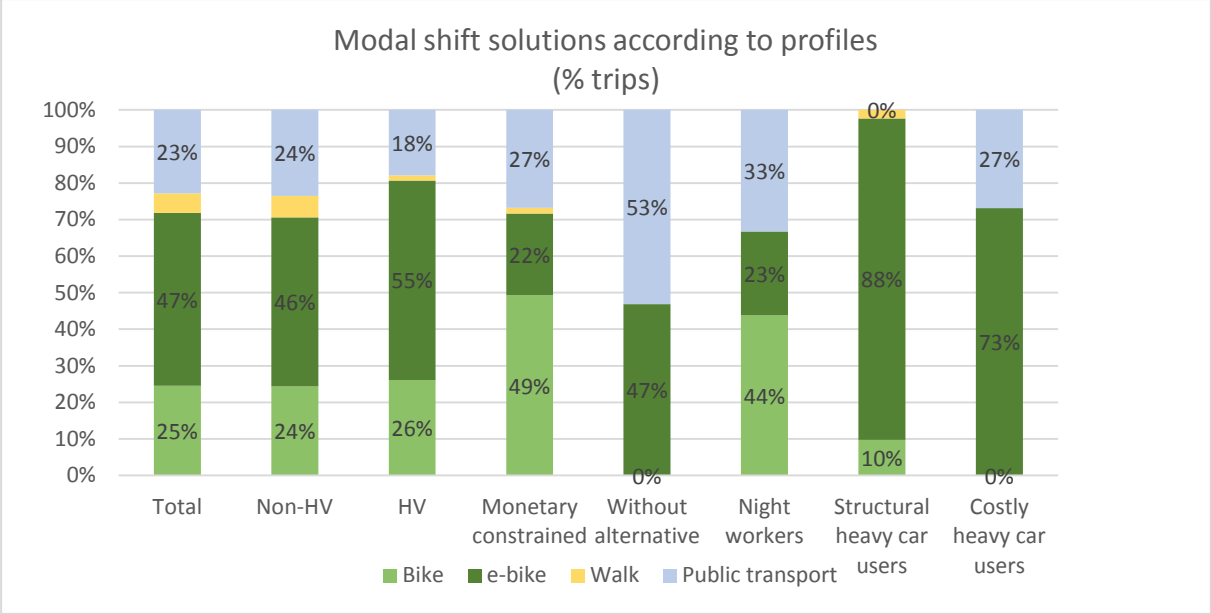


Figure 9: Modal shift solutions by mode for non-HV and HV households, and for each HV household profile (% of journeys)

We also explore the impacts of the two variants of the scenario B:

1. Comparing the results of scenarios A (Appendix F) and B, a larger perimeter implies greater impacts on both HV and non-HV households and higher difficulties of adaptation. Indeed, 23.7% of the affected households may remain without modal shift solutions and with constrained trips under scenario A, while this share increases to 30.2% under the scenario B. Among them, 15.7% (1,530/8,710) are HV in scenario A and 17.6% (750/4,787) in scenario B.
2. The modification of the ban schedule reducing the time window to 8AM-8PM (Appendix D) does not considerably change the number of affected households. Indeed, it would allow 709 households to avoid the impacts in scenario A and 530 in scenario B, a reduction of respectively 3.5% and 1.8% of affected households in each scenario.

5.3. Purchasing a new car: level of income and subsidies

The last solution to face the consequences of a LEZ is to buy a LEZ-compliant vehicle. We evaluate the potential for buying a new car for the HV households without any modal shift solution and with constrained trip purposes (Table 6 – line situation 4). Considering households below the median income (21.5k€/year/cu) may not afford to buy a LEZ-compatible car, 51% of households in scenario B and 41% in scenario A (Figure 6) have no solution. Among them, the situation is particularly complicated for the 295 low transport-affordability households in scenario B and 190 in scenario A

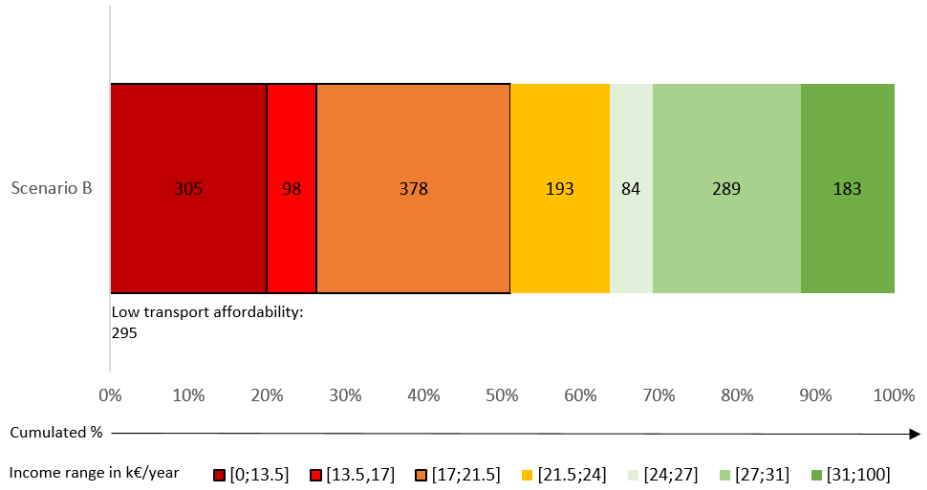


Figure 6 - Income shares associated to the households without modal shift solution and constrained by their destination
Note: The income ranges are defined according to the deciles in the EMC2: 21.5k€ corresponds to the median income per cu. For instance, 28% of the households without modal shift solution and with a constrained destination have an income below 17 k€/year/cu.

6. Discussion

6.1. Support policies and strategies to limit the LEZ impact on HV households according to profiles and to adaptation possibilities

Our results show that HV households are over-represented among households affected by the LEZ and that they have fewer adaptation solutions available than non-HV households. Beyond that, our approach identifies precisely HV households impacted by the LEZ. This is useful to define recommendations according to the households' profiles and their residential locations.

Modal shift is a solution with great potential for helping households affected by the LEZ to adapt. There are many actions to be taken to encourage modal shift.

Encouraging modal shift towards cycling and electric cycling

Our results highlight the great potential of conventional and e-bikes. The effective deployment of this potential is first and foremost conditional on the implementation of vast infrastructure development programs to enable the use of these modes of transport in complete safety, as safety issues are still an obstacle to the adoption of these modes (Cebeci et al., 2023).

Psychological levers must also be targeted. Programs to raise awareness of the benefits of active modes of transport, both in terms of individual health and the impact on well-being, should also be rolled out. Indeed, Bouscasse et al. (2022b) show that individual health benefits induced by physical activity when walking or cycling and collective health benefits induced by lower pollution because of modal shift toward car alternatives are both significant determinants of active mobility modal choice. Climate change concern can also contribute to reduced car use and sustainable mobility (Mouratidis and Næss, 2024). It is also important to show that cycling is easy and enjoyable. This can reinforce self-determination (I ride my bike because I like it, I feel it makes me feel good physically and psychologically) and the intention to ride a bike (Rejeb et al., 2023). Free test days to try the use of a conventional bike or an e-bike could also encourage changes in mentalities and habits.

Various research studies have suggested that social influence could be an important lever when it comes to encouraging people to adopt active mobility (Maness et al., 2015). Lambotte et al (2024) show in particular that interactions between colleagues in the workplace can encourage adoption by peers of active mobility: when a person adopts an active mode of transport, the individuals with whom they interact in the workplace are more likely to also use an active mode of transport. The company should therefore be a privileged place to set up actions in favor of active mobility.

Our results show particularly the enormous potential of the electric bicycle for the ‘without alternative’, ‘costly heavy car users’ and ‘structural heavy car users’ profiles, whose modal shift potential (in terms of number of journeys) is 47%, 73% and 88% respectively. Good quality electric bicycles to cover relatively long distances on a daily basis are still expensive to buy, which may slow down their adoption by households. It is therefore important for these groups to be encouraged through awareness-raising programs, which can take the form of low-cost rentals or loans for several weeks. In particular, ‘structural heavy car users’ have an important modal shift potential to e-bikes. Therefore,

developing bike self-services in Grésivaudan, where many of these households live, might be very helpful.

Finally, purchase subsidies can also be welcome, particularly when this is accompanied by the scrapping of a car. For instance, in France, a €1,500 bonus supports the purchase of an e-bike when a car is scrapped. This solution makes it possible to replace a car that can no longer be used in the LEZ.

Encouraging modal shift towards public transport

The issue related to public transport accessibility is crucial for HV and non-HV households impacted by the LEZ, as this can be a solution for a quarter of their trips. Among impacted HV households, this is the case for all the profiles except for 'structural heavy car users'. In areas where the public transport system is efficient enough, an increased economic accessibility through incentive measures such as a price reduction and/or gratuity and harmonization of fares between different transport operators may encourage people to switch to public transport as shown in Rejeb et al. (2024). But it is important to improve public transport accessibility issues in the sectors particularly poorly deserved (such as Sud Isère and Bièvre). The 'without alternative' profile is particularly concerned. In such sectors, the first objective would be to improve the public transport system provision; as this is hard to set up quickly, it would be interesting to evaluate if the organization of a carpool system could answer to the needs of some households.

Encourage easy adaptation for HV households that cannot rely on modal shift

Among the five typical profiles of HV households, three profiles may have important difficulties to adapt to the LEZ: 1. Monetary constrained households, 2. Households living far from the basic amenities and without access to public transport, and 3. Households with a heavy car use, -and potentially car dependency issues- and high mobility costs. For those who do not have access to public transport, cannot switch to active modes and cannot modify their destination, the development of self-service (as in Grenoble) cars offers an option for those who occasionally need to use a car, but it may be necessary to buy a LEZ-compatible car. A monetary subsidy targeted on HV and low transport-affordability households could be needed: considering our assumptions, 295 households (0.1% of the global sample) are both poor, HV and have no alternative but to purchase a LEZ-compatible car.

Beyond these particular cases of great vulnerability and poverty, subsidies conditioned on income level and possibly on modal shift possibilities will be necessary. In the Grenoble Metropolis, households earning less than 21,690€/year per consumption unit are eligible to a monetary subsidy. This subsidy may be attributed to shift to active modes (bike, e-bike) or to buy a new car.

The level of the subsidy needed will depend on the impact of the LEZs on the price of LEZ-compliant vehicles consistent. With the LEZ generalization, the second-hand car market becomes increasingly constrained, with few opportunities to find car that meets the LEZ requirements at an affordable price (De Vrij and Vanoutrive, 2022). The impact of the introduction of LEZs on the car market, on the vehicle fleet and on the evolution of the price of non-LEZ-compatible cars on the one hand and LEZ-compatible cars on the other has been little studied. Börjesson et al (2020) is one of the few academic studies on this subject. Their evaluation of drivers' losses is calculated based on observed price changes on the used car market: prices of used diesel cars that would be banned in the LEZ (model years 2014 and earlier) sank by over €400 on average in Sweden, in anticipation of the LEZ introduction. Recent press articles estimate LEZ-compatible second-hand cars (Crit'Air 2 or less) cost more than 6,000€ in cities with a LEZ (20minutes, 2023). Moreover, new electric vehicles cost 45 to 50% more than a conventional car (Tabarot, 2023). It would be advisable to consider measures that either limit the increase in the price of LEZ-compliant cars, or allow this to be factored into subsidies.

A temporary LEZ to alleviate the burden on 'night workers' profile

In order to deal with night workers issues, implementing a temporary LEZ instead of a permanent LEZ would alleviate the burden that it may represent for these households, without significantly decreasing the LEZ's overall environmental efficiency (see Appendix D). This could increase public acceptability towards the LEZ implementation which is probably why decision-makers in the Grenoble Metropolis have opted for a temporary LEZ.

Personalized advice to help adapt to the LEZ

A personalized advice system to help HV and non-HV households adapt to the LEZ could be implemented. Its objectives would be:

- assessing the modal shift solutions available to households;

- making certain financial assistance conditional on the impossibility of modal shift and on a per-unit income below the median income;

The approach adopted by the Grenoble conurbation, which provides personalized advice on modal shift solutions as part of the adaptation to the LEZ, is a step in this direction.

6.2. A monitoring system to evaluate the impact of the LEZ on HV households

Policies to combat air pollution are too often implemented without any precise and robust evaluation of their specific impact on air quality, social justice and household practices. It would be interesting to seize the opportunity presented by the introduction of the LEZ to remedy this situation. This could be done, in addition to the household travel surveys carried out every 5 years, by providing evaluation indicators as part of the personalized advice scheme.

6.3. Long-term urban planning implications of LEZs

In this work, we consider a fixed exogenous urban structure and these results do not take account of specific urban planning dynamics. Among the possible impacts of LEZs in terms of long-term urban planning is the relocation of some retail outlets outside the perimeter of the LEZ and of some employment areas. But beyond that, in the medium term, urban planning has an important role to play in reducing car dependency and increasing the accessibility of certain areas, in particular through functional mix, which ensures that an area combines employment (including services, school and shops) and housing (Camagni et al., 2002). This would help to create secondary hubs for economic activities and reduce heavy car use to the urban core (Chardonnel et al., 2017).

7. Conclusion

The work developed in this article shows that it is possible to assess *ex-ante* the impacts of a LEZ on transport vulnerabilities and poverty, using a rigorous approach based on the VulMob multidimensional indicator. The impact of the LEZ is assessed taking into account the capacity for adaptation, i.e. modal shift and change of destination for journeys and households affected by the LEZ. Modal shift seems an adaptation solution with great potential for all households which could improve the environmental and health performance of LEZs. Nevertheless, results in the Grenoble

case study show that not only are vulnerable households more affected by the LEZ than other household but also more of them remain without solution except buying a LEZ-compliant car.

However, the approach developed has certain limitations.

For example, other assumptions about distance or additional time for alternatives to the car, in order to define the potential for modal shift, could be considered, depending on the reasons for travel.

Modal shift calculations could have been carried out in greater detail if the necessary data had been available. For example, no account has been taken of people's age or disabilities (which would reduce the potential for modal shift), nor of multimodal or car-pooling possibilities (which would increase the potential for modal shift). However, the assumptions for a shift to active modes are not very demanding (particularly in terms of distance), so that the shift must be possible for a large proportion of the population. Furthermore, the upward effects would certainly offset the downward effects.

We could also have used a multimodal model such as the one developed for the Grenoble conurbation to model modal shift. In these models, the mode of transport is chosen by means of a discrete choice model in which the generalized cost (summing up the financial and temporal cost of the journey) plays a predominant role. Only changes in infrastructure (increased public transport supply, reduced accessibility by car via a LEZ, etc.) or in the financial conditions of mobility can therefore lead to an increase in the share of modes of transport other than the car. In particular, they do not take into account structural changes in behavior or preferences that would lead agents to accept or even wish to cycle or walk longer distances than at present, because of the environmental or health benefits (increased physical activity). Our aim is to calculate a 'potential' modal shift, which could theoretically be made and not what will actually be achieved by optimizing time and cost, as is the case in multimodal transport models.

Finally, the particular sequence of adaptation solutions adopted considers modal shift as the preferred solution and the purchase of a new car as the last solution. This choice, which is open to discussion, is based on the idea of maximizing all the co-benefits of the LEZ made possible by maximum modal shift (environmental, health and welfare benefits).

Nevertheless, the approach developed in this article should be generalized in order to inform the specific support policies to be implemented for vulnerable households who are affected by the LEZ.

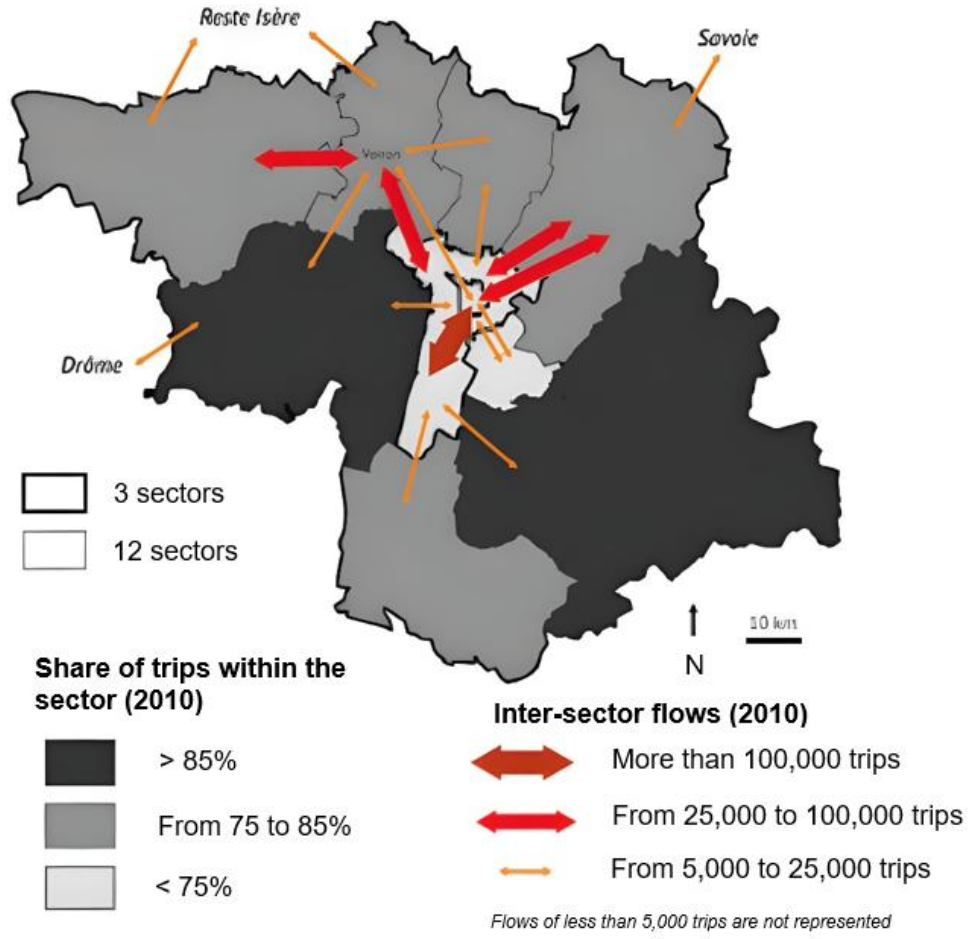
We have carried out an assessment of the LEZ as envisaged in the Climate and Resilience Act, based on Crit'Air stickers, but other LEZ designs or types of policy aimed at restricting car traffic could also be studied.

Grenoble is a particular city: local average income is higher than the national average income level and Grenoble city and metropolis have good cycling and public transport infrastructure. Over the period 2016-20, Grenoble tops the rankings of French towns and cities for the modal share of cycling between home and work (17.4%). These elements may reduce the vulnerability of households living in the Grenoble area to the implementation of the LEZ and limit the transferability of results to other urban contexts. It would then be very interesting to replicate the methodology to very different urban contexts in terms of modal share of active modes, income levels and city size (Marseille, Limoges and Saint Etienne, cities with a lower average income, were at the bottom of the table, with modal shares of less than 2%). It would also be relevant to analyze specific features such as coastal towns with a tourist appeal that has a strong impact on property prices and tend to push the local population to the outskirts of town centers (Bayonne-Anglet-Biarritz conurbation). Vulnerability profiles different from those of the Grenoble region could emerge, as well as a typology of specific urban contexts according to HV profiles..

Appendix

Appendix A: Mobility flows within and between the different sectors (source: Résultats EMD 2010 SMTC Grenoble Alpes Métropole)

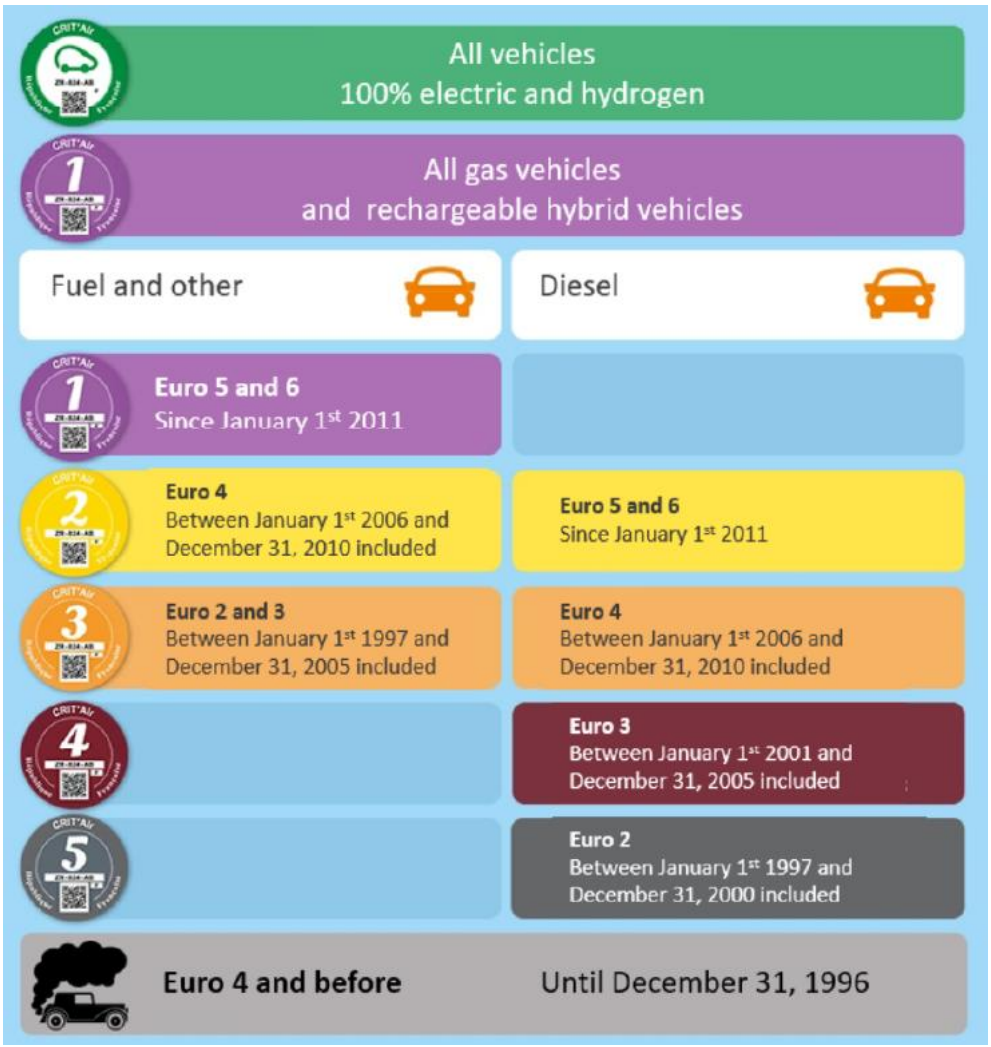
f



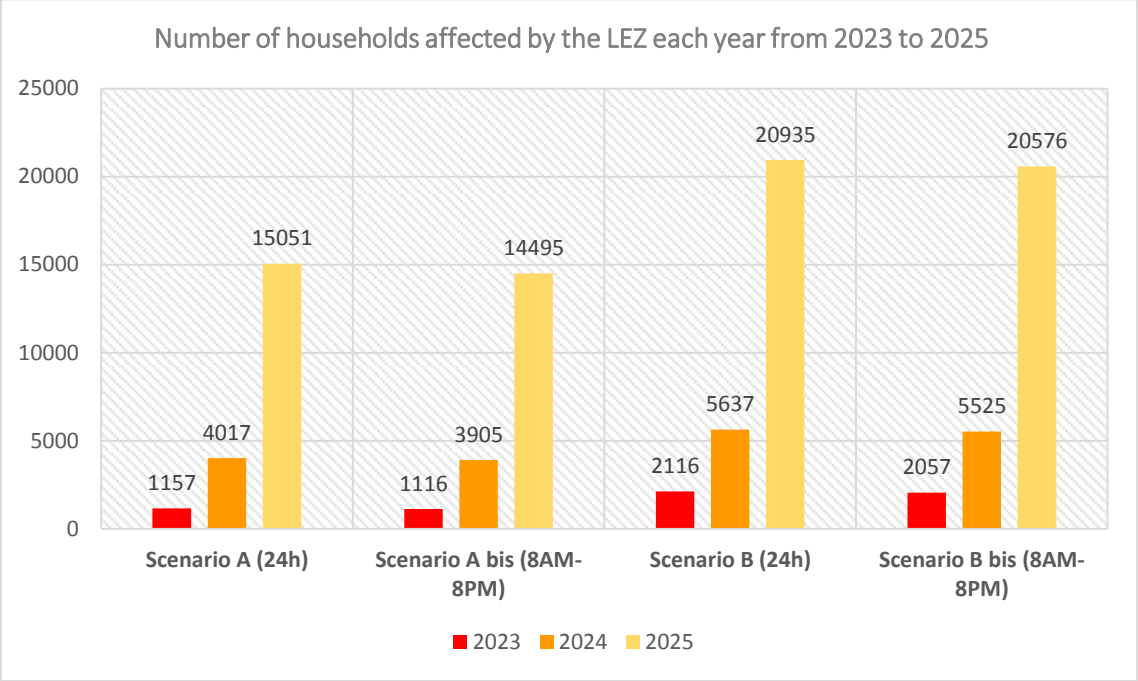
Appendix B : Evolution of the modal shares in number of trips (source: EMD and EMC2 data)

Mode	Share of trips			
	Global area		Metropolis only	
	2010	2020	2010	2020
Car	59.4	53.6	46.1	39.7
Public transport	10.7	10.6	16.2	15.7
Walking	24.9	29.2	32.6	35.9
Biking	2.5	4.7	3.9	7.3
Other	2.5	1.9	1.2	1.4
Total	**100**	**100**	**100**	**100**

Appendix C: Crit'Air stickers

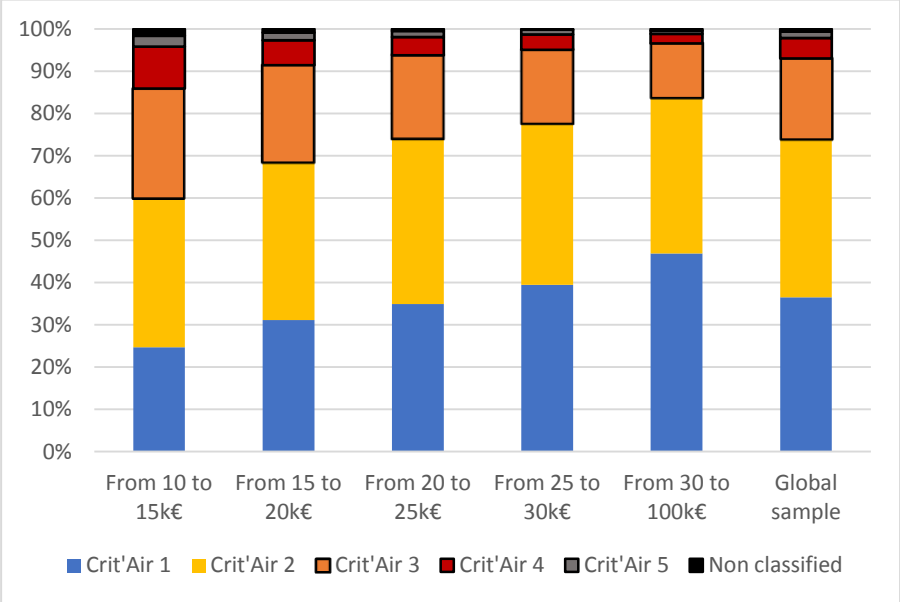


Appendix D: Results of the different LEZ scenarios



Ban year	Scenario A (24h)	Scenario A bis (8AM-8PM)	Scenario B (24h)	Scenario B bis (8AM-8PM)
2023	1,157	1,116	2,116	2,057
2024	4,017	3,905	5,637	5,525
2025	15,051	14,495	20,935	20,576
Total	**20,225**	**19,516**	**28,688**	**28,158**

Appendix E: Crit'Air sticker associated to the households' best car according to the annual income by consumption unit (source: EMC2 data)



Appendix F

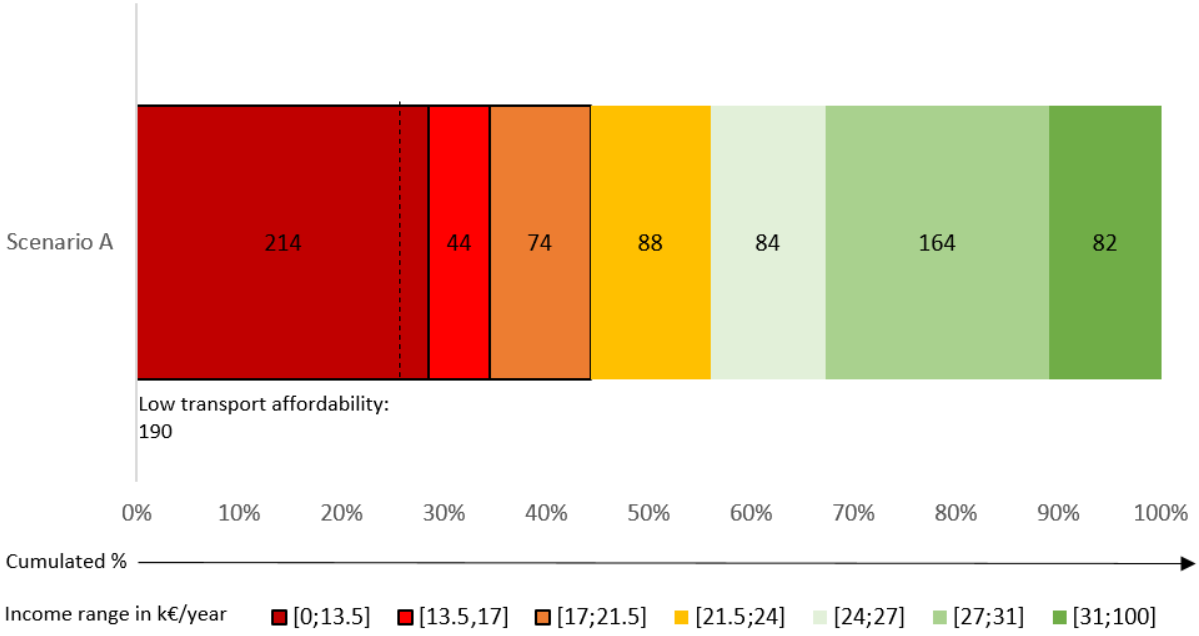
Table F.1 – Households analysis for scenario A

Scenario A	Households analysis							
	Total	Non-HV	HV	A- Monetary constrained	B- Without alternative	C- Night workers	D- Structural heavy car users	E- Costly heavy car users
1- **Total** number of households	359 427	324 678	34 749	3 452	5 705	10 702	5 000	6 024
% of all households (Total - 1)	*100,00%*	*90,33%*	*9,67%*	*0,96%*	*1,59%*	*2,98%*	*1,39%*	*1,68%*
2- Households **affected by the LEZ** (by 2023)	20 225	18 074	2 151	332	246	383	358	491
% of all households (Total - 1)	*5,63%*	*5,03%*	*0,60%*	*0,09%*	*0,07%*	*0,11%*	*0,10%*	*0,14%*
%of all, non-HV and HV households (Total, non-HV, HV - 2)	*5,63%*	*5,57%*	*6,19%*	*9,62%*	*4,31%*	*3,58%*	*7,16%*	*8,15%*
3- Households affected by the LEZ + **No Modal report**	7 011	6 080	931	102	188	143	70	373
% of all households (Total - 1)	*1,95%*	*1,69%*	*0,26%*	*0,03%*	*0,05%*	*0,04%*	*0,02%*	*0,10%*
% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)	*34,7%*	*33,6%*	*43,3%*	*30,7%*	*76,4%*	*37,3%*	*19,6%*	*76,0%*
4- Households affected by the LEZ + No modal report + **Constrained destination**	4 787	4 037	750	79	57	116	70	370
% of all households (Total - 1)	*1,33%*	*1,12%*	*0,21%*	*0,02%*	*0,02%*	*0,03%*	*0,02%*	*0,10%*
% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)	*23,7%*	*22,3%*	*34,9%*	*23,8%*	*23,2%*	*30,3%*	*19,6%*	*75,4%*
5- Households affected by the LEZ + No modal report + Constrained destination + **Financially constrained (low transport affordability)**	871	678	193	92	3	10	2	81
% of all households (Total - 1)	*0,24%*	*0,19%*	*0,05%*	*0,03%*	*0,01%*	*0,29%*	*0,04%*	*0,76%*
% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)	*4,3%*	*3,8%*	*9,0%*	*27,7%*	*1,2%*	*2,6%*	*0,6%*	*16,5%*

Table F.2 – Trips analysis for scenario A

Scenario A	Car trips analysis by HV profiles and mode of transport for modal report							
	Total	Non-HV	HV	A- Monetary constrained	B- Without alternative	C- Night workers	D- Structural heavy car users	E- Costly heavy car users
1- **Total** number of car trips	956 858	885 093	71 765	9 817	13 740	19 974	10 506	11 403
% of all trips (Total - 1)	*100,0%*	*92,5%*	*7,5%*	*1,0%*	*1,4%*	*2,1%*	*1,1%*	*1,2%*
2- Trips **affected by the LEZ** (by 2025)	56 126	48 624	7 502	1 316	485	1 493	2 195	1 279
% of all trips (Total - 1)	*5,9%*	*5,1%*	*0,8%*	*0,1%*	*0,1%*	*0,2%*	*0,2%*	*0,1%*
% of all, HV and non-HV trips (Total, HV, Non-HV - 2)	*5,9%*	*5,5%*	*10,5%*					
% of affected trips with a modal shift solution	*67,7%*	*68,1%*	*63,2%*	*77,2%*	*20,2%*	*50,8%*	*7,1%*	*18,5%*
... by Bike	*16,6%*	*18,3%*	*10,9%*	*25,4%*	*0,0%*	*22,0%*	*7,0%*	*0,0%*
... by E-bike	*33,7%*	*31,9%*	*39,7%*	*20,5%*	*3,5%*	*14,2%*	*0,1%*	*6,3%*
... by Walking	*1,6%*	*1,7%*	*0,3%*	*1,7%*	*0,0%*	*0,0%*	*0,0%*	*0,0%*
... by Public transport	*15,8%*	*16,2%*	*12,3%*	*29,6%*	*16,7%*	*14,5%*	*0,0%*	*12,2%*
3- Trips affected by the LEZ + **No Modal report**	18 014	15 253	2 761	298	387	734	180	1 042
% of all trips (Total - 1)	*1,9%*	*1,6%*	*0,3%*	*0,0%*	*0,0%*	*0,1%*	*0,0%*	*0,1%*
% of all, HV and non-HV affected trips (Total, HV, Non-HV - 2)	*32,1%*	*31,4%*	*36,8%*	*22,6%*	*79,8%*	*49,2%*	*8,2%*	*81,5%*
4- Trips affected by the LEZ + No modal report + **Constrained destination**	11 147	8 991	2 156	236	90	606	180	940
% of all households (Total - 1)	*1,2%*	*0,9%*	*0,2%*	*0,0%*	*0,0%*	*0,1%*	*0,0%*	*0,1%*
% of all, HV and non-HV households (Total, HV, Non-HV - 2)	*19,9%*	*18,5%*	*28,7%*	*17,9%*	*18,6%*	*40,6%*	*8,2%*	*73,5%*
5- Trips affected by the LEZ + No modal report + Constrained destination + **Financially constrained** (low transport affordability)	2 042	1 486	556	201	12	61	31	189
% of all households (Total - 1)	*0,2%*	*0,2%*	*0,1%*	*0,0%*	*0,0%*	*0,0%*	*0,0%*	*0,0%*
% of all, HV and non-HV households (Total, HV, Non-HV - 2)	*3,6%*	*3,1%*	*7,4%*	*15,3%*	*2,5%*	*4,1%*	*1,4%*	*14,8%*

Figure F.1 – Income shares associated to the HV households without modal shift solution and constrained by their destination

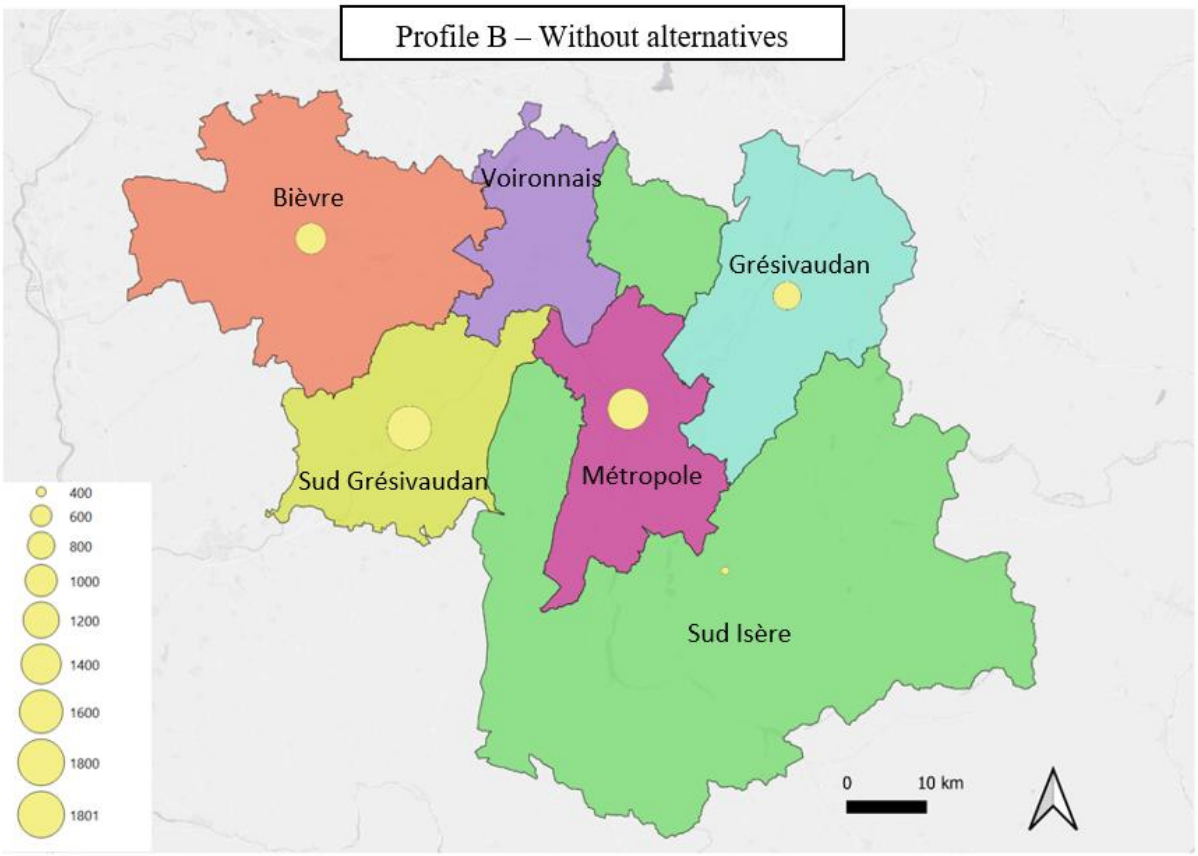


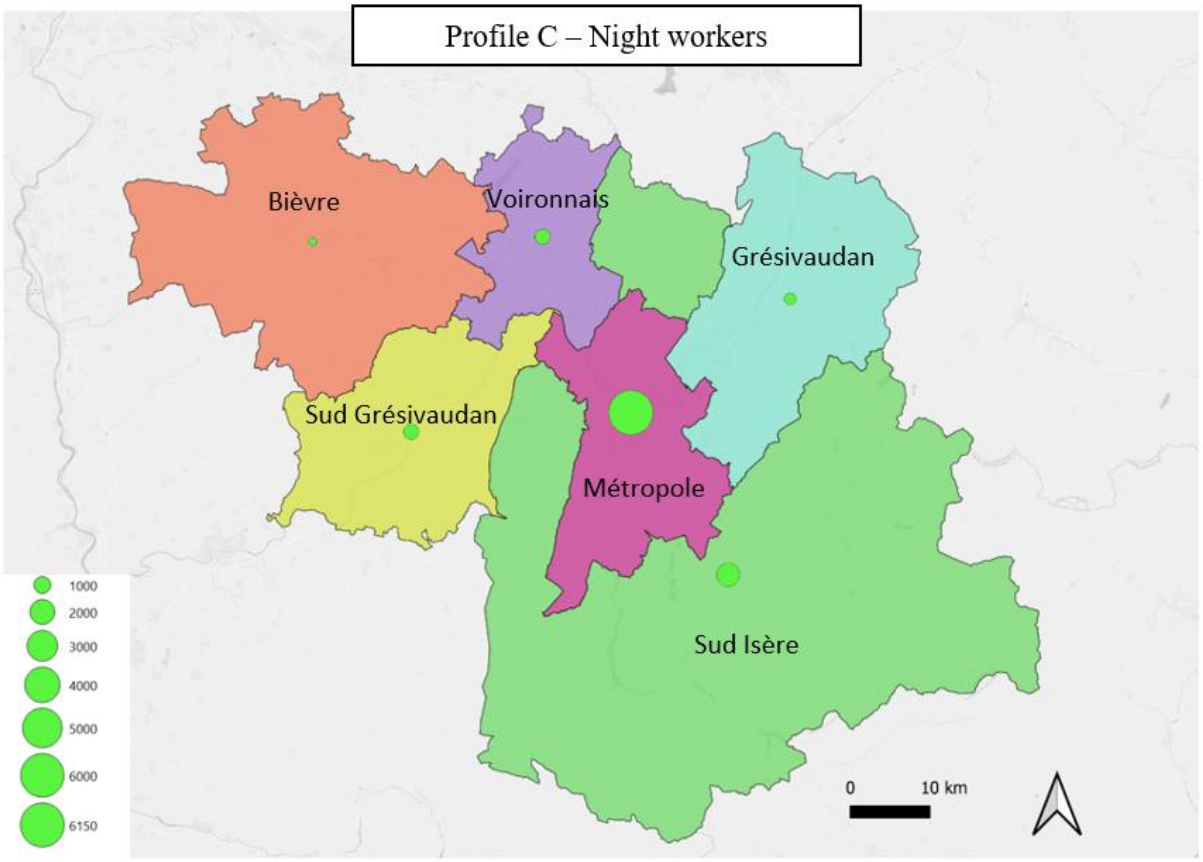
Appendix G - Residential location of the households in each profile

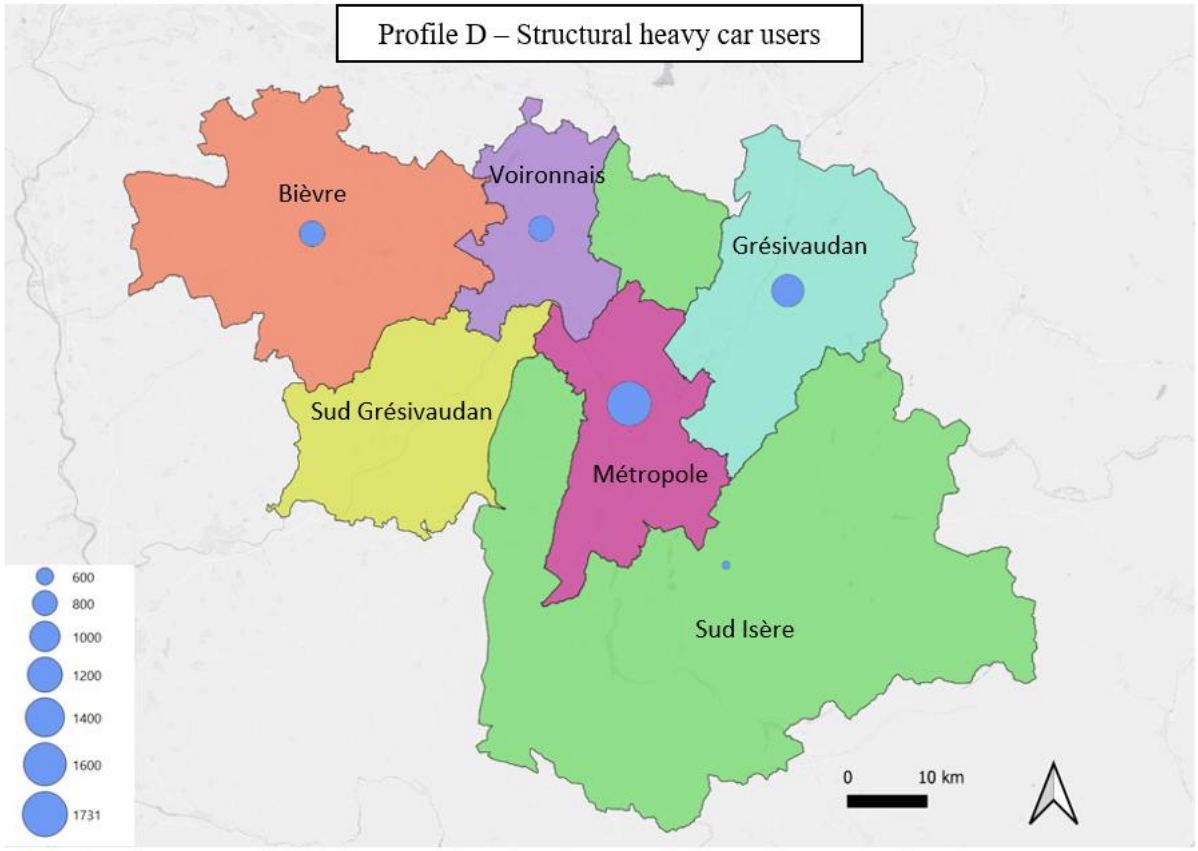
Table G.1 – Distribution of the residential location of the households in each profile (Blandin et al. 2023)

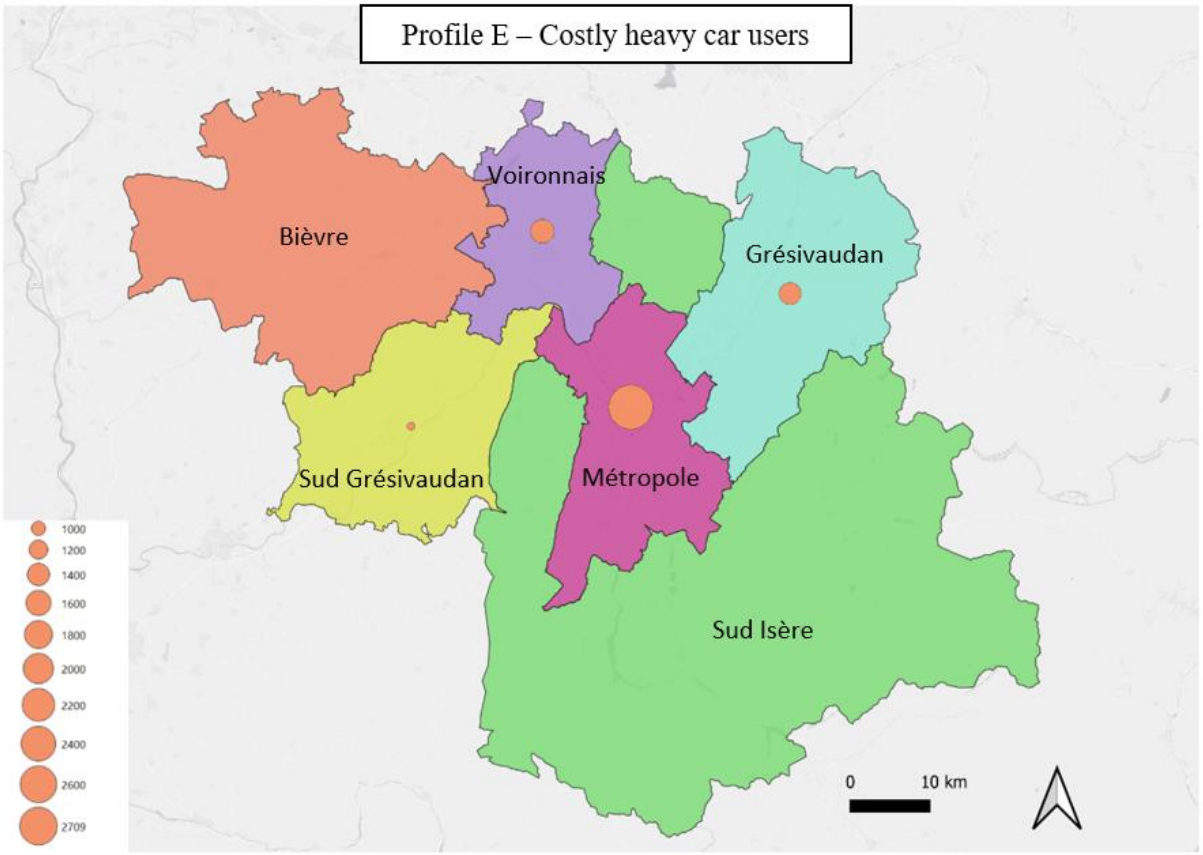
Sectors	A monetary constrained	B without alternative	C night workers	D structural heavy car users	E costly heavy car users
Grésivaudan		15.6	5.8	22.3	19.9
Sud Grésivaudan		31.5	8.0		14.1
Sud Isère	31.2	7.0	16.1	9.9	
Bièvre	23.6	18.1	4.7	16.7	
Voironnais	21.1		7.9	16.5	21.0
Métropole	24.1	27.8	57.5	34.6	45.0
TOTAL	100	100	100	100	100
Number of households	3,452	5,705	10,702	5,000	6,024

Figures G.1 to G.5 – Residential locations of the different profiles

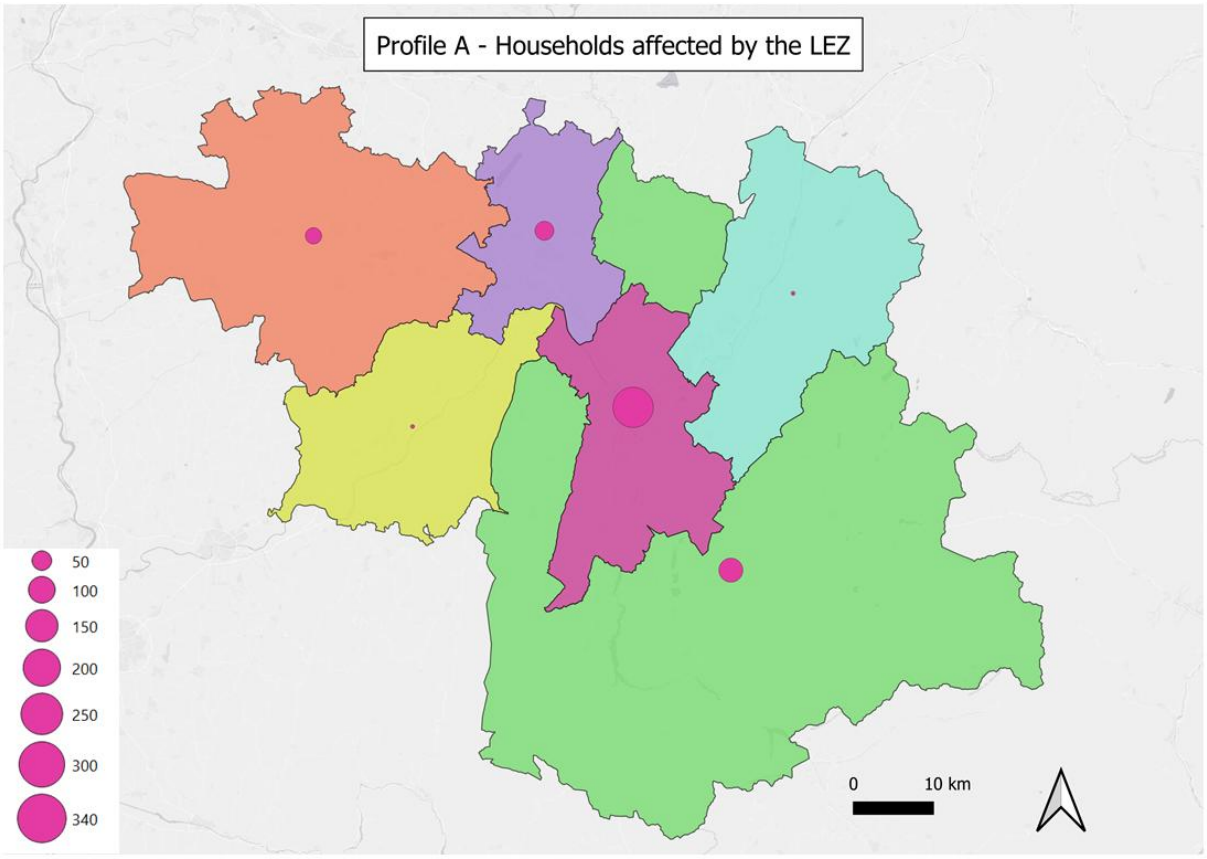

Profile B – Without alternatives
Bièvre
Voironnais
Grésivaudan
Sud Grésivaudan
Métropole
Sud Isère
400
600
800
1000
1200
1400
1600
1800
1801
0
10 km

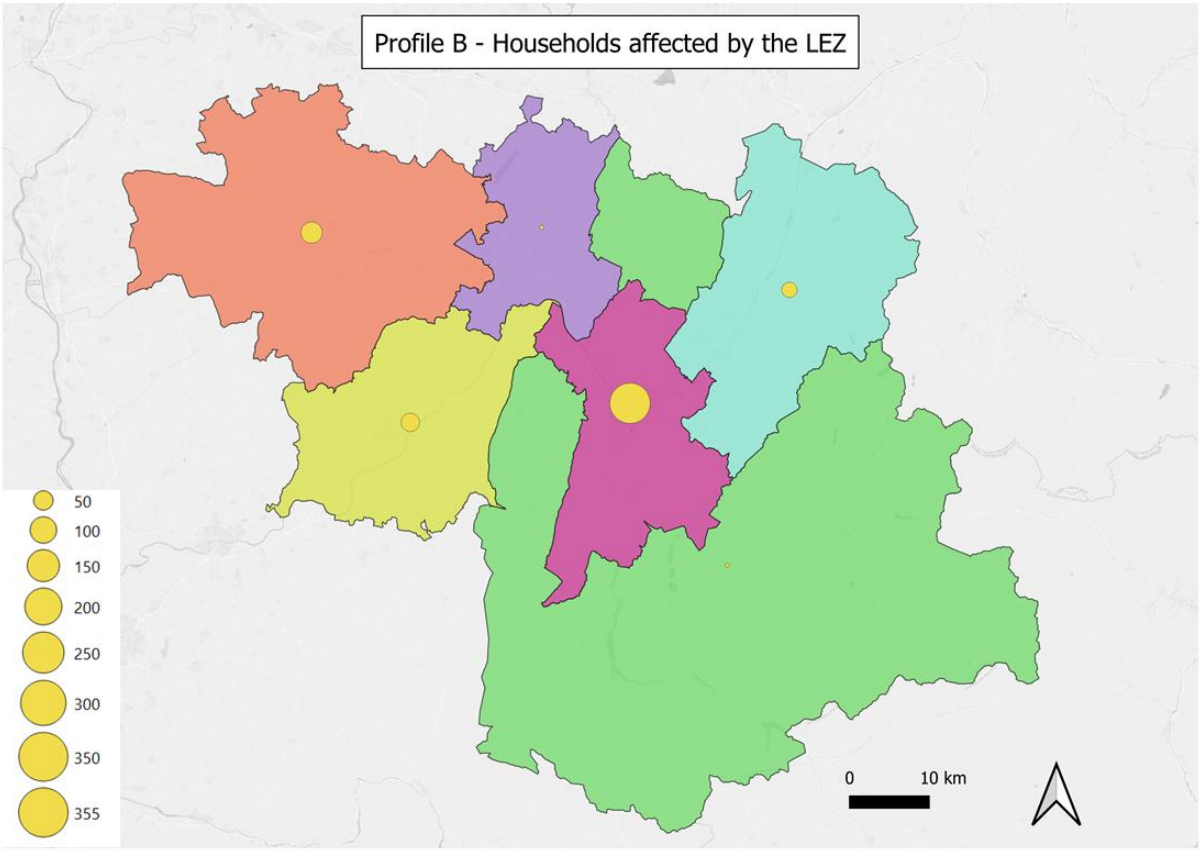

Profile C – Night workers
Bièvre
Voironnais
Grésivaudan
Sud Grésivaudan
Métropole
Sud Isère
1000
2000
3000
4000
5000
6000
6150
0
10 km

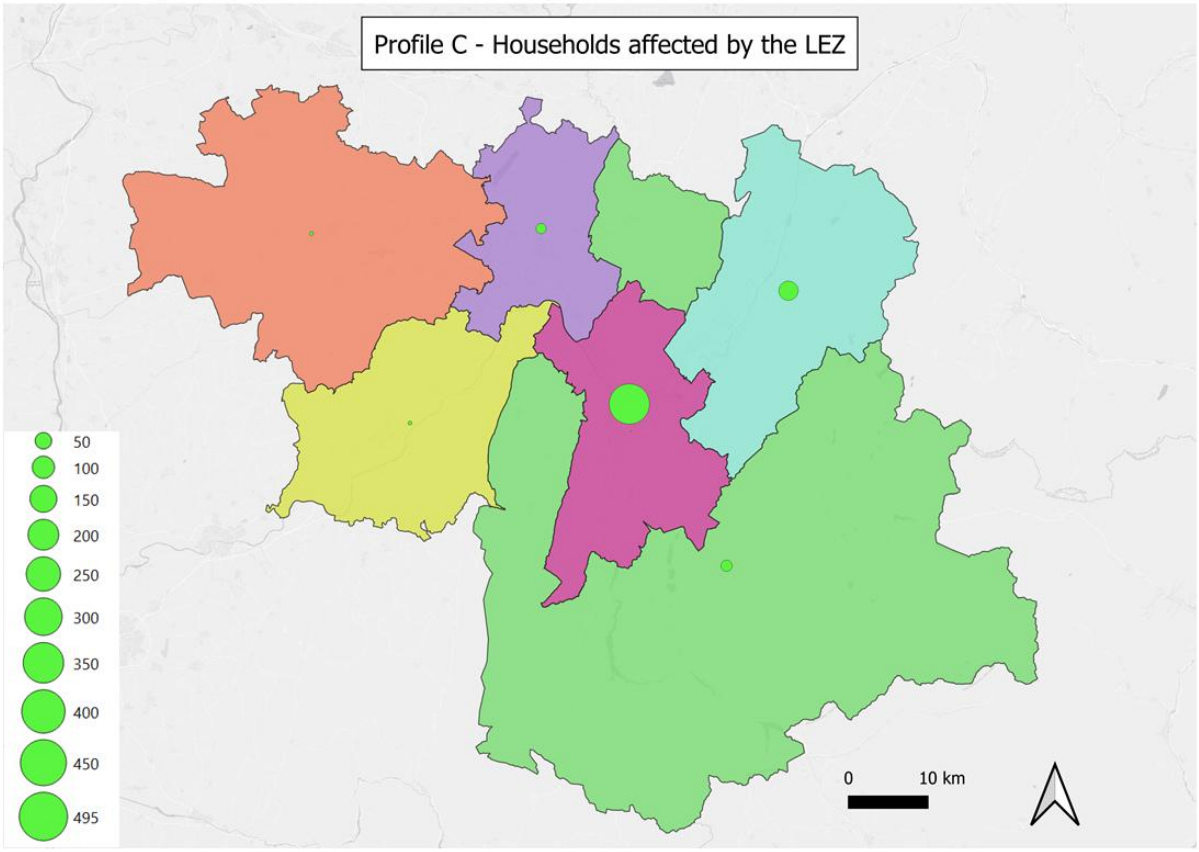

Profile D – Structural heavy car users
Bièvre
Voironnais
Grésivaudan
Sud Grésivaudan
Métropole
Sud Isère
600
800
1000
1200
1400
1600
1731
0
10 km

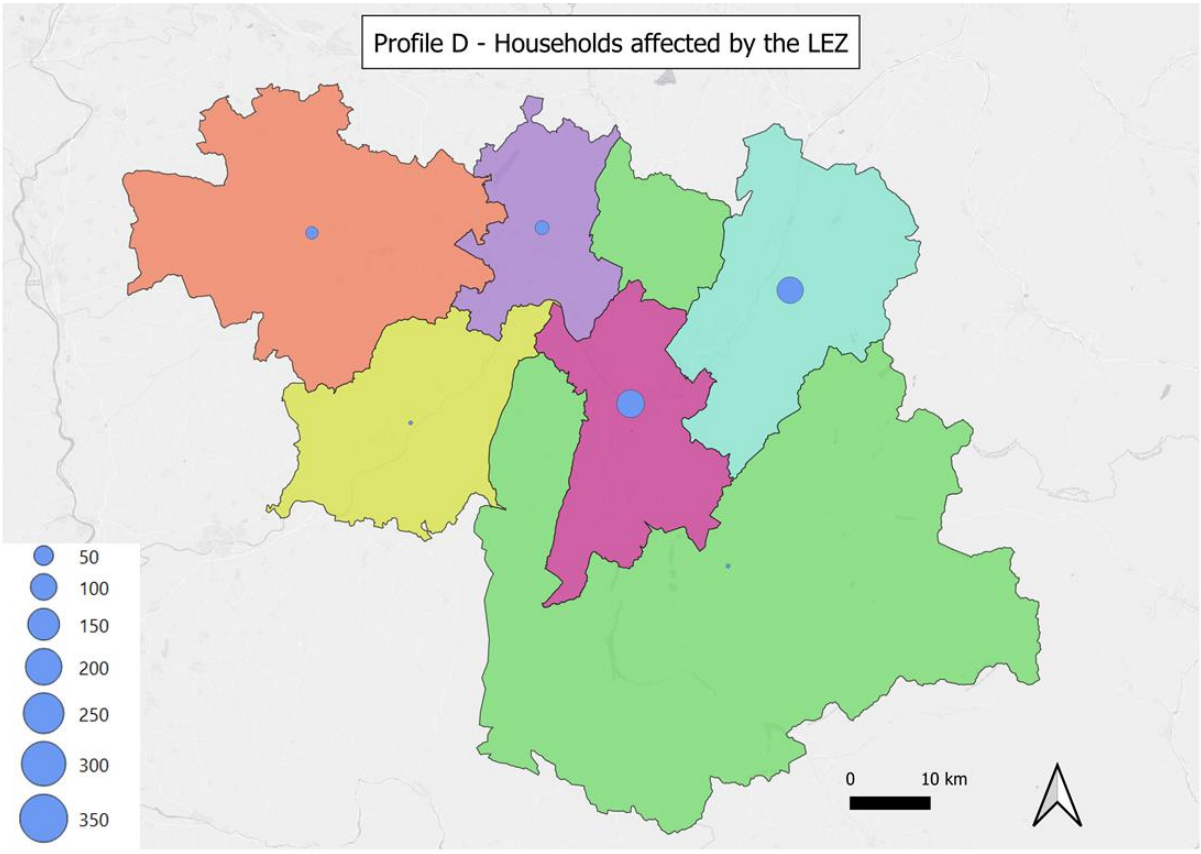

Profile E – Costly heavy car users
Bièvre
Voironnais
Grésivaudan
Sud Grésivaudan
Métropole
Sud Isère
1000
1200
1400
1600
1800
2000
2200
2400
2600
2709
0
10 km

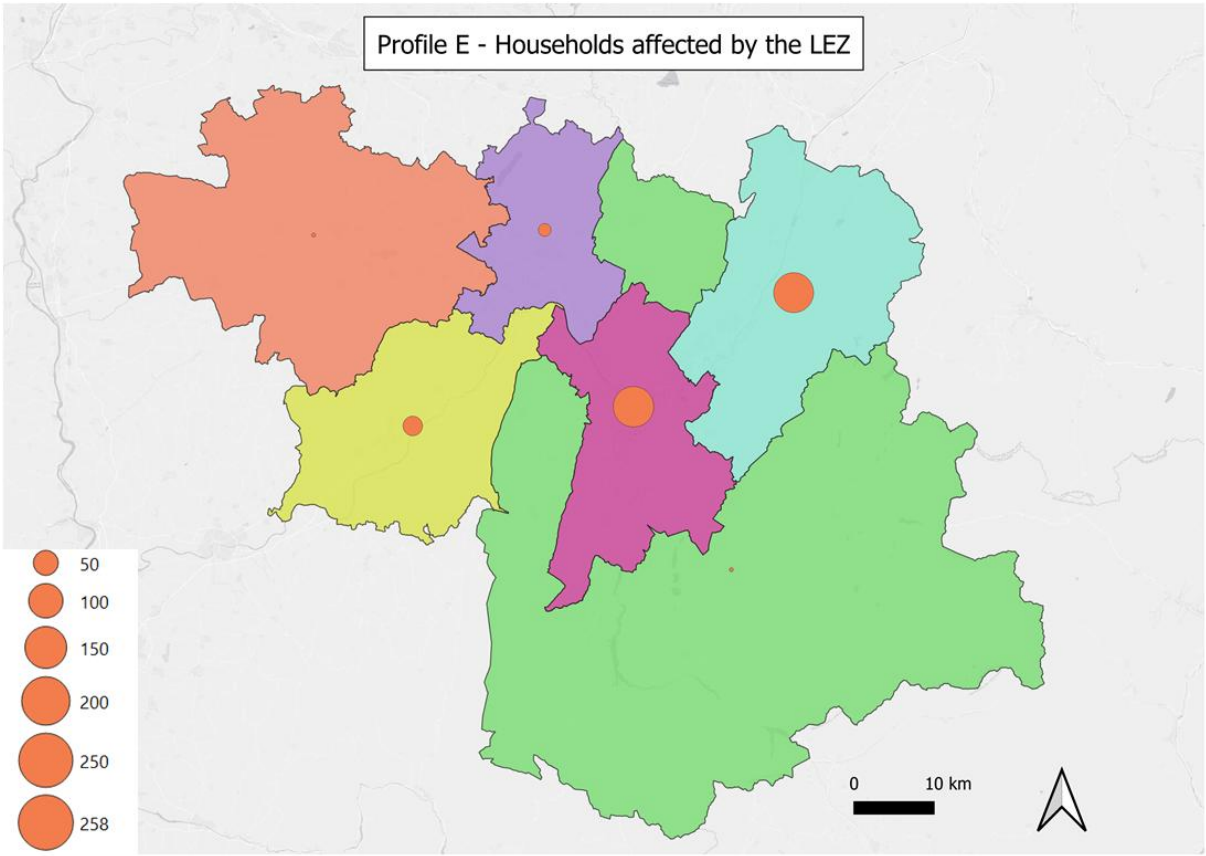
Appendix H – Residential locations of the different profiles oh HV households according to their profiles




Profile B - Households affected by the LEZ
50
100
150
200
250
300
350
355
0
10 km


Profile C - Households affected by the LEZ
50
100
150
200
250
300
350
400
450
495
0
10 km


Profile D - Households affected by the LEZ
50
100
150
200
250
300
350
0
10 km


Profile E - Households affected by the LEZ
50
100
150
200
250
258
0
10 km

Funding:

This work was supported by the French National Research Agency in the framework of the ‘‘Investissements d’avenir’’ program (ANR-15-IDEX-02) through the projects CDP IDEX UGA MOBILAIR and CDTool IDEX UGA ACME

References

Aldred, R., Goodman, A., 2020. Low Traffic Neighbourhoods, Car Use, and Active Travel: Evidence from the People and Places Survey of Outer London Active Travel Interventions. Findings. https://doi.org/10.32866/001c.17128.

Blandin, L., Bouscasse, H., Mathy, S., 2023. Identification and Typology of the Mobility Highly Vulnerable Households Using Vulmob, a New Composite Indicator. https://doi.org/10.2139/ssrn.4527095

Bouscasse, H., Gabet, S., Kerneis, G., Provent, A., Rieux, C., Ben Salem, N., Troude, F., Mathy, S., Slama, R., 2022a. Designing local air pollution policies focusing on mobility and heating to avoid a targeted number of pollution-related deaths: forward and backward approaches combining air pollution modeling, health impact assessment, and cost-benefit analysis. Environment International, 159, 107030.

Bouscasse, H., Mathy, S., Rejeb, R., & Treibich, C. (2022b). Is the impact of transport modes on health an individual determinant of transport mode choice. In *ISCTSC 2022-The 12th International Conference on Transport Survey Methods*.

Camagni, R., Gibelli, M. C., & Rigamonti, P. (2002). Urban mobility and urban form: the social and environmental costs of different patterns of urban expansion. *Ecological economics*, *40*(2), 199-216.

CEREMA, 2020. Enquête mobilité certifiée Cerema (EMC2) - aire grenobloise.

Cebeci, H. İ., Güner, S., Arslan, Y., & Aydemir, E. (2023). Barriers and drivers for biking: What can policymakers learn from social media analytics?. *Journal of Transport & Health*, *28*, 101542.

Chardonnel, S., Talandier, M., Tabaka, K., & André-Poyaud, I. (2017). Centralités des espaces périphériques et complémentarités territoriales: un enjeu de durabilité pour la Région Urbaine de Grenoble. *Environnement Urbain/Urban Environment*, (Volume 12).

Charleux, L., 2014. Contingencies of environmental justice: the case of individual mobility and Grenoble's Low-Emission Zone. Urban Geography 35, 197–218. https://doi.org/10.1080/02723638.2013.867670

Clean Cities Campaign and Transport & Environment (2022). The development trends of low and zero-emission zones in Europe. Tech.rep. URL: https://cleancitiescampaign.org /wp-content/uploads /2022/07/The-development-trends-of-low-emission-and-zero-emission-zones-in-Europe-1.pdf

De Vrij, E., & Vanoutrive, T. (2022). 'No-one visits me anymore': Low Emission Zones and social exclusion via sustainable transport policy. Journal of Environmental Policy & Planning, 24(6), 640-652.

Fageda, X., R. Flores-Fillol and B. Theilen (2020), "Price versus quantity measures to deal with pollution and congestion in urban areas: A political economy approach", Vol. 7, https://doi.org/10.1016/j.jeem.2022.102719.

Gonzalez, J.N., Perez-Doval, J., Gomez, J., Vassallo, J.M., 2021. What impact do private vehicle restrictions in urban areas have on car ownership? Empirical evidence from the city of Madrid. Cities 116, 103301. https://doi.org/10.1016/j.cities.2021.103301.

Jia, N.; Zhang, Y.; He, Z.; Li, G. Commuters' acceptance of and behavior reactions to license plate restriction policy: A case study of Tianjin, China. Transp. Res. Part D Transp. Environ. **2017**, 52, 428–440.

Lambotte, M., Mathy, S., Risch, A., & Treibich, C. (2023). Disentangling peer effects in transportation mode choice: The example of active commuting. *Journal of Environmental Economics and Management*, *121*, 102868.

Lindsey, R., Tikoudis, I., & Hassett, K. (2023). Distributional effects of urban transport policies to discourage car use: A literature review.

Liotta, C."What drives inequalities in Low Emission Zones' impacts on job accessibility in France?" Submitted to Transportation Research Part D.

Lucas, K., 2012. Transport and social exclusion: Where are we now? Transport Policy, URBAN TRANSPORT INITIATIVES 20, 105–113. https://doi.org/10.1016/j.tranpol.2012.01.013

Maness, M., Cirillo, C., & Dugundji, E. R. (2015). Generalized behavioral framework for choice models of social influence: Behavioral and data concerns in travel behavior. *Journal of transport geography*, *46*, 137-150.

Mattioli, G., 2017. "Forced car ownership" in the UK and Germany: socio-spatial patterns and potential economic stress impacts. Social Inclusion 5, 147–160. https://doi.org/10.17645/si.v5i4.1081

Mattioli, G., 2014. Where Sustainable Transport and Social Exclusion Meet: Households Without Cars and Car Dependence in Great Britain. Journal of Environmental Policy & Planning 16, 379–400. https://doi.org/10.1080/1523908X.2013.858592

Morton, C., Mattioli, G., and Anable, J. (2021). Public acceptability towards low emission zones: The role of attitudes, norms, emotions, and trust. Transportation Research Part A: Policy and Practice, 150:256–270.

Mouratidis, K., & Næss, P. (2024). Climate change concern as driver of sustainable mobility and reduced car use. Transportation Research Part D: Transport and Environment, 134, 104345.

Parkhurst, J., 2017. The Politics of Evidence: From evidence -based policy to the good governance of evidence. Taylor & Francis.

Raux, C.; Souche, S. The Acceptability of Urban Road Pricing A Theoretical Analysis Applied to Experience in Lyon. J. Transp. Econ. Policy **2004**, 38, 191–215.

Rejeb, R., Bouscasse, H., Chalabaev, A., & Mathy, S. (2023). What is the role of active mobility habits in the relationship between self-determination and modal shift intentions? A mediation analysis. *Transportation research part F: traffic psychology and behaviour*, *99*, 289-305.

Rejeb, R., Bouscasse, H., Mathy, S., Treibich, C., 2024. Les déterminants de l'acceptabilité sociale des ZFE en France: le cas de la future ZFE de Grenoble. Working Paper GAEL; (revise and resubmit) Developpement Durable et Territoires.Tabarot, P., 2023. Rapport d'information fait au nom de la commission de l'aménagement du territoire et du développement durable relatif aux zones à faibles émissions mobilité (ZFE-m), enregistré à la Présidence du Sénat le 14 juin 2023.

Tarriño-Ortiz, J., Soria-Lara, J.A., Gómez, J., Vassallo, J.M., 2021. Public Acceptability of Low Emission Zones: The Case of "Madrid Central." Sustainability 13, 3251. https://doi.org/10.3390/su13063251

Verbeek, T., & Hincks, S. (2022). The 'just'management of urban air pollution? A geospatial analysis of low emission zones in Brussels and London. Applied Geography, 140, 102642.

Woo, S. H., Jang, H., Lee, S. B., & Lee, S. (2022). Comparison of total PM emissions emitted from electric and internal combustion engine vehicles: An experimental analysis. Science of The Total Environment, 842, 156961.