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Residential location and mobility choices: A cross-analysis of vulnerabilities, environmental policies and perceptions.

Lola Blandin

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THÈSE

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Choix de localisation résidentielle et de mobilité : Une analyse croisée des vulnérabilités, politiques environnementales et perceptions.

Residential location and mobility choices: A cross-analysis of vulnerabilities, environmental policies and perceptions.

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*A toutes celles, dans le monde, que l'on voudrait empêcher de penser,
d'étudier,
de briller,
de vivre,
d'être libre.*

A Nous Toutes.

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Abstract

In a context of energy transition, followed by escalating energy prices and housing crisis, the public policies need to meet environmental and climate challenges must take account of the most vulnerable households. These vulnerabilities result in particular from the residential location of households, which imposes certain constraints on their mobility choices. These individual choices of location and mobility are made based on objective dimensions, but are also influenced by households' perceptions, for example in terms of accessibility or exposure to environmental risks. These perceptions, which are more or less in line with exposure, may in fact lead to choices that increase vulnerability. This thesis aims to shed light on vulnerability issues in the context of mobility and residential location choices, taking into account the influence of individual perceptions and public policies. The first chapter develops VulMob, a composite indicator designed to identify vulnerable households in terms of mobility, as well as poor households. This makes it possible to establish typical vulnerability profiles and to better understand which households may be particularly affected by energy shocks or public policies aimed at reducing car use. Applying this indicator to the Grenoble urban area, we identify 9.6% of households as highly vulnerable and 5.5% as transport poors. In particular, five vulnerability profiles are identified: 1. the monetary poors, 2. those without alternatives, 3. night workers, 4. and 5. heavy car users (structurally / monetarily). Based on this inventory of vulnerabilities, the second chapter assesses the *ex-ante* impacts of a Low Emission Zone policy on the most vulnerable, propose adaptation solutions at the individual level in the Grenoble urban area, and identify households to which public policy will have to pay particular attention, as they might be car-dependent and without identifiable alternative. The results show that highly vulnerable households are the most impacted by the policy, but also that up to 56.5% of them will remain without any adaptation solution. In this context of reducing car dependency, we take a broader perspective in chapter 3 by focusing on peri-urban households, who live with a low access to public transport and are often concerned by car dependency issues. We therefore study the influence of perceived accessibility on the choice of a transport mode for peri-urban households, in the city of Santiago de Chile. Using a discrete choice model with latent variables, this chapter underlines the importance of playing on subjective criteria such as the pleasantness of public spaces or cycling facilities to increase perceived accessibility and thus draw individuals' preference towards active modes. Finally, the fourth chapter, based on discrete choice models, explores whether households consider environmental risks (objective and perception) when choosing for a new residential location in France, using an original survey. While the results show the significant but limited influence of objective measures of pollution, flood risk, clay shrinkage risk and the presence of natural areas on individual preferences, they also highlight the considerable heterogeneity of these preferences. The level of perception of environmental risks can therefore strongly modify individual preferences in terms of residential choices.

Keywords: Vulnerability, low-emission zone, mobility, residential location, discrete choices, environmental risks

Résumé

Dans un contexte de transition énergétique, suivi d'une hausse des prix de l'énergie et d'une crise du logement, les politiques publiques nécessaires pour répondre aux défis environnementaux et climatiques doivent prendre en compte les ménages les plus vulnérables. Ces vulnérabilités résultent notamment de la localisation résidentielle des ménages qui impose certaines contraintes sur leurs choix de mobilité. Ces choix individuels de localisation et mobilité sont faits en fonction de dimensions objectives mais sont également influencés par les perceptions des ménages, par exemple en termes d'accessibilité ou d'exposition à des risques environnementaux. Ces perceptions plus ou moins fidèles à l'exposition réelle peuvent de fait conduire à des choix aggravant les vulnérabilités. Cette thèse vise donc à éclairer les questions de vulnérabilité dans le contexte des choix de mobilité et de localisation résidentielle, en tenant compte de l'influence des perceptions individuelles et des politiques publiques. Le premier chapitre développe un indicateur composite VulMob, qui vise à identifier les ménages vulnérables à la mobilité ainsi que les ménages pauvres, afin de dresser des profils de vulnérabilité et de mieux comprendre quels types de ménages peuvent être particulièrement affectés par les chocs énergétiques ou les politiques publiques de réduction de l'usage de la voiture, et dans quelles conditions. En appliquant cet indicateur à l'agglomération grenobloise, nous identifions 9,6% des ménages comme très vulnérables (faisant face à au moins six vulnérabilités) et 5,5% comme pauvres. En particulier, cinq profils de vulnérabilité ont été identifiés : 1. les pauvres monétaires, 2. les sans alternatives, 3. les travailleurs de nuit, 4. et 5. les conducteurs contraints (structurellement / monétairement). Sur la base de cet inventaire des vulnérabilités, le deuxième chapitre vise à évaluer les impacts *ex ante* d'une politique de zone à faibles émissions sur les plus vulnérables, à proposer des solutions d'adaptation au niveau individuel dans l'agglomération grenobloise, et à identifier les ménages auxquels les politiques publiques devront accorder une attention particulière, car ils peuvent être dépendants de la voiture et ne pas avoir d'alternative identifiable. Les résultats montrent que les ménages très vulnérables sont les plus touchés par la politique, mais aussi que jusqu'à 56,5 % d'entre eux resteront sans solution d'adaptation. Dans ce contexte de réduction de la dépendance à la voiture, nous adoptons une perspective plus large dans le chapitre 3 en nous concentrant sur les ménages périurbains, qui vivent avec un faible accès aux transports publics et sont souvent concernés par les questions de dépendance à la voiture. Nous étudions donc l'influence de l'accessibilité perçue sur le choix d'un mode de transport pour les ménages périurbains, dans le contexte de Santiago du Chili. En utilisant un modèle de choix discret avec des variables latentes, ce chapitre souligne l'importance de jouer sur des critères subjectifs tels que l'agrément des espaces publics ou les aménagements cyclables pour augmenter l'accessibilité perçue et ainsi orienter la préférence des individus vers les modes actifs. Enfin, le quatrième chapitre, basé sur des modèles de choix discrets, examine si les ménages prennent en compte les risques environnementaux (objectifs et perçus) lorsqu'ils choisissent une nouvelle localisation résidentielle en France, à l'aide d'une enquête originale. Si les résultats montrent l'influence significative mais limitée des mesures objectives de la pollution, du risque d'inondation, du risque de retrait-gonflement des argiles et de la présence d'espaces naturels sur les préférences individuelles, ils mettent également en évidence la grande hétérogénéité de ces préférences. Le niveau de perception des risques environnementaux peut donc fortement modifier les préférences individuelles en termes de choix résidentiels.

Mots clés : Vulnérabilité, zone à faibles émissions, mobilité, localisation résidentielle, choix discrets, risques environnementaux

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0. General introduction

0.1. Context: the chain of vulnerabilities implied by residential choices

The last decade has been characterized by the emergence of various social movements, which asked for more equity in the society. In France, the Yellow Jackets movement that began in autumn 2018 was initially motivated by the announcement of an increase in the carbon tax in line with France's more ambitious climate goals and was then reinforced by rising crude oil and fuel prices, a high cost of living and economic inequalities. The movement argued that a disproportionate burden of taxation in France was falling on the working and middle classes, especially in rural and peri-urban areas. In Chile, a similar movement appeared in October 2019. The Estallido Social, a series of massive demonstrations and severe riots started in Santiago and took place in all regions of Chile until 2021. The protests were in response to a raise in the Santiago Metro's subway fare, an increasing cost of living due to the housing market crisis and important socio-economic inequalities. These two examples, from the two countries covered in this thesis, demonstrate the interdependence of transport costs and residential location, and the social implications of this interdependence. In particular, the weight of transport costs in household budget is central, whether it concerns car or public transport use.



Figure 0.1 The Yellow Jacket movement in France (left) and the Estallido social in Chile (right)
(Sources: @ManifestationGiletsJaunesParis and Marcelo Hernandez)

At the same time, many climate walks were organized all over the world following the COP26 in Glasgow (2021). More than 200 protests were organized worldwide, for instance in Sydney, Paris, London, Nairobi, Mexico to require that governments take climate action more seriously. These protests proved the concerns of a young generation – represented by Greta Thunberg – that raises the alarm on the urgent need to act against climate change and global warming. In addition to the lack of strong action, they also denounce the unfairness of the ecological transition, as illustrated by the feeling that the rich are destroying the planet by polluting more and making little efforts to reduce their impact, while the poorest pollute less but should make a major contribution to the reduction effort.

Therefore, there are two contradictory movements in the population, some focusing on budget issues and others on environmental issues. These different movements in fact highlight a demand for social justice in the implementation of the ecological transition and more specifically of climate policies, which could require a strong adaptation capacity that, as things stand, could be out of reach for part of the population. In particular, they underline that fighting climate change should not be done at any cost and should provide alternative solutions and support to the most vulnerable households.

In the end, different challenges mix and clash. First, individual residential choices can lead to a dependence on energy consumption, creating vulnerability to energy prices. Second, vulnerability to climate policies can lead to increasing inequalities. These issues raise a certain ambiguity: on the one hand, a demand to combat climate change, and on the other, a desire to preserve old habits by using cheap cars. In theory, addressing these two aspects at the same time could mean shortening the distances travelled, and therefore rethinking residential location choices. In fact, residential location conditions

mobility, but mobility is also a choice. These two choices are therefore strongly linked and are conditioned by many different constraints (financial, organizational, job-related). They are also influenced by the way people perceive their environment and the associated risks. Therefore, taking action on these specific sectors requires considering the existing vulnerabilities, the potential impacts of environmental policies and the role of individual perceptions.

0.1.1. Understanding mobility behaviors induced by residential choices

In France, by the end of the 1960s, the population started to strongly increase in the urban centers, which led to an increase of housing prices in cities (Dumont, Guieysse, & Rebour, 2022). Therefore, city centers were quickly snapped up and filled to capacity. In a context of low energy prices, and as a consequence of the Pompidou government's all-car policy (Sauvy, 1968), many households decided to relocate in the suburbs where they can afford a bigger house and have an access to natural areas. In this context, the suburbanization process started and led to the expansion of cities to enable households to live more or less close to the services and jobs offered by the city. First, the suburbanization process implied higher distance between residential places and essential services or jobs: in the 1960s, the average commuting trip in France was 3 km long *versus* 13.3 km in 2019 (Enquête Mobilité des Personnes, 2019). Second, the housing prices increase in city centers was followed by a decrease of private cars costs, and the French car fleet grew up from 20 million in 1980 to 41.2 million in 2023 (Ministère de la Transition Ecologique, 2023).

In this sense, choosing for a residential place is the result of a trade-off between transport times and land prices (Alonso, 1964; Muth, 1969; Mills, 1972; Fujita, 1989; Duranton et al., 2015). In particular, suburbanization process led to a specific spatial distribution of housing prices, with few cheap dwellings available in central neighborhoods. In some cities, many households with low income cannot properly choose for their residential location, as they are constrained by financial issues (Tiznado-Aitken, Lucas, Muñoz, & Hurtubia, 2022). This has gradually led to residential segregation in many cities. (i.e. the spatial separation of population groups between urban neighborhoods) (Massey & Denton, 1988). In France, the segregation issue arises essentially in socio-economic terms, but is also related to ethnic concerns, in particular in disadvantaged neighborhoods (Pan Ké Shon, 2010). Gaschet and Le Gallo (2005) showed that the “socio-economic distance” between executives and low-skilled workers resulted in an important socio-spatial segregation in the municipalities of Paris, Lyon, Bordeaux and Dijon areas. Studying the 50 biggest French urban areas, Madoré (2015) confirmed this result explaining that the socio-spatial hierarchy (corresponding in the spatial classification of households according to their living standards) is well marked in all cities, with a stronger segregation in dense cities compared to the peripheries.

Beyond socio-economic issues, reducing residential choices to a simple arbitration between transports costs, commuting time and real estate market prices would hide the existing heterogeneity in households' preferences and characteristics. For instance, households with children may opt for a house with more bedrooms, living away from urban centers at the cost of longer commuting times, while single workers may prefer living close to their workplace to enjoy the urban amenities. Some households may also prioritize having a garden or living in a less polluted or noisy area.

As a result, these segregation patterns may lead to socio-economic and environmental inequalities (Schaeffer, Cremer-Schulte, Tartiu, & Tivadar, 2016a). Therefore, the choice of a residential place conditions in particular the quality of the environment in which people decide to live, but consequently, also the negative externalities they will have to face. These choices are particularly constraining, as the rent of a flat, the purchase of a new car, or the personal organization (in terms of job constraints for instance) represent long-term binding choices.

Thus, residential location brings both constraints and opportunities in terms of mobility and access to services. Mobility constraints and habits are therefore the consequence of residential location choices. In our contemporary societies, mobility conditions the access to opportunities and services by being able to move around and get from one place to another. Regardless of the residential location, everyone should be able to reach essential activities and services. In other words, quality of life increases with the ability – regardless of physical or cognitive disabilities, gender, age or socioeconomic status – to get to work, meet people and have access to health care, education, shopping, and culture. More specifically, in suburban areas, car is often the only available transport mode. Consequently, residential choices are often conditioned by the need to buy one or more cars or find other alternatives to access services and jobs, which are mainly located in and around urban centers. In this sense, residential choices structurally determine mobility, and in particular the use of transport modes. This is why mobility and residential issues should always be considered together (Coulombel, 2018).

Besides the importance of mobility in our societies, transport and residential sectors are also associated to negative externalities and important climate change issues. On the one hand, the transport sector is the largest contributor to France's greenhouse gas (GHG) emissions and accounts for 31% of the emissions in 2019. More specifically, within the transport sector, road transport is by far the biggest emitter accounting for more than 70% of transport related GHG emissions, 16.1% of ambient PM_{2.5}, 10.8% of ambient PM₁₀ and 37% of NO_x emissions worldwide (EEA, 2019). On the other hand, residential buildings (housing) accounts for 17% of the global GHG emissions, among which 75% are related to heating systems. Wood heating can also cause significant air pollution when burnt under bad conditions. If wood is considered as non-GHG emitter, various pollutants are emitted when wood is burnt, including a significant amount of fine particles, which are particularly damaging to human health (fine particles PM₁₀ and PM_{2.5}). In this sense, transport and housing cause substantial negative impacts on the environment and human health, such as air pollution, noise and urban heat islands. In particular, air pollution has major and proven effects on mortality and morbidity, mainly through cardiovascular and respiratory health. In 2019, around the world, nine out of ten people in urban areas were exposed to levels of fine particulate matter (PM_{2.5}) from outdoor air pollution above the 2005 World Health Organization (WHO) guideline value (average annual PM_{2.5} concentration of 10 µg/m³), and even more so at the current guideline value of 5 µg/m³. It represents a major public health problem: exposure to ambient PM_{2.5} causes approximately 4.2 million deaths each year worldwide, 417,000 in Europe, and approximately 40,000 in France (WHO, 2022).

0.1.2. Evaluating multidimensional vulnerabilities implied by residential and mobility choices

0.1.2.1. *Vulnerability or vulnerabilities?*

We have already mentioned the vulnerability issues arising from residential location and mobility choices. In this thesis, we explore the concept of vulnerability in different contexts: for instance, the vulnerability to natural risks such as floods, or the vulnerability to fuel price increase. In this sense, vulnerability can be defined, measured, interpreted and applied in various ways, and there is no universal theory or definition of vulnerability. In particular, each discipline reviewed tends to consider vulnerability in a slightly different manner. In this sense, Alwang et al. (2001) proposed an attractive multi-disciplinary definition of vulnerability based on five identified principles:

- a) Vulnerability is a prospective concept, defined as the probability of suffering a loss in the future relative to a reference level;
- b) A household may be vulnerable to a future loss of well-being, and this vulnerability is due to uncertain events;
- c) The degree of vulnerability depends on the risk characteristics and the household's ability to cope and/or adapt to it;

- d) Vulnerability depends on a time horizon. A household may be vulnerable to risks over a month, a year or a shorter period;
- e) The poor and near-poor tend to be vulnerable because of their limited access to resources (in the broadest sense) and their limited ability to cope with risks.

In the words of Adger (2006), "*vulnerability is most often conceptualized as being constituted by components that include exposure and sensitivity to perturbations or external stresses, and the capacity to adapt*", meaning that the overall vulnerability depends on three factors: exposure, sensitivity, adaptation (see Figure 0.2). To be vulnerable, a household should be threatened by a risk, a change or more generally, a modification of its current life conditions that may have an impact of its well-being (exposure). It also has to be sensitive to this risk: for instance, a household without car will not be sensitive to an increase in fuel prices. Vulnerability is also influenced by the potential for adaptation, which is often related to the financial aspect, but not only. For instance, a compensatory measure (societal environment) may help increasing the adaptive capacities.

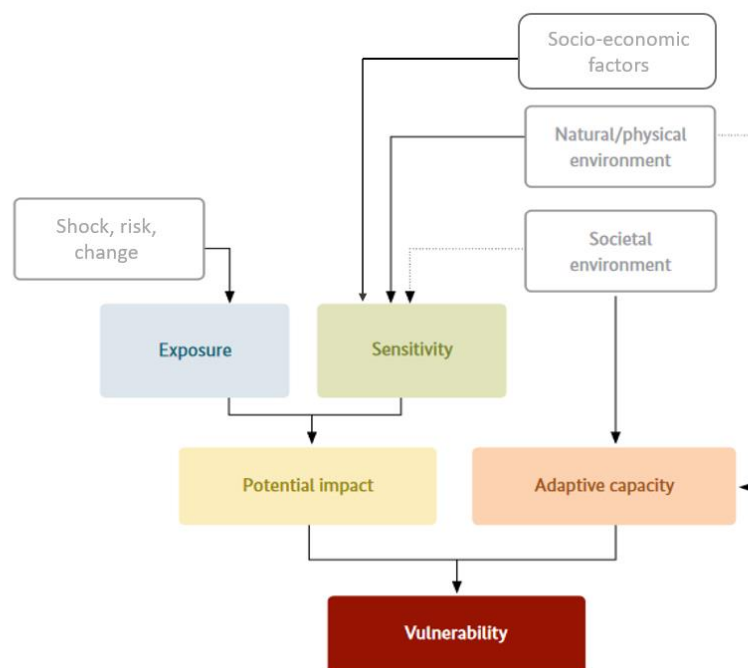


Figure 0.2 Components of vulnerability (Source: adapted from *The Vulnerability Sourcebook* (GIZ, 2017))

Based on these definitions, we can therefore assume that living in a specific residential location may be at the root of different vulnerability issues. Indeed, the existing socio spatial segregation, the environmental features, risks, and the mobility issues associated to this residential place are important characteristics that may affect well-being. In this sense, vulnerabilities can take several forms: socio-economic vulnerability, environmental vulnerability (to environmental hazards (Cutter, Boruff, & Shirley, 2003), to climate change (Otto et al., 2017), to climate policies (Kortetmäki & Järvelä, 2021)) or more specifically fuel/mobility vulnerability, that can even lead to fuel/transport poverty (Mayer, Nimal, Nogue, & Sevenet, 2014). In the following sub-sections, we focus on environmental and mobility vulnerabilities, which are particularly of interest in this thesis.

0.1.2.2. Environmental vulnerabilities

The chosen residential location conditions the environment in which a household is going to live, including several specific parameters such as air quality, environmental risks, and access to green spaces or recreational areas. This choice could therefore implies being affected by environmental vulnerabilities or requires being able to adapt to cope with environmental risks.

First, focusing on air quality, many studies conclude that groups with a low socioeconomic status tend to be more exposed to air pollutants and toxicants and highlight the uneven distribution of environmental burden between social groups (Finkelstein et al., 2005; Chaix et al., 2006; Marshall, 2008; Laurian and Funderburg, 2014; Verbeek, 2019). A meta-analysis conducted for years 2010-2017 in Europe confirmed that higher deprivation indices and low economic positions are usually linked with higher levels of pollutants without distinction (Jonathan Fairburn, Schüle, Dreger, Karla Hilz, & Bolte, 2019). There is therefore good evidence that higher deprivation indices and low economic position are usually linked with higher levels of pollutants exposure such as particulate matter and oxides of nitrogen in Scotland (Jon Fairburn, Walker, & SMITH, 2005), Sweden (Chaix et al., 2006), the Netherlands (Kruize & Bouwman, 2004) and France (Havard et al., 2009; Lanier et al., 2019). In particular, a recent study in France identified that 60% of neighborhoods of the bottom 10% of income are exposed to PM_{2.5} levels that exceed the WHO standard, while 80% of the neighborhoods of the next 10% complies with this standard (Champalaune, 2021). The same is observed at the city-level in London (Goodman, Wilkinson, Stafford, & Tonne, 2011) and Grenoble (Morelli et al., 2019). Yet, this last study also underlines that the city shape conditions these conclusions; for instance, in Lyon, mid-income classes appear to be the most affected. Other studies on specific services, also showed similar exposure inequalities, such as Carrier et al. (2014) found that NO₂ concentrations near schools are positively associated with levels of deprivation and schools with a higher index of deprivation tend to be located in the most polluted areas in Montreal.

Second, at both country and individual levels, the most deprived are also the most vulnerable to the impacts of climate change (Guivarch & Taconet, 2020), but also more generally to multi-hazard risks such as tornados, hurricanes or floods (Räsänen et al., 2016; Forzieri et al., 2016). Indeed, in this case, vulnerabilities are often associated with bad quality dwellings (shantytowns *versus* permanent buildings), but also to access to clean water and sanitation. The scale of global warming impacts is therefore correlated with vulnerabilities and limit the adaptation capacities (Hallegatte, 2016). Vulnerabilities are therefore exacerbated by pre-existing inequalities of various kinds, which interact together.

To limit these environmental vulnerabilities, access to parks and green spaces constitute an important potential for adaptation. Indeed, green spaces in neighborhoods are critical components of the built environment and are also often inequitably distributed across public space. Yet, in North America, many studies showed that most of the tree cover was strongly positively related to socio-economic advantage (Shanahan et al., 2014; Landry and Chakraborty, 2009; Pham et al., 2012; Schwarz et al., 2015).

0.1.2.3. *Mobility vulnerabilities*

Besides environmental vulnerabilities, the choice of a residential location may be at the root of mobility vulnerabilities. Because of different factors, such as high mobility costs, large travel distances, fuel prices, job or family-related constraints, some households may have to face difficulties, which might be described as mobility vulnerabilities. Indeed, being vulnerable cannot be reduced to the financial aspect and depends on a combination of factors that refer to different dimensions: economic dimension, specificity of distances and trips, family structure, ability to switch to other modes, etc.

Mobility vulnerabilities may emerge from different sources. First, vulnerabilities may be the consequence of environmental policies aiming to face the externalities of transport contributions to global warming and the related emissions. Considering the importance of road-related emissions, transport policies often aim to tackle car issues, with a particular focus on air pollution effects. Such public policies and interventions can take different forms, such as new infrastructures (e.g. the extension of existing public transport networks or the construction of cycling paths) or pricing strategies (e.g. taxing the most polluting car or providing free public transport). These measures may also be based on regulations (for instance, limiting the production of fuel-based vehicles in the industrial sector) or on information and awareness campaigns. Yet, these policies may have heterogeneous impacts among

social groups both in terms of health benefits and economic impacts (Sanchez, 2018). Many empirical studies have been developed all around the world, in Rio (Pereira, Banister, Schwanen, & Wessel, 2019), San Francisco (Bills & Walker, 2017) or Seattle (Franklin, 2006) and confirm that transport policies may exacerbate rather than reduce socio-spatial inequalities, and therefore underline the necessity for redistribution measures, especially for low-income households.

Among those measures, Low Emission Zones (LEZ) are now commonplace in Europe. LEZs were created to improve air quality and protect the health of inhabitants of cities in major metropolitan areas where air pollution is significantly high. LEZs are based on a perimeter where only the least polluting vehicles are allowed to move around. In France, the Climate and Resilience Act (2021) has introduced the obligation to implement a LEZ, by December 2024, in all agglomerations of more than 150,000 inhabitants. This would have represented around forty conurbations but the French government finally backed down from this obligation in July 2023 in particular for fear that these zones would not be accepted by part of the population. The LEZs will only be compulsory in the five metropolitan areas where the regulatory thresholds for NO₂ are regularly exceeded: Lyon, Paris, Rouen, Marseille and Strasbourg.

If such policy is supposed to benefit people living both inside and outside of the restriction's perimeter, as showed in Paris (Poulhès and Proulhac, 2021), other studies underline that the LEZ implementation could in fact have the opposite effect and increase the pre-existing health inequalities by improving the health of the richest more than that of the poorest. Several studies in Rome (Cesaroni et al., 2012) or in Paris (Host et al., 2020) concluded that a LEZ was efficient in reducing traffic-related air pollution and health impacts (such as premature deaths or asthma) but most of these health gains were deviated towards wealthier residents.

From a social perspective, the LEZs mobility restrictions do not only affects households living in the delimited perimeter and therefore increase the risk of social exclusion, which corresponds to a lack of resources, rights, goods and services, and the inability to participate in the normal relationships and activities (Levitas et al., 2007; Lucas, 2012). Indeed, as seen for instance in Antwerp, some people living in the LEZ feel guilty when friends from outside the zone visit them, forcing them to respect the restrictions imposed by the LEZ. (De Vrij & Vanoutrive, 2022). The situation can therefore be complicated from a social relations point of view for those who do not have the means to buy a cleaner but more expensive vehicle.

Besides environmental policies, new mobility vulnerabilities can also arise from changes in travel conditions. These changes may occur following different events. For instance, the current geopolitical context and the Ukraine's invasion by Russia led to an increase in fuel prices that is particularly challenging for heavy car users and car dependent households. At the same time, the COVID-19 pandemic, which restricted trips to the bare minimum and led to the adoption of teleworking, also modified mobility habits, even if the long-term effects remain unclear for now. Yet, public transport services were avoided and individual car travelling was preferred, encouraging car purchase at some point (Kim et al., 2023; Vega-Gonzalo et al., 2023). Therefore, depending on the capacity to adapt to these sudden shocks and outbreaks, mobility vulnerabilities may emerge or not.

0.1.2.4. *Vulnerability versus poverty*

When vulnerability is mentioned, the first thing that often comes to mind is the most modest households. The poor and near-poor tend to be vulnerable because of their limited access to resources (in the broadest sense) and their limited ability to cope with risks (Alwang et al., 2001). In the transport sector, the concept of "*transport poverty*" is recent and emerged from the transposition of "*fuel poverty*" to the transport sector in order to designate households who are not able to meet all their mobility needs. Yet, this concept is recent and has no established definition in the academic or policy literature so far. It is currently used to describe situations when people do not have access to essential services or work

because of a lack of mobility options. Some of the elements leading to transport poverty suggested in the literature include no transport availability, poor transport accessibility, low transport affordability, important travel times or inadequate transport conditions (Lucas et al., 2016).

If the study of transport poverty sheds light on those who are currently poor, many mobility vulnerabilities could also lead to a situation of poverty in the future, if households are not able to adapt and cope with the situation. Yet, vulnerability is different from poverty issues. Indeed, being vulnerable cannot be reduced to the financial aspect and depends on a combination of factors, which can be economic, but also organizational, structural or job-related, for instance. Indeed, taking the example of a heavy car user that might be affected by a car ban (LEZ) or an increase in fuel prices will not necessarily be vulnerable if he can switch to other transport modes, such as active modes or public transport. Therefore, depending on the ability to adapt in order to reduce car-dependence, observed vulnerabilities will not be the same and may concern different population clusters, who are not necessarily poor.

0.1.2.5. An accumulation of vulnerabilities raising a social justice issue

Vulnerabilities of various kinds can be accumulated and affect certain population groups, in particular the most vulnerable and the poorest. Indeed, besides the Paris Agreement ambition, many studies showed that the countries that contributed the most to climate change will also be the less impacted by its effects (Islam and Winkel, 2017; Guivarch and Taconet, 2020; Chancel et al., 2022). Indeed, least developed countries produced less than 4% of global CO₂ emissions but have suffered 69% of deaths caused by climate disasters since 1972 (UNCTAD, 2022). Within countries, the most deprived households tend to contribute less to emissions but are the most likely to be exposed to the negative climate change effects. In France, GHG emissions tend to increase with the standard of living (A. Pottier, Combet, Cayla, Lauretis, & Nadaud, 2020), as well as fine particles emissions (Fosse et al., 2022).

At last, climate policies tend to generate transition costs that could fall most heavily on those most vulnerable to the effects of global warming (Reghezza-Zitt, 2023). In particular, many studies show that the risk of negative social and distributional outcomes of climate mitigation policies increases “in contexts characterized by high levels of poverty, corruption and economic and social inequalities” (Markkanen and Anger-Kraavi, 2019, p.837) (see for instance Hunsberger et al., 2014; Larson et al., 2015; Westholm, 2016). At once, climate policies can lead to inequalities when their costs fall more heavily on those with lower income or when certain social categories are excluded from their benefits.

Focusing in particular on the transport sector, emissions are also very heterogeneous according to the standard of living. In France, the richest households travel almost three times more than the poorest. This variability in transport emissions can be decomposed by looking at the differences in travelled distances and the transport modes. In particular, the availability of transport equipment has an important role: the share of households without private car decreases steadily with the standard of living. In Paris, Leroutier (2020) found that individuals’ travel-related CO₂ emissions tend to unequivocally increase with income. Simultaneously, residential choices have strong influence on emissions as they affect both mobility and the available transport modes. For instance, rural people tend to travel largest distances than urban people and often use more emitting transport modes. On a representative weekday, Leroutier and Quirion (2022) found that top 20% emitters contribute to 85% of NO_x emissions, 78% of CO₂ emissions and 78% of PM_{2.5} emissions in the transport sector.

Therefore, the fact that the most deprived households are also the most likely to be affected by climate change impacts and climate policies, but also the smaller contributors to emissions and damages raises an important issue of social justice. Indeed, social justice aims to ensure fair treatment of individuals and groups and that every socio-economic group receives a fair share of social and economic benefits, as well as environmental benefits.

On the one hand, while social justice and environmental degradation were perceived as two opposing issues, the social movements of Environmental Justice invite us to look at their interactions (Mohai, Pellow, & Roberts, 2009). As an example, the recent "climate walks" that took place worldwide illustrate that the ecological crisis and related social issues now constitute a transnational concern shared by people in different countries (Schlosberg & Collins, 2014). These protests put pressure on decision-makers to take fair measures that are in line with the consequences of global warming issues individuals are currently facing, by taking a pro-poor approach. In particular, the demand for a healthy environment for all and an equitable distribution of environmental benefits (such as green spaces) and damages (such as pollution, or flood risks) is central. Indeed, when observing the correlation between environmental externalities and the most precarious territories, the affected populations underline the cumulative impacts of social, environmental and political inequalities they suffer from (Driquet & Lejeune, 2017).

On the other hand, the requirement for fairness and equity in the distribution of goods and services, accessibility for people, affordability of all types of services (including property), echoes the Transport Justice concept (Litman, 2002; Bullard et al., 2004). Indeed, Transport Justice underlines that accessibility is an essential requirement for the achievement of social justice, through its contribution to reducing social exclusion (Julian Hine, 2008). Transport Justice therefore argues that governments have to provide every person with adequate transportation and thus of mitigating the social disparities that have been created in the past, with a particular concern for the disadvantaged (Martens, 2016). In this sense, social justice challenges, whether related to environmental or mobility vulnerabilities and inequalities, are strongly interconnected and interdependent.

In order to reduce the vulnerabilities induced by residential choices, two main levers can be used. First, environmental vulnerabilities, which are directly related to the perceived environmental risks, should be carefully assessed when choosing for a place of residence. Second, changing mobility behaviors by encouraging modal shift to alternatives to the car may also allow limiting mobility vulnerabilities associated to the choice of a transport mode.

0.1.3. Improving risk perceptions in order to limit environmental vulnerability issues

In general, a risk corresponds to "a situation, event, or activity, which may lead to uncertain adverse outcomes affecting something that we care about" (Böhm and Tanner, 2018, p.16). The two essential components of risk are the severity and uncertainty of the adverse outcome (or loss), which are particularly difficult to assess. Moreover, if risks are objectively studied and quantified, different external factors also play a role in how people will cope with these risks.

In particular, risk approaches are fundamentally determined by risk attitudes and perceptions (i.e. the individual's inclination for risk taking that emerge from his or her personality) (Vasvári, 2015). These perceptions create a bias in the subjective evaluation of risks at the individual level. Risk perception is the judgement that people make about the characteristics and severity of a risk. Therefore, risk perceptions often differ from statistical assessments of risk, since they are affected by a wide range of affective (emotions, feelings, moods, etc.), cognitive (gravity of events, media coverage, risk-mitigating measures, etc.), contextual (framing of risk information, availability of alternative information sources, etc.), and individual (personality traits, previous experience, age, etc.) factors.

Different technical, economical, psychological, sociological and anthropological approaches of risk perceptions have been developed (Renn, 1992). A well-established approach to studying risk perception is the psychometric paradigm (Slovic, 1987), which aims to identify the 'cognitive map' of diverse risk events, activities, or technologies and its underlying psychological dimensions that lead individuals to perceive something as more or less risky. Then, the conceptualization of The Social Amplification of Risk Framework - an interdisciplinary approach - attempted to explain the process by which risks are

amplified when receiving public attention (social amplification), or attenuated when receiving less public attention (social attenuation) (Kasperson et al., 1988).

These different approaches allowed identifying the main factors influencing risk perceptions which are listed and described in Table 0.1.

Table 0.1 Main factors explaining risk perceptions (Source: Authors' own elaboration)

Factor	Description	References
Extraordinary events	At first, it would seem logical that more frequent events are more easily retrieved in memory, yet major “shocking” events tend to stay in minds and are therefore perceived to be more frequent	Kahneman and Tversky (2012)
Frequency	People tend to overestimate small frequencies and to underestimate larger ones when judging the frequency of various dangers	Lichtenstein et al. (1978)
Temporal discounting	Perceptions are more influenced by recent or current events than by those occurring years earlier	Böhm and Pfister (2005)
Familiarity	Perceptions are biased by the familiarity and affect with the risk source, which reduces the sensory perception of danger and/or make them judge the risk as low and the benefit as high	Finucane et al. (2000)
Unrealistic optimism	Unrealistic optimism can be observed when people believe that negative events tend to happen to others rather than themselves	Weinstein (1980)
Protected values	Asking people to ‘put a price’ on things they consider protected – related to their values, ethics and moral – can induce strong negative affective reactions	Baron and Spranca, (1997); Hanselmann and Tanner, (2008)
Reliability and clarity of information sources	Different descriptions of the risks may create framing effects that can alter people decisions	Tversky and Kahneman (1981)
Trust and confidence	Trust in state-operated risk control and risk management programs encourages more risky choices	Colquitt et al. (2007); Earle (2010)

Global warming and the current worldwide pathway of emissions considerably increased the likelihood of being affected by irreversible environmental changes (IPCC, 2023). Therefore, the associated natural disasters – such as floods, storms, cyclones, earthquakes, forest fires, landslides or heat waves – are a source of risks that should seriously be considered.

Environmental risks differ from other risks in a number of ways. Firstly, environmental risks are characterized by a high degree of complexity and uncertainty, entailing intricate causal relationships and multiple consequences. Secondly, environmental risks often emerge from the accumulation of behaviours of many individuals (for example, the widespread use of fossil fuels) rather than from a single activity, which makes the mitigation of these risks particularly difficult. Lastly, the consequences of environmental risks are often temporally delayed and geographically distant. For instance, the people who contribute to a risk (for instance by emitting GHG) are not necessarily the ones who will suffer from the consequences (future generations).

The existing environmental risks are well documented at the local scale. However, these objective environmental risks might be under or over perceived, as risk perceptions constitute a significant aspect of individual behaviors. Examining how people perceive environmental risks is therefore crucial to understand their decisions and behavior in the face of exposure to these risks (Böhm & Tanner, 2018).

Indeed, the perceptions of environmental risks are often not consistent with the objective measures of exposure, which means that, once again, households relocate to a place according to their own perceptions of the local environment rather than focusing on objective features. The difficulty of perceiving the real level of one's own vulnerability is partly due to the failure to perceive the extent to which individuals and societies are responsible for disasters (Wachinger, Renn, Begg, & Kuhlicke, 2013). Indeed, perceiving vulnerability implies accepting the fact that risks are also the result of factors internal to societies and are not just hazard consequences. Consequently, this low level of perception often generates an underestimation of risks (Nezlek and Zebrowski, 2001; Kim et al., 2018).

Indeed, households often wrongly evaluate their exposure to air quality and/or noise pollution. In Madrid, Chasco and Le Gallo (2013) showed that housing prices are better explained by subjective evaluation factors than by objective measurements of air and noise pollution, which is consistent with Adamowicz's findings in Alberta, Canada (1997). Indeed, they showed that residents in wealthier neighborhood do not perceive their environment as being highly polluted as they are influenced by their belief that air quality in other neighborhoods across the city is far worse.

The same is observed with flood risks, which have been broadly studied in the literature. Lechowska (2018) made a systematic review on floods risk perception and identified several factors that may influence perceptions. First, worry or direct previous experience of a natural hazard is highly significant. Then, being prepared to the event (behavioral factor) and being informed (awareness) appeared to be particularly important. As a conclusion, flood risks have been particularly well explored from a subjective point of view in the literature. Similar analysis have been conducted on the perceptions of earthquakes (Palm, 1998; Armaş, 2006) or tornados in the US (Ellis et al., 2018; Jauernic and Van Den Broeke, 2016). They all concluded on the importance of subjective factors and in particular of previous experiences. In fact, when considering multi-hazards risks, people tend to relocate according to their expectations on hazard proximity, previous hazard experience and perceived personal risk (Lindell & Hwang, 2008).

Therefore, the implementation of adaptation measures to the different climate impacts and associated risks should be based on evaluations including both objective variables and subjective perceptions of risks in order to better fit to actual behaviors. Indeed, if perceptions are not in line with objective variables, adaptation measures will not be efficient in tackling vulnerability issues. At the same time, perceptions may also lead individuals to adopt adaptation strategies that might not bring the most benefits. For instance, several studies analyzing how farmers' perceptions might explain constraints to climate change adaptation have been conducted in developing countries. They found that a perceived insufficient information was a significant factor explaining the reluctance in adopting adaptation measures (see for instance Datta et al., 2022; Pickson and He, 2021). In this sense, perceptions are a central factor to consider for policymaking and in particular for the adoption of adaptation strategies.

0.1.4. Changing mobility behaviors to reduce the impacts and vulnerabilities induced by transport mode choices

Besides dealing with environmental vulnerabilities, the second main challenge is also to reduce mobility vulnerabilities. To do so, the main lever applies to changing mobility behaviors towards less polluting, less time-consuming and/or cheaper transport modes. It is therefore essential to understand mode choice determinants in order to encourage households to shift to public transport or active modes rather than using a car.

0.1.4.1. *Mode choice determinants*

The determinants of mobility and modal shift behavior are numerous and multidimensional (see Figure 0.3). To identify them, De Witte et al. (2013) adopted a multidisciplinary approach, defining modal

choice as “the decision process to choose between different transport alternatives, which is determined by a combination of individual socio-demographic factors and spatial characteristics, and influenced by socio-psychological factors”. Their review of 76 modal choice papers led to the definition of three categories of objective factors: 1) socio-demographic indicators (such as age, gender, education, income, car availability or household structure), 2) journey characteristics indicators (travel purpose, travel time, distance, trip chaining, or weather) and 3) spatial indicators (parking or proximity to infrastructures and services). The socio-psychological factors are made of previous experiences, lifestyle, habits, and perceptions. More recently, Javaid et al. (2020) conducted a meta-analysis of 75 review papers dealing with the determinants of the adoption of active modes (low-carbon modes). The literature review leads to a classification of modal shift determinants into three main categories: 1) individual factors such as attitudes, beliefs or habits; 2) social factors (social influence, social norms); and 3) infrastructure factors (land-use, transport system quality and costs).

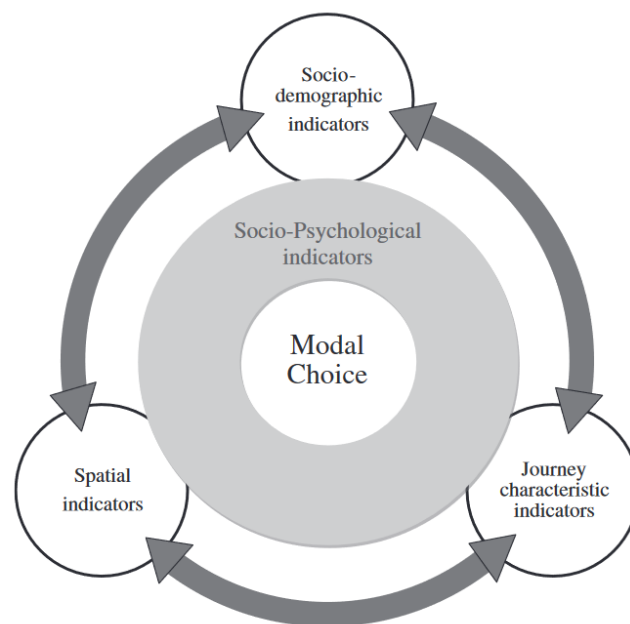


Figure 0.3 Framework for structuring modal choice determinants (Source: De Witte et al. (2013))

Both reviews highlight that if mode choice is particularly well explained by journey characteristics and/or infrastructures factors, subjective factors such as perceptions are rarely studied and less significant than other factors. For instance, these perceptions may include travel times and costs for different travel modes, because the variation in modes of payment can lead to a difference in price perceptions and the way the time is experienced (comfort, delay) can influence the choice.

The socio-psychological approach aims at explaining modal choice by the study of attitudes of individuals with regard to the available transport means. The concepts of intentions and habits are important elements in this approach. From 1965, Lovelock underlined the importance of psychological variables in understanding mode choice. Then, many researchers agreed that modal choice should not only be studied based on objective measurements, but should also take into account subjective features (see for instance Hine and Scott, 2000; Van Acker et al., 2010; Lang et al., 2011; Bamberg, 2012). Javaid’s review indeed confirmed that perceptions about common travel behavior (descriptive social norms), especially if supported by perceived normative beliefs of others (injunctive norms), highly influence mode shift. Consequently, modal choice should not only be studied by considering economic aspects, but also factors from transport geography and social psychology fields.

0.1.4.2. The influence of perceptions on mode choice

Perceptions are at the root of mobility habits and choices, as they are expected to condition behaviors. Indeed, as these perceptions influence individuals' mobility behaviors, they might also be the source of mobility vulnerabilities or even worse, transport poverty. A typical example is the underestimation of the mobility costs (time and money) associated to their residential place (Tiznado-Aitken et al., 2022). This is why including perceptions when studying mobility behaviors is particularly relevant for policymaking.

Several empirical studies included attitudinal factors and perceptions to explain mode choice. In the US, a study on commuting mode choice showed that demographic variables and attitudinal variables are extremely important in explaining mode-choice behavior. In particular, results underline that the contribution of attitudinal factors is greater than that of demographic variables (Kuppam, Pendyala, & Rahman, 1999). A study focusing in particular on buses also showed that perceptions of the reliability and comfort of bus services have a more significant impact on passengers' preferences than perceptions of availability and safety in China. In France, a study carried out in the Rhône-Alpes region also showed that the perception of a high level of comfort was a determining factor in the choice of public transport mode (Bouscasse & de Lapparent, 2019). Then, when comparing train *versus* airplane, air travelers preferences are mainly driven by minimizing their perceived travel time while train users value travel time productivity (Dällenbach, 2020), which is confirmed by another study conducted in Rhône Alpes about delays (Bouscasse & de Lapparent, 2020)

Among all perceptions and attitudes that have been explored in the literature, accessibility perception constitutes another important factor, which is also determining for residential choices (Blijie, 2005). If accessibility has conventionally been measured focusing on travel time and distance to a number of pre-determined destinations, the concept of perceived accessibility has been of interest during the last decade in order to capture the individual perspective of accessibility using a certain travel mode (Lättman, Friman, & Olsson, 2016) and/or to specific places. The introduction of this concept in new studies showed that accessibility studies that tend to understand individual's behaviors cannot only be limited to "calculated accessibility" (Pot, van Wee, & Tillema, 2021a).

In particular, studies on perceived accessibility indicate that self-reported evaluations of accessibility are often a poor match with calculated accessibility measures, meaning that objective accessibility was not necessarily the reason why people decide to choose a specific transport mode ((Lotfi and Koohsari (2009); Dewulf et al. (2012); Curl et al. (2015); Curl (2018); Van der Vlugt et al. (2019). This mismatching has been explored in different settings and for different population groups. For instance, in Australia, Ryan et al., (2016) showed that older people experience the lowest accessibility while middle age perceive the highest. In Sweden, Lättman et al. (2018) showed that levels of objective accessibility do not allow predicting perceived accessibility in a given residential area, but also highlighted that levels of perceived accessibility differ between main transport modes. Therefore, incorrect perceptions of accessibility may also be at the root of mobility vulnerabilities and should therefore be considered in policy impacts evaluations.

0.1.5. Summary and needs in the literature

Climate and environmental policies are often focused on the transport and housing sectors because of their important contributions to emissions. Yet, the literature has shown that these policies may create or exacerbate pre-existing inequalities.

If fuel poverty and vulnerability issues have considerably interested researchers, especially when focusing on the housing sector, the whole field of vulnerabilities implied by residential choices remains to be explored. Indeed, the identification of transport-related vulnerabilities and in particular, the possibility to conduct a multi-dimensional evaluation of these vulnerabilities is particularly limited. If some indicators exist to measure vulnerabilities related to car use, fuel expenses, low-income or travel

times, integrating these complementary dimensions all together remains an important challenge. Moreover, to our knowledge, there is no existing methodology allowing the definition of territory-specific profiles of vulnerable households. Yet, this would constitute a particularly useful tool for decision-making, in particular when reproducible at the city level.

At the same time, climate action urges and decision-makers implement new policies at the national and local levels without necessarily have the hindsight to understand the expected social impacts. If LEZs are very common all over Europe, their implementation in France started recently and was suddenly stopped in June, 2023 following a Senate recommendation. To our knowledge, most of the studies dealing with LEZs particularly focus on environmental and health efficiency, but few are exploring expected socio-economic or mobility impacts, especially prior the implementation. In this context, attempts to improve air quality in cities could lead to a worsening of the situation for vulnerable households, which represents a major challenge in terms of social justice (De Vrij & Vanoutrive, 2022). Yet, this evaluation is essential to ensure public acceptability of the policy but also to adapt the LEZ to the local context and define accompanying measures in order to minimize their impact on the most vulnerable people. Indeed, the recent reversals in France show that the more LEZs are locally adapted and specific, the more likely they are to be accepted, implemented and therefore efficient. Hence, this underlines the importance of an *ex-ante* study.

Studying transport poverty also raises the important issue of car-dependency, which is particularly common in suburban areas. Indeed, changing mobility habits towards cleaner modes implies increasing accessibility for those who currently depend on the car. Yet, in the urban margins, public transport is not always a realistic option. Moreover, accessibility as traditionally measured by travel times or distances-based indicators are not sufficient to truly assess households' behaviors and preferences. In fact, perceived accessibility appears to better explain the choice of a travel mode, which shows the importance of including and analyzing perceptions of car users when designing accessible and sustainable transport systems (Lättman, Friman, & Olsson, 2020). Researchers therefore recently started to integrate perceived accessibility in their studies, but this work remains mainly limited to the Global North context and to urban centers, while peri-urban areas received less attention.

Then, as the choice of a residential place both conditions mobility habits, but also determines the environmental quality (air quality, access to green spaces, hazards risks), it is central to understand to which extent environmental risks are taken into account in residential location choices in order to be able to limit vulnerabilities. Indeed, nowadays in the context of climate change, we might think that people tend to give more value to the environmental attributes, while at the same time, balancing between budgetary constraints and travel distances. If some environmental attributes have been integrated in residential choices models, they have mostly been studied individually. Moreover, the role of perceptions is once again central and has been less studied in the literature. It would therefore be of interest exploring if individuals' perceptions of several environmental factors may have a significant impact on residential choices and to which extent these perceptions may increase or reduce the exposure to environmental risks.

The rest of this introduction is organized as follows. First, we detail the research question of the thesis and then present our case studies. Then, we briefly present our different sources of funding. We finish with the outline of the thesis, presenting the main results of each chapter.

0.2. Contributions of this thesis

0.2.1. Research questions

If mitigation measures are often perceived as opposed to the households' interests, it is however essential to build a just ecological transition in order to strengthen social cohesion, reduce inequalities and offer

desirable and sustainable alternatives for the future. To do so, the ecological transition requires taking into account the different dimensions of vulnerabilities and inequalities: socio-economic, exposure, contribution and cumulative vulnerabilities at individual level. This also raises the issue of the political feasibility of this transition. In particular, the recent social movements show the importance of considering these social dimensions carefully. Therefore, understanding mobility and housing choices through the prism of the different dimensions of vulnerabilities, public policies and perceptions is crucial to set up a just and fair ecological transition.

This thesis aims to shed light on the issues of household vulnerability in this context of energy transition. This is particularly relevant to define ambitious environmental policies without forgetting the associated social justice issues. Therefore, **the central question of this thesis** is: *How do public policies and individual perceptions influence mobility and housing decisions, and subsequent vulnerabilities?*

We answer this main research question by defining four sub-questions.

First, it is important to be able to identify the most vulnerable households, who are often the most affected by energy shocks or public policies. In particular, in a specific territory, different profiles of vulnerabilities may emerge according to the specificities of households' residential places. In the literature, many indicators exist in order to measure transport poverty-related phenomena, such as financial difficulties, car dependency, lack of accessibility, but there is a need in creating an indicator that would allow exploring all these cumulated vulnerabilities at once and identifying typical profiles. Our **first research question** is therefore: *what tool can be used to identify the most vulnerable households in terms of mobility in a given territory?* To answer this question, we designed VulMob, a composite indicator to evaluate vulnerabilities and poverty at the local scale and applied it to the Grenoble area.

In particular, the French strategy to limit both GHG and pollutant emissions from the transport sector was initially including a LEZ implementation in about 40 urban areas. Even if this project were suddenly stopped in June 2023, it remains important to assess the potential impacts of LEZs in order to define modalities that could increase acceptability and help define compensatory policies to provide support to vulnerable households whose potential for adaptation is limited. Yet, most of the literature avoid exploring the *ex-ante* socio-economic impacts of a LEZ implementation or do it afterwards. Our **second research question** is therefore: *what are the impacts of a LEZ on mobility vulnerabilities?* In particular, we put an emphasis on distinguishing the impacts on poor and vulnerable households and the rest of the population by analyzing mobility behaviors based on the Local Households Travel Surveys.

Nevertheless, public policies aimed at limiting car dependency must take account of how people perceive their mobility potential. To do so, it is also important to understand the subjective determinants of mode choice in car-dependent settings. In peri-urban areas, which are often disconnected from public transport networks and therefore strongly car-dependent, the potential for modal shift is often limited. Therefore, studying perceptions, and specifically perceived accessibility, may be enlightening to find solutions to improve mobility. Yet, in the literature, these issues are mostly studied from an objective point of view, and focus more specifically on the urban core, more specifically in a Global North context. Our **third research question** is: *to what extent subjective dimensions, and more specifically perceived accessibility, play a role in car dependency in peri-urban, car-dependent contexts?* We answered this question by developing an integrated choice and latent variable model that has been applied to four peri-urban municipalities located around Santiago de Chile.

Finally, as residential choices and mobility habits are closely linked, if people move outside urban centers, for example to live in a larger house with a garden, this is often at the expense of accessibility. It is therefore essential to strike a balance between good environmental quality and mobility potential. Indeed, in the current global warming context, the multi-hazards risks associated with climate change are very likely to increase (IPCC, 2023). Therefore, our **last research question** focuses on

understanding to *what extent environmental risks and natural areas are taken into account when choosing a residential place?* We answer this question using discrete choice models designed to explain residential choice at the municipality scale in France.

The thesis is organized in four chapters and follows the general structure described in Figure 0.4.

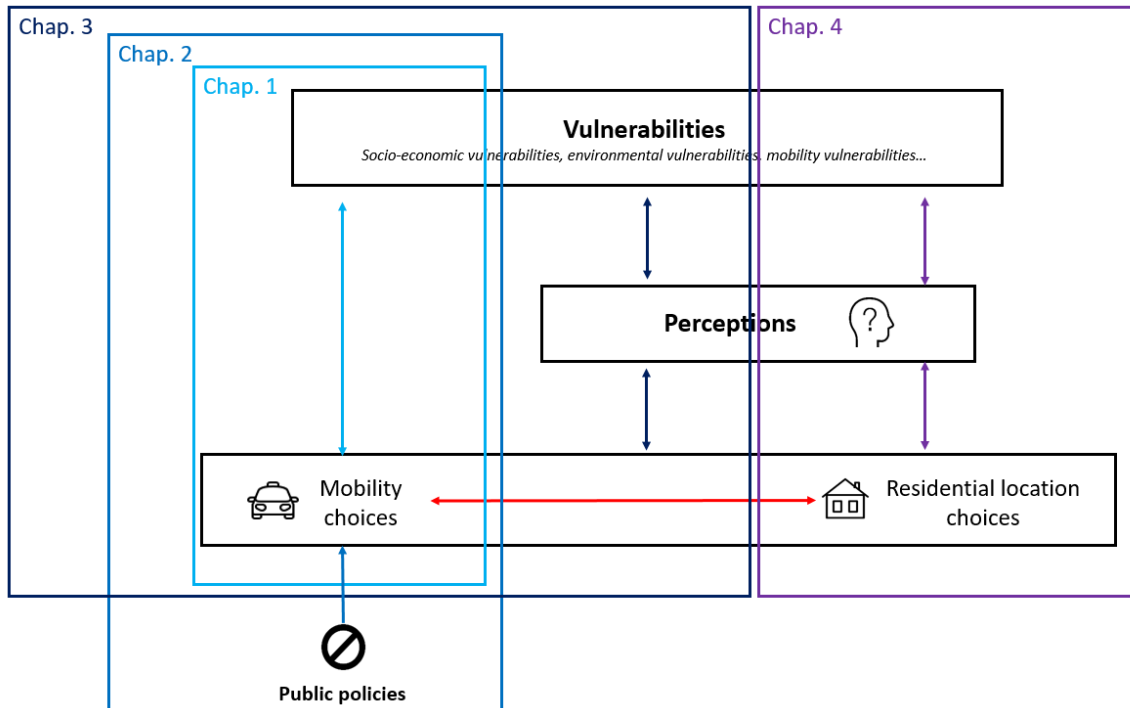


Figure 0.4 Structure of the thesis

0.2.2. Case studies

The different chapters focus on three study areas: chapters 1 and 2 takes Grenoble (France) as a case study, then, chapter 3 focuses on Santiago (Chile), while chapter 4 is based on the whole metropolitan France. This last case study will not be detailed.

0.2.2.1. Grenoble, France

We chose Grenoble as a first case study for this thesis. As the Grenoble Applied Economics Lab (GAEL) is located in Grenoble, our research team has developed over the years solid relationships with local decision makers and institutions, which is a great advantage in terms of knowledge of the territory specificities and access to useful data. Moreover, the implementation of a LEZ for personal vehicles in the Grenoble area, which overpasses air quality thresholds, was required in the context of the *Loi Climat et Résilience* (2021), even if the requirement was finally cancelled in June 2023. Grenoble was also one of the first conurbation to implement a LEZ for delivery vehicles in 2019, as well as a “zone 30”, limiting speed to 30km/h in the urban center.

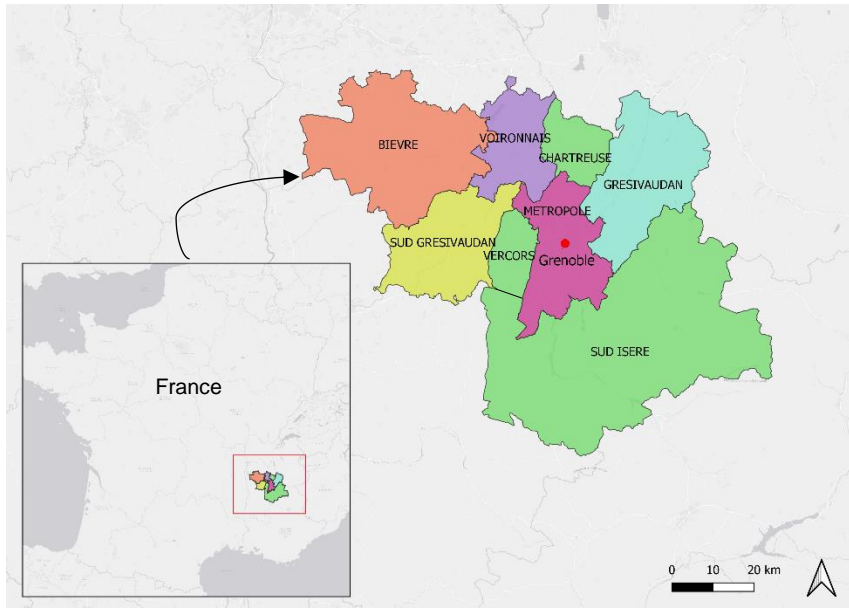


Figure 0.5 Location of the Grenoble metropolitan area (Source: Authors' own elaboration)

The Grenoble-Alpes Metropolis (in pink in Figure 0.5) is located at in the French Alps in the Southeast of France. It includes the city of Grenoble (158,240 inhabitants) and 48 neighboring municipalities, hosting altogether a population of about 450,000 inhabitants on an area of about 550 km². The Grenoble area is commonly described following a seven sectors scheme, defined from existing mountain massifs: Bièvre, Voironnais, Grésivaudan, Sud-Grésivaudan, Sud-Isère, Chartreuse and Vercors surround the Metropolis.

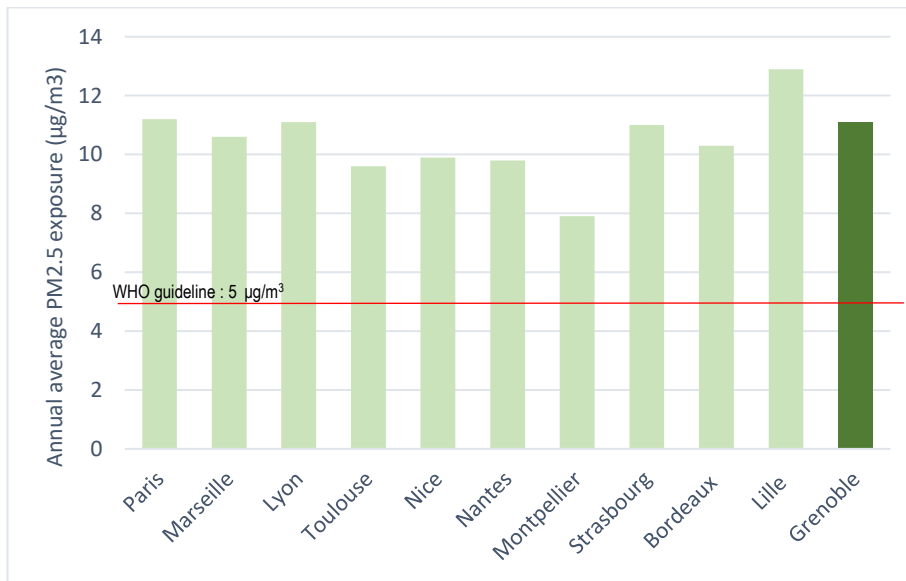


Figure 0.6 Mean annual pollution (PM_{2.5}) in the ten biggest French conurbations and Grenoble (source: EEA data, 2021)

Grenoble is surrounded by three mountain ranges, but it is one of the flattest city in France. This has important implications for air quality, as mountains tend to restrict air flows and thus concentrate fine particles and increase local air pollution (see Figure 0.6). This particular topographical situation has consequences in terms of the organization of the territory of the conurbation with an altitude rising very quickly as you move away from the center and towards one of the three mountain ranges. As a result, it is more difficult to set up public transport networks outside Grenoble than in most other French cities.

An ecologist mayor has led Grenoble since 2014. The city is often considered as a pioneer in France in terms of ecological and environmental issues and was elected “European Green Capital” in 2022. In particular, a proactive public transport and bicycle policy has been developed during the last past years.

It is an attractive place for students and highly skilled workers, thanks to its university and its dynamic labor market (with a job access rate of 38% compared to 34% on average in France). The unemployment rate is low (5.8% in the Grenoble area compared to 7.0% in France in 2023 (Data Emploi¹, T4 2022)) and job opportunities in the industrial sector are important. Households are thus on average wealthier and more educated than in most French urban areas of comparable size. Indeed, nearly a quarter of the area's employed workers are executives, compared to a fifth in the reference area. Moreover, the mean income per habitant in the Grenoble Metropolis is higher than in the rest of France (respectively, 25,801€/year and 22,040€/year (INSEE, 2022)).

However, this favorable situation hides strong income inequalities and residential segregation dynamics. The city of Grenoble hosts both wealthy and disadvantaged households. Indeed, the municipality is characterized by significant income inequalities: the richest 10% of households earn almost 4 times as much as the poorest 10%, the widest gap in the metropolitan area. Despite a high standard of living, 27,000 people live below the poverty line, representing a poverty rate of nearly 20% (compared to less than 15% for the metropolitan area as a whole). In Grenoble, families with children and single pensioners are over-represented in situations of monetary insecurity. The social diagnosis of the Grenoble metropolitan area reveals that 23,000 households are estimated to be fuel poor (i.e. cannot afford to warm their house at a reasonable cost, given their income) in 2020 (ADES, 2023). Grenoble is also known for its deprived urban neighborhoods, with a high concentration of poor, unemployed, low skilled and immigrant people. Indeed, unlike other cities in France, precarious people tend to live in the urban core (a half of the area's welfare subsidies recipients live in Grenoble (INSEE, 2015)), where they can have an access to public transport and services, but at the same time are also more affected by air quality issues.

¹ See <https://dataemploi.pole.emploi.fr/>

0.2.2.2. Santiago, Chile



Figure 0.7 Map of Chile
(Source : Maps of World)

Santiago de Chile constitutes the second case of study. This region is particularly interesting for the purpose of this thesis considering the social justice movements that recently took place there. My earlier studies have already led me on several occasions in Latin America, and this new experience has been possible thanks to a kind invitation of Professor Giovanni Vecchio. This part of my thesis has been conducted at the Instituto de Estudios Urbanos y Territoriales (IEUT), Pontificia Universidad Catolica de Chile, a research institute that focuses on urban studies and mobility issues and regroups researchers mainly interested in geography, urban planning, economics and transport engineering.

In 2012, in Latin America, almost 80% of the population lived in cities, being the most urbanized region in the world (UN, 2012). In particular, urban areas are essential in the spatial organization of Chile, as almost 90% of the population live in a city. Indeed, the three main Metropolitan Regions (MRs) of the country generate more than 63% of the GDP and 60% of the population lives in the central Metropolitan Region of Santiago.

Chile, located in western Latin America, is the southernmost country in the world and the closest to Antarctica, stretching along a narrow strip of land between the Andes Mountains and the Pacific Ocean. The country hosts more than 17 million inhabitants. Chile stretches over 4,300 km north to south, but only 350 km at its widest point east to west. This encompasses a remarkable variety of climates and landscapes, with the driest desert in the North and glaciers in the South. The Andes Mountains are also the reason why many Chilean cities have to face important air quality issues, as for instance in Santiago.

Santiago, the capital and main city of Chile, is located in the central area of the country, surrounded by mountains, and hosts more than 6 million inhabitants spread in numerous municipalities. Those municipalities were former rural towns that have been progressively integrated to the “Gran Santiago”. Yet, in the Metropolitan Region, each municipality operates independently, with no overarching metropolitan authority. In this sense, the functional organization of the Santiago MR can be described considering 48 municipalities, as 14 others municipalities also have strong connections with the urban core (Fuentes, Pezoa, Fuentes, & Pezoa, 2018).

Chile is considered as a high-income economy and is one of the most stable nations in South America, leading Latin America in competitiveness, per capita income, globalization, peace, and economic freedom. The Pinochet dictatorship (1973-1990) had important consequences on the development of Chile. On the economic front, his regime was marked by the liberalization of the economy, the freedom of trade and the opening of the country to international competition, reforms inspired by the "Chicago boys", breaking with previous interventionist economic policies. The supporters of these reforms praised the situation of “economic stability” that Chile achieved under Pinochet’s regime, but the extent, or even the reality, of this economic success opened to numerous debates.

In particular, the historic development of Santiago has been strongly modified by the dictatorship and the implementation of strong neoliberal policies. In particular, the eradication processes conducted among the National Policy for Urban Development (1979 – 1985) led to the displacement of thousands of low-income households from the northeastern quadrant of the metropolis towards its western and southern margins (see Figure 0.8). This phenomenon exacerbates the existing socio-spatial inequalities and segregation both in the metropolis and between the municipalities (Garreton, 2017). In particular, the wealthiest residents are currently living in the eastern part of Santiago, where most of activities are located, while the most vulnerable households are more likely to live in the west, far from the job opportunities. This results in an unequal location of jobs but also of wealth in the Santiago Metropolitan Region. Suazo-Vecino et al. (2020) show that this evolution of the city was detrimental to the vulnerable families, significantly increasing the average travel time to the center of the city and inequality among different socioeconomic groups. In particular, low-income households appear to be the most affected and results suggest that they would benefit from policies driving the evolution of the center of activities towards them.

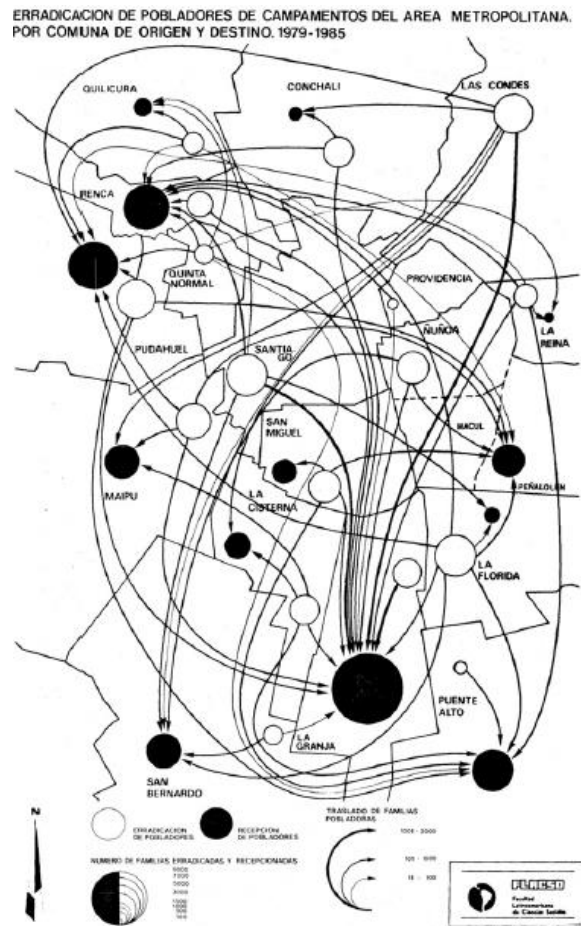


Figure 0.8 The eradication process in Greater Santiago (Source: Morales et al., 1990)

Note to the reader: Hollow circles show the original location of the eradicated families and black-filled circles indicate their destinations. Communities were deliberately divided in order to dismantle eventual resistance organizations.

Because of the unequal repartition of the activities and the important spatial segregation observed in the Metropolitan Region, mobility is therefore a key issue in Santiago.

In Santiago, car use has been increasing, especially since the pandemics, therefore increasing the travel times associated with "congestion costs". In Buenos Aires, Blanco and Apaolaza (2018) found a significant correlation between the possession of a car and the level of income. Indeed, in Santiago, high-income often implies shorter travel times and a more important car use. Moreover, households with the highest income travel more, quicker and have a better access to the car on average (Iglesias, Giraldez, Tiznado-Aitken, & Muñoz, 2019). Yet, if the urban extension seems to be correlated with higher travel times, it depends on whether the car or the public transport is preferred by households. The preference of the private vehicle is often justified by the comfort and the cheapness of the vehicles, as cars in Chile have a lower final price than in the rest of the countries of the region. However, not everyone can afford its purchase and use, and the low-income population income is captive of public transport. For those who can afford it, results show a very high inelasticity compared to the direct cost of its use: despite the fuel price increase, there is no traffic reduction in the short or medium term (Cortés Salinas, Figueroa Monsalve, & Moreno Alba, 2016).

In particular, in peri-urban areas, the only existing public transport infrastructures are bus services that are not included in the integrated public transport system TranSantiago. Yet, some peripheral areas are characterized by equal or even higher travel times than in peri-urban areas, which are spatially further from the economic center, though (Vecchio & Tiznado-Aitken, 2022). This shows that some specific areas are not easily reachable without using a car. For instance, in Guadalajara, moving from the peri-urban to the urban core can take it can take from an hour to more than 2 hours (González Pérez, 2018).

Yet, the travel times are not the only one issue to be faced: in the peri-urban areas, the bus stop can be far from the residential location and the trip can also be dangerous, for instance if walking at night or close to a highway is necessary to get home. Focusing in particular on the access to services such as education, a study shows that most of the opportunities of higher quality and free public school are concentrated in central and peri-central zones (Tiznado-Aitken, Muñoz, & Hurtubia, 2021). Consequently, peripheral areas, where a large proportion of the public-school demand resides, need closer opportunities to improve their access to this essential service.

0.2.3 Funding

The Grenoble IDEX funded this thesis as part of a large interdisciplinary project called MobilAir. This thesis also constitutes a part to three other interdisciplinary research projects: ACME, PACC-MACS and ClimAir.

The MobilAir project: Mobility and improvement of air quality (2018 – 2021), coordinated by S. Mathy (environmental economist, GAEL) and R. Slama (epidemiologist, IAB), funded by IDEX Grenoble.

MobilAir (<https://mobilair.univ-grenoble-alpes.fr/mobilair/>) develops an integrated approach applied to the Grenoble urban area and aims to provide methods and tools that can be replicated in other cities in France or abroad. The project has three main objectives corresponding to three Working Packages (WP): WP1. A better comprehension of the population's exposure to pollution; WP2. A detailed understanding of the determinants of mobility behavior and WP3. Support for public decision-making. It gathers researchers from local laboratories of different disciplines working on one or more aspects of air pollution: transport, environmental and health economists (GAEL), sociologists, behavioral psychologists (SENS), geographers (PACTE), epidemiologists (IAB, INSERM), atmospheric modelers (ATMO-AuRA, IGE and LEGI), transport and land use modelers (LJK).

The ACME project: Air quality and Climate at urban scale: an interdisciplinary assessment on health, Mobility, Economic issues and inequalities (2022 – 2025), coordinated by S. Mathy (environmental economist, GAEL) & G. Uzu (atmospheric chemist, IGE), funded by CDTools Université Grenoble Alpes.

The past work from the MobilAir research project aimed to identify measures that would make it possible to significantly reduce urban air pollution and its impacts, using a multidisciplinary approach. The ACME project follows on from the existing work that was completed as part of MobilAir and extends the research to include the impacts of climate change, whose causes and solutions are inseparable from those of air pollution. Social issues are central to the definition and implementation of air pollution and climate policies that are transversal to the entire ACME project. In an action research approach, ACME also proposes tools for the general public and public decision-makers to encourage the adoption and implementation of ambitious policies.

The PACC-MACS project: Atmospheric Pollution and Climate Change: scenarios on urban mobility, urbanism and heating to protect health (2020 – 2023), coordinated by R. Slama (epidemiologist, IAB), funded by ADEME Primequal.

The objective of project is to evaluate the medium-term impact (by 2050) of different local scenarios (on the scale of an urban agglomeration) concerning mobility, heating and urban planning (urban albedo, green spaces), on air quality, greenhouse gas emissions, local temperature and health, and to estimate the costs associated with each scenario, taking into account climate change. The project follows the MobilAir project developed in Grenoble. PACC-MACS will allow to enlarge the considered scenarios (by including scenarios related to the surface of green spaces), the considered environmental factors (via a temperature modelling), and behavioral factors (physical activity), and especially by focusing on the future climate of the Grenoble area.

The ClimAir project: Climate change and air pollution in an urbanized area: health impacts and economic costs of mitigation scenarios (2022 – 2025), coordinated by C. Staquet (atmospheric modeler, LEGI), funded by the French National Research Agency (Agence Nationale de la Recherche).

ClimAir is an extension of the PACC-MACS project. This project is an innovative and ambitious interdisciplinary project involving climate and air quality modelling, epidemiology, environmental economy and social sciences. The novelty is to consider climate change and air pollution jointly, in addressing mitigation and adaptation policy to climate change over the 21st century. Health impact, economic costs and social inequalities are quantified from scenarios of climate change mitigation (via the reduction of air pollution) and adaptation, with a focus on the most vulnerable population. Another novel point is to investigate the impacts of climate change at the scale of an urban area, while countries are usually considered in the literature. This downscaling is built upon an original chain of numerical models fed with outputs of the latest generation of global climate models.

The visiting to the Pontificia Universidad Católica de Chile has been partially funded by the Université Grenoble Alpes and the Grenoble Applied Economics Lab. The research conducted there was funded by the Centro de los Objetivos de Desarrollo Sostenible para América Latina y el Caribe (CODS) and the Centro de Desarrollo Urbano Sustentable (CEDEUS), ANID/FONDAP 1522A0002.

0.2.4. Outline of the thesis

We answer the main research question by defining four sub-questions, each of them constituting a separate chapter of the thesis. This section presents the main analyses and results of each chapter.

0.2.4.1. *Chapter 1: Identification and typology of the mobility highly vulnerable households using VulMob, a new composite indicator*

In today's societies, providing everyone with access to safe, affordable, accessible and sustainable transport systems enables access to jobs and services, but must also meet the imperative of social inclusion (Cass et al., 2005; Preston and Rajé, 2007; Stanley et al., 2011).

Yet, in a context where mobility is largely provided by individual motorized transport (Mattioli, 2021), some low-income households have high fuel and mobility costs, which put them under severe economic pressure that can be defined as "transport poverty". Beyond that, a wide range of mobility vulnerabilities exists. These vulnerabilities arise from changes in the conditions in which individual mobility takes place: for example, from rising fuel prices or the introduction of policies aimed at reducing the negative externalities of the private car, such as the LEZ. However, depending on the ability of households to adapt, vulnerabilities will not be the same. Thus, whether or not one is vulnerable depends on a combination of factors that refer to different dimensions: economic dimension, specificity of distances and trips, family structure, ability to switch to other modes, work schedules, etc.

It is therefore important to be able to identify both vulnerable and transport-poor households and the different combinations of mobility vulnerabilities in order to develop policies that must be geographically specific according to the characteristics of the territory, but also in terms of targeted population. These issues are central to implement just and fair policies that aim at reducing the externalities of cars. Indeed, policies in the transport sector are often singled out as increasing transport poverty or vulnerabilities. If social justice issues are not taken into account, the implementation of such measures could be blocked (Fandio, Maheu, Nicolas, Bouzouina, & Déprés, 2020). In this chapter, we try to answer the following question: *What tool can be used to identify the most vulnerable households in terms of mobility in a given territory?*

To answer this question, we developed a composite indicator to assess, in a territory (such as an urban area), the number of households in the different situations of mobility vulnerability and/or in a situation

of "transport poverty" as a consequence to changes in mobility conditions (fuel price increases, policies, new infrastructures). We elaborated the VulMob indicator following the OECD-JRC guidelines (Nardo et al., 2005, Nardo et al., 2008). It is made of thirteen individual factors organized in four dimensions: financial resources, work constraints, car dependency and structural constraints.

We applied this indicator to the Grenoble area using the EMC² data that precisely describes the mobility habits of more than 7,500 households living in the area (both inside and outside of the Metropolis). The results of this analysis allowed identifying 9.6% of the global population as "highly vulnerable" (i.e. cumulating at least six vulnerability factors) and 5.5% as transport poor (cumulating two financial issues factors). 1.3% of households have been identified as being both transport poor and high vulnerable and should therefore receive special attention from the public authorities. A hierarchical clustering analysis identified five profiles of highly vulnerable households: some are monetary constrained; others are heavy car users, work by night or face territorial accessibility issues. These results show the importance of considering the sectors specificities to implement the most adapted answers to limit vulnerabilities.

In chapter 1, we only focus on the orange attributes detailed in Figure 0.9.

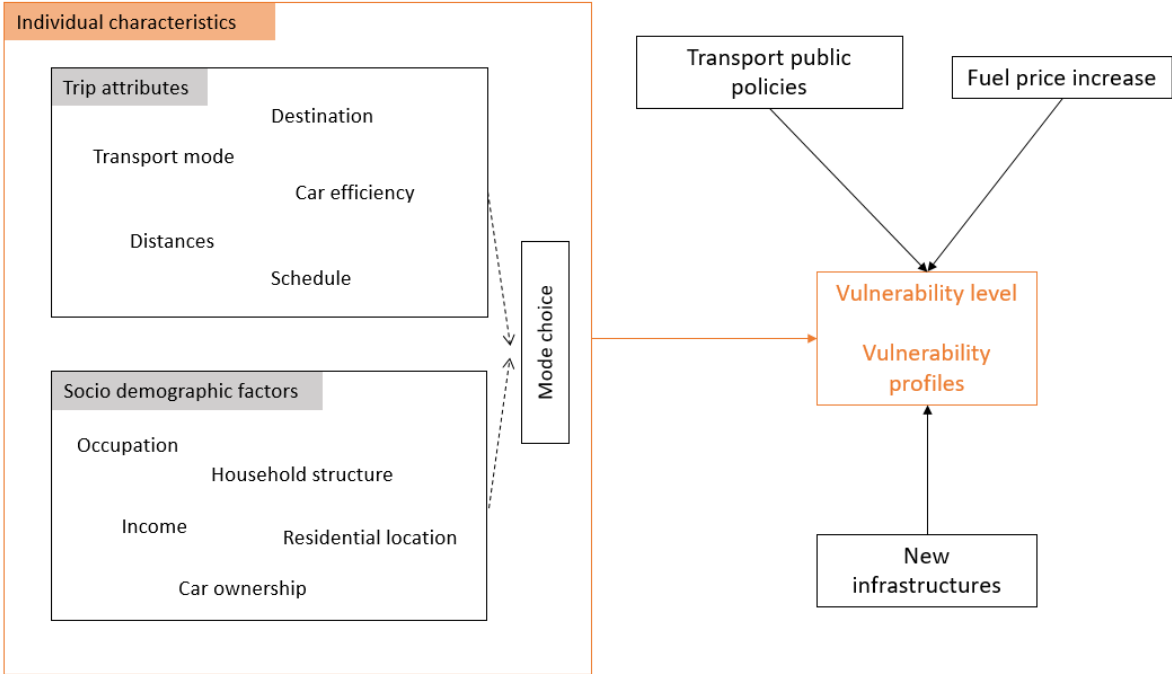


Figure 0.9 Structure of chapter 1

0.2.4.2. Chapter 2: Evaluation of the ex-ante impacts of a LEZ implementation in the Grenoble area

The transport sector is one of the most important in terms of greenhouse gas and atmospheric pollutant emissions and therefore constitutes a main environmental issue. In this context, LEZs have been implemented all over Europe. They aim to limit the circulation of the most polluting vehicles in urban zones in order to improve air quality. Positive impacts of LEZs on air quality have been proven in many European cities (Cesaroni, 2012; Ferreira et al., 2015; Lebrusán and Toutouh, 2021). Yet, the socio-economic impacts remain less studied and are at stake in this second chapter.

In France, the fear that the most fragile households would be the most affected by LEZs had slowed their adoption. For instance, in 2012 the implementation of a priority action area for air quality (*in French, Zone d'Actions Prioritaires pour l'Air*) was finally cancelled because of the fear of the low

acceptability of these zones (Charleux, 2014). In 2021, the Loi Climat et Résilience generalized the implementation of LEZs in all French urban areas exceeding the limit values. Yet, the project was once again suddenly stopped in June 2023 following a Senate recommendation that warned in particular about the expected negative social impacts. Grenoble was one of the cities that should have set up such a LEZ targeting individual mobility. The city set up a committee of experts to define the implementation procedures. Despite the government's decision to halt the process, Grenoble has stayed the course and implemented the LEZ at the beginning of summer 2023... It was therefore necessary to identify the households that may be affected by the LEZ and the nature of their pre-existing vulnerabilities in order to increase acceptability and define adapted compensatory policies.

We contribute to this literature using the Grenoble area as a case study to assess the ex-ante impacts of a LEZ implementation. In particular, we try to answer to the following question: *What are the impacts of a LEZ on mobility vulnerabilities?* This evaluation is particularly important to implement an ambitious and efficient policy but also to define compensatory measures to facilitate the LEZ acceptability. The objective of this chapter is therefore to first propose and ex-ante evaluation of the LEZ impacts at the individual level, both on vulnerable and non-vulnerable populations in the Grenoble area, but also to explore the potential for adaptation of households. As members of the scientific committee for the LEZ implementation, we presented the results of this chapter to the local decision makers of the Grenoble Metropolis.

To answer this research question, we relied on the EMC² data once again. We designed four design scenarios for the LEZ implementation (two perimeters and two schedules) and assessed which trips would be affected. Then, for the affected households and trips, we explored three potential steps of adaptation. First, we considered the potential for modal shift (considering distances, loops and elevation), then the potential for trip modification (considering the purposes) and finally the possibility of purchasing a new car (considering the income level).

Results show that the larger perimeter would therefore affect 28,688 households (8.0% of the global population), an increase of 41.8% compared with the smallest perimeter. However, a temporary LEZ² does not considerably reduce the number of affected households but could increase acceptability. In addition, the effects of the LEZ are not evenly distributed across the population, with households identified as highly vulnerable in Chapter 1 being particularly affected. Modal shift offers a solution for 57% of the affected households and concerns 68% of the trips. Trips of vulnerable households are only slightly more dependent on the car (63.2% are transferable to other modes compared with 68.1% for non-vulnerable households) but vulnerable households are more likely to have at least one trip that is not transferable to other modes (58.8% *versus* 43.5%).

Active modes (walking, cycling) constitute a great opportunity for modal shift and are a solution that is equally accessible to both types of households (vulnerable and non-vulnerable). Yet, public transport appears to be less accessible for vulnerable households. In particular, when exploring the vulnerability profiles, some specific profiles (such as costly heavy car users) are particularly threatened by the lack of an adaptation solution.

In chapter 2, we only focus on the blue attributes detailed in Figure 0.10.

² A temporary LEZ operates only during daytime and workdays

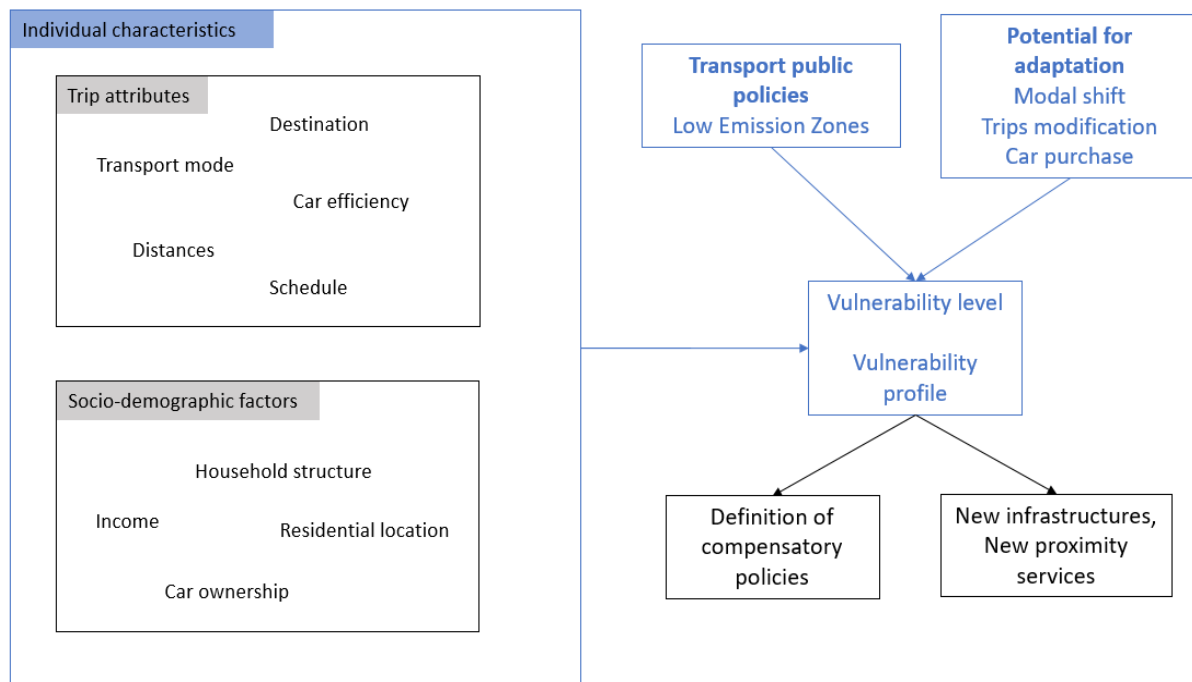


Figure 0.10 Structure of chapter 2

0.2.4.3. Chapter 3: Car dependency in the urban margins: the influence of perceived accessibility on mode choice

In a context characterized by the need to reduce car dependency, this third chapter takes a step back and focuses on the influence of perceptions to explain mobility choices. Indeed, the efficiency of transport policies and the actual potential for adaptation to these policies relies on understanding how people choose their transport mode. Exploring the influence of perceptions on mode choice can offer new levers that could be activated to promote other modes. In particular, car dependence induces to transport poverty and mobility vulnerabilities. In a car dependent context, people are forced to use a car to move and access activities and opportunities that are essential to satisfy their needs, due to the lack of alternative transport modes and the absence of such opportunities in the vicinity of their residence (Mattioli, 2016).

Most of the studies focus on objective features, whereas subjective dimensions could also explain the forms of accessibility vulnerabilities experienced in car dependent settings. As the concept of perceived accessibility explains, how individuals rate their environment and their subjective ability to reach a destination and access opportunities does not necessarily reflect the results of objective accessibility evaluations (Lättman et al., 2016; 2018). Yet, subjective dimensions such as perceived accessibility have received less attention, even if they could further confirm – or even question – the findings of objective evaluations.

In this third chapter, we aim to examine to what extent perceived accessibility influences modal choices in a car dependent setting. Thus, we answer the following question: *To what extent subjective dimensions, and more specifically perceived accessibility, play a role in car dependency in periurban, car-dependent contexts?* We focus on Santiago de Chile, a Latin American setting in which the issues of transport poverty have been widely examined, but only partially considering their subjective dimensions. In particular, we intend to compare peripheral and periurban settings, which share a functional dependence from zones of the city in which most opportunities (jobs, health, etc.) are concentrated, but have different socioeconomic conditions and different access to public transport (Tiznado-Aitken et al., 2023).

To answer this question, we examined the data of a phone survey conducted in 2020 as part of the *Centro de los Objetivos de Desarrollo Sostenible para América Latina y el Caribe* (CODS) project, involving 300 households in four peripheral and periurban municipalities of the Metropolitan Region of Santiago. We developed an integrated choice and latent variable model that includes households' attributes, trip attributes and psychometrics indicators. A factorial analysis conducted on these psychometrics indicators allowed to identify the perceived accessibility latent variable that is integrated in the model.

Results showed that perceived accessibility has a negative net impact on the utilities for motorized modes, which means that a low perceived accessibility increases the likelihood of choosing car, and even more public transport. Moreover, residents from peripheral municipalities tend to perceive a higher accessibility than households from periurban areas, which are excluded from the public transport system. These findings show the importance of providing nearby opportunities and convenient alternatives to the car in order to limit car dependency, especially in periurban areas.

In chapter 3, we only focus on the green attributes detailed in Figure 0.11.

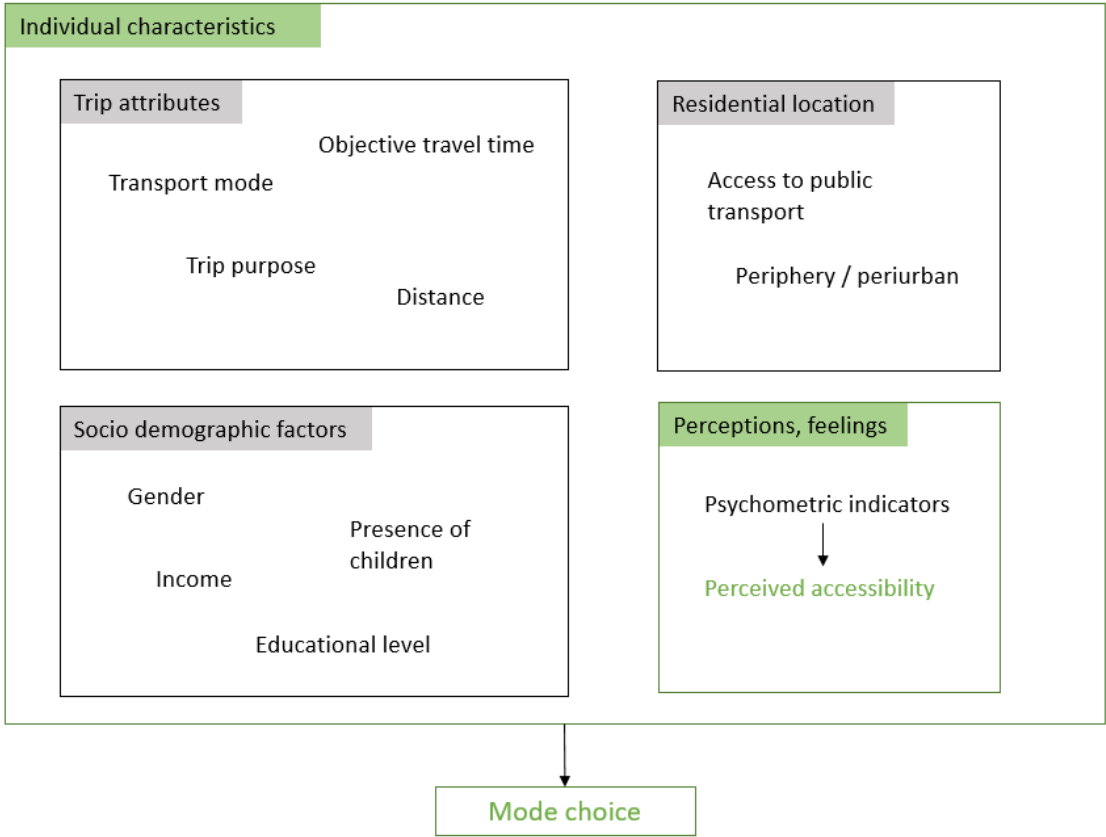


Figure 0.11 Structure of chapter 3

0.2.4.4. Chapter 4: Did you care about environmental risks and natural areas when choosing where to live? A discrete choice analysis in France

In the current climate change context, the risk of exposure to multi-hazard and extreme environmental risks is increasing. In France, floods, air pollution or even heat waves constitute major environmental and health issues. Adaptation solutions may also rely on the presence of environmental attributes, such as natural areas. Therefore, exploring the determinants of residential choices are particularly interesting in order to understand whether these environmental risks and natural areas influence residential choices.

In this last chapter, we aim at understanding to what extent environmental attributes are taken into account when choosing for a residential place, considering both objective exposure indicators and perceptions. We consider three different environmental risks: air pollution, flood, clay swelling; and one attribute: access to natural areas, as a proxy for considering the mitigation of urban heat islands. We aim to understand *to what extent environmental risks and natural areas are taken into account when choosing for a residential place?* A major objective of this work is therefore to show the effect the declared consideration of these attributes on residential choices at the municipality level.

To do so, our study is based on an original dataset that was collected in 2023 with an online survey that involved 1,871 respondents. We developed two discrete choice models. The first one is based on a multinomial logit (MNL) regression that includes housing prices, income, density, number of jobs, distance to work and both objective and subjective environmental attributes. Then, we developed a latent class model composed of two classes defined by income, children and occupation.

Our MNL model shows the influence of environmental attributes and risks on residential choices. Environmental risks such as flood risks and clay risks have a negative and significant effect on preferences while natural areas are positively evaluated. Yet, this model gives few insights on the importance of environmental perceptions. This led us to the assumption that the consideration of environmental risks and natural areas is heterogeneous among the population. We therefore developed a LC model in order to assess these heterogeneous concerns.

The LC model fits better and highlights the existing differences among population groups, even if omitted variables are also revealed. Results highlight that households who took into account environmental features when choosing for their residential place all tended to choose less polluted areas, while a small group of retired low-income households also value limited natural areas and municipalities that are less exposed to clay swelling risks. Thus, studying together both objective and subjective effects of environmental risks appears to be particularly relevant to fully understand residential choices.

In chapter 4, we only focus on the yellow attributes detailed in Figure 0.12.

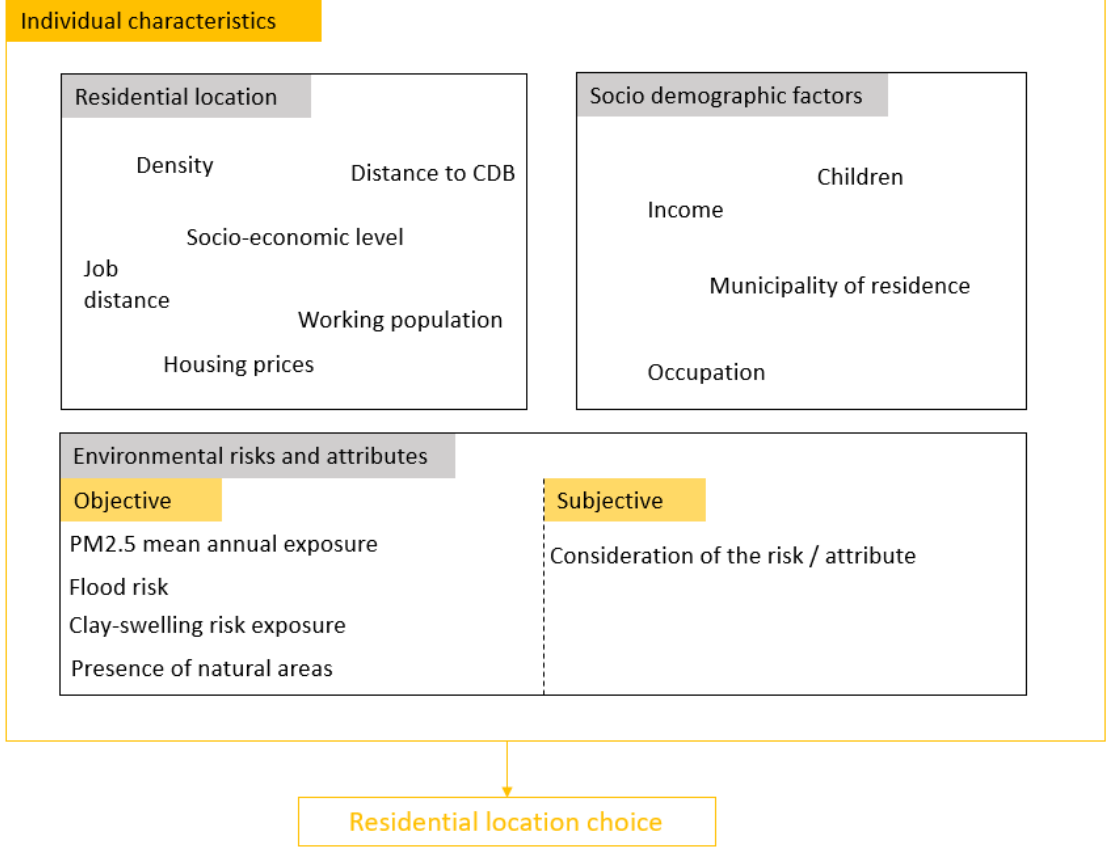


Figure 0.12 Structure of chapter 4

Scientific dissemination

1. Publications

Chapter 1 and 2, jointly done with H el ene Bouscasse³ and Sandrine Mathy⁴.

- ◆ Blandin, L., Bouscasse, H., Mathy, S. (2023). Typology of the highly vulnerable households using VulMob: a new composite indicator designed to evaluate mobility vulnerabilities (*submitted to Energy Economics*) [data analysis, data curation, investigation, writing]
- ◆ Blandin, L., Bouscasse, H., Mathy, S. (2023). Assessing the ex-ante impacts of a low-emission zone on vulnerable households in Grenoble, France (*submitted to Energy Policy*) [data analysis, data curation, investigation, writing]
- ◆ Blandin, L., Bouscasse, H., Mathy, S. (2023). Impact des zones   faibles  missions sur la vuln rabilit  et la pauvret  des m nages en mati re de mobilit  (*submitted to Economics et Statistics*) [data analysis, data curation, investigation]

Chapter 3, jointly done with Giovanni Vecchio^{5,6}, Ricardo Hurtubia^{4,7,8} and Ignacio Tiznado-Aitken⁹.

- ◆ Blandin, L., Vecchio, G., Hurtubia, R., Tiznado-Aitken, I. (2023). Car dependency in the urban margins: the influence of perceived accessibility on mode choice (*submitted to Transportation Research Part A*) [software, data analysis, data curation, investigation, writing]
- ◆ Hurtubia, R., Blandin, L., Vecchio, G., Tiznado-Aitken, I. (forthcoming). Accesibilidad percibida y decisiones de movilidad en contextos dependientes del auto. In Rojas, C., Vecchio, G., Ladr n de Guevara, F. (eds.), *Ciudades accesibles y equitativas*. Santiago de Chile: Ril editors [software, data analysis, data curation, investigation]

Chapter 4, jointly done with H el ene Bouscasse³, Sandrine Mathy⁴, Mohamed Hilal¹ and Marie-Laure Breuill ¹.

- ◆ Hilal, M., Blandin, L. (2023). "Habitants expos s au retrait-gonflement des argiles et/ou aux risques d'inondation", <https://doi.org/10.57745/W9N5Z9>, Recherche Data Gouv. [conceptualization]

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⁸ Pontificia Universidad Cat lica de Chile, Department of Transport Engineering and Logistics, Vicu a Mackenna 4860, Macul, Santiago, Chile

⁹ Department of Human Geography, University of Toronto Scarborough, Toronto, Canada

2. Presentations and conferences

2021

- ◆ GAEL doctoral students seminar, Grenoble, France
- ◆ Residential Costs & EMC² Seminar, Grenoble, France
- ◆ 8th Annual conference of the French Association of Environmental and Resource Economists (FAERE), Grenoble, France

2022

- ◆ XVI World Conference of Spatial Econometrics Association, Warsaw, Poland
- ◆ Transport and urban planning cross-disciplinary seminar, Santiago, Chile
- ◆ Jornadas de Investigación del IEUT, Santiago, Chile

2023

- ◆ III Simposio Internacional de Doctorandos del CEDEUS, Santiago, Chile
- ◆ 10th Annual conference of the French Association of Environmental and Resource Economists (FAERE), Montpellier, France

3. Political decision support

- ◆ Citizen consultation on the Grenoble's LEZ, Grenoble, France (2022)
- ◆ Feedbacks on the implementation of a LEZ to local decision-makers, Bayonne, France (2023)

4. Trainings

- ◆ Spatial Econometrics Advanced Institute (SEAI 2021), online (1 month, 2021)
- ◆ VU Amsterdam Summer School: The Economics of Urbanization, Amsterdam, Netherlands (1 week, 2022)
- ◆ Workshops on simple features, clustering of spatial data, data to grid aggregation in R, Warsaw, Poland (2 days, 2022)
- ◆ 5th edition of CIRED International Summer School in Economic modelling of Environment, Energy and Climate, Paris, France (1 week, 2023)

5. Research stay

4-months research stay at the Pontificia Universidad Católica de Chile (2022) Hosted at the Instituto de Estudios Urbanos y Territoriales (IEUT) and at the Centro de Desarrollo Urbano Sustentable (CEDEUS), Santiago, Chile.

Chapter 1

Identification and typology of the mobility highly vulnerable households using VulMob, a new composite indicator

Abstract

Mobility enables us to find jobs, go to school or meet people. However, long distances, high costs, car dependency and poor accessibility are sources of mobility vulnerabilities. The current rise in fuel prices may have a strong impact on mobility, especially for households that rely heavily on their cars. Moreover, the need to reduce air pollution requires the implementation of ambitious environmental policies. It is therefore necessary to identify transport-poor households, affected by financial issues, as well as vulnerable households whose mobility would be strongly impacted by changes in individual mobility conditions and would have difficulties to adapt to this situation. To this end, we construct VulMob, a composite indicator made up of 13 individual factors organized in four dimensions: financial resources, work constraints, heavy car use and structural constraints, such as accessibility or household structure. We apply this indicator to the Grenoble area, in France. Our results show that 9.6% are highly vulnerable, meaning that they face at least six vulnerability issues and 5.5% of the households are transport-poor. A typology of five profiles of highly vulnerable households shows that some are financially constrained; others are heavy car users, work at night or face territorial accessibility problems.

Keywords: mobility, transport poverty, transport, vulnerability, composite indicator, public policy

1.1. Introduction

Mobility is often presented as the “right of rights”, because it opens access to basic services and facilities that determine everyone’s socioeconomic conditions: education, employment, administrative and health services (Van Ham, 2002; Thisse et al., 2003; Gobillon et al., 2007). In this sense, the Sustainable Development Goals for 2030 (United Nations, 2018) point out the need to “provide access to safe, affordable, accessible and sustainable transport systems for all” (SDG 11.2). More broadly, mobility issues respond to a logic of social inclusion and are closely related to the spatial aspects of mobility (Cass et al., 2005; Preston and Rajé, 2007; Stanley et al., 2011).

In the Global North, mobility is largely provided by individual motorized transport. In particular, the European Union counts 560 cars per 1,000 inhabitants. This situation is the result of an economic development process and land-use planning, structured during the last decades in a context of cheap fossil fuels driving to suburbanization and the lengthening of daily distances travelled, creating a strong dependence on private cars (Mattioli, 2021). Such a dependence leads to situations of transport poverty and vulnerability that echo the notion of fuel poverty, which is common in the literature.

The literature concerning fuel poverty defines “fuel poor” households as the one with low incomes and a high share of expenses dedicated to heating (Dubois, 2012 employs the term of “*high energy needs*”; Darby (2012) speaks about “*household energy consumption, (...) and cost of delivered energy*”). A similar definition could be adopted concerning transport for households spending a high share of their income in mobility expenses (Smart and Klein, 2017; Nicolas et al., 2012). Some low-income households have high mobility costs while having low incomes, which impinge on their living expenses and put them under severe economic pressure. These households might be called “*transport-poor*”.

The notion of transport-poor describes a current, static state that can be observed at time t . However, in a structurally changing world, it is also important to have a dynamic approach to understand which households might be affected by changes such as a rise in fuel prices, as seen in recent years with the COVID-19 pandemic, followed by the war in Ukraine, or the introduction of policies aimed at reducing the negative externalities of the private car, such as the Low Emission Zones (LEZs).

For this purpose, we use the concept of vulnerability, which allows us to identify households that will find it difficult to adapt in the event of a major change in the transport system, whether this change is exogenous or endogenous. This concept goes beyond the simple (but necessary) financial question. Indeed, there are other causes and circumstances that may make some households vulnerable to changes in the conditions in which they are used to travelling, whether because of heavy car use or because of family or work constraints. For these households, an increase in the price of fuel, a change in transport supply or public policies to reduce car use, can have a significant impact on their lifestyle and some of them may find it very difficult to adapt, at least in the short to medium term, due to financial, spatial, family or work constraints.

The idea of adaptive capacity is central to the concept of vulnerability. Indeed, depending on the capacity of households to adapt in order to reduce their car use, the level of vulnerability will not be the same. For example, an increase in fuel prices will have a different impact on a low-income household that uses a car a lot, depending on whether they can switch to public transport, walking or cycling. A household with a member who works nights will also be less adaptable than a household with active members working at traditional work hours. Certain family structures, such as single-parent families or families with several children, may also reduce adaptive capacity, but again this depends on travel distances and modal shift opportunities. Vulnerability thus depends on a combination of factors relating to different dimensions: financial dimension, specificity of distances and trips, family structure, ability to switch to other modes of transport...

In short, households that are both transport poor and highly vulnerable (HV) have a low capacity to adapt themselves and will require special attention from the public authorities. Therefore, it is important to be able to identify transport poor and vulnerable households within a territory in order to develop policies adapted to the local population and geographically specific according to the characteristics of the territory. These issues are central to implement just and fair policies that aim at reducing the externalities of cars. Indeed, policies in the transport sector are often singled out as increasing the transport poverty or vulnerabilities of the most vulnerable households. If social justice issues are not taken into account, the implementation of such measures could be blocked (Fandio et al., 2020).

The objective of this chapter is to propose a composite indicator (CI) to assess, in a territory (such as an urban area), the number of households in a situation of transport poverty and the different types of vulnerability in terms of transport to changes in mobility conditions (fuel price increases, policies, new infrastructure). Although applied to a given territory, the objective of replicability is central, which requires that this indicator be based on data usually collected in mobility surveys. We elaborated the VulMob CI following the OECD-JRC guidelines (Nardo et al., 2005, Nardo et al., 2008), made of thirteen individual factors organized in four dimensions: financial resources, work constraints, heavy car use and structural constraints.

The chapter is organized as follows. Section 1.2 is a literature review on transport poverty and related mobility vulnerabilities. Section 1.3 describes the methodology to build the VulMob indicator. Section 1.4 details the results of the application of the VulMob indicator to mobility patterns of households living in the Grenoble area. Finally, section 1.5 presents the limits of our work and discusses our main conclusions.

1.2. Transport poverty and mobility vulnerabilities: a story of concepts

The term of “*fuel poverty*” first appeared in the literature in the 1980s in the UK, and was initially used to designate households having difficulties to heat their houses adequately (Bradshaw & Hutton, 1983). Then, the concept was extended to households spending more than 10% of their budget on energy (Boardman, 1991) and the government decided to consider required (and not actual) expenditures to include household’s restrictions in the definition. This definition has been progressively transposed to the transport sector, to designate households who dedicate an important share of their income to daily mobility, which led to the emergence of the term “*transport poverty*”.

Since then, research on transport poverty has progressed and different terminologies have been used in a generic way to describe many concepts related to transport poverty issues (Mattioli, Lucas, & Marsden, 2017). On the one hand, transport poverty is used with a global meaning to describe any kind of inequalities related to transport (Velaga et al., 2012; Lucas et al., 2016) and other related concepts such as “social exclusion related to mobility” (Preston & Rajé, 2007) or “transport disadvantage” (Currie, 2011; Hine et Mitchell, 2003). On the other hand, in a more specific context, it describes the affordable prices of transport (Gleeson & Randolph, 2002) in relation with other concepts such as “transport affordability” (Litman, 2013; Lucas et al., 2016, Cao and Hickman, 2018) “forced car ownership” (Currie and Senbergs, 2007; Curl, 2018) or “car economic stress” (Mattioli and Colleoni, 2016; Mattioli, 2017). Few years after, researchers also started to explore this concept in France, drawing parallels with fuel poverty (Saujot, 2012; Coulombel and Leurent, 2012). They also studied the related inequalities (Jouffe and Massot, 2013; Jouffe, 2014), and considered specific concepts such as transport affordability (focusing on mobility expenses) (Nicolas et al., 2001; Nicolas and Pelé, 2017), accessibility (Orfeuill, 2004), forced car ownership (Mignot, 2004; Motte-Baumvol et al., 2010; Belton Chevallier et al., 2018)

Seeing the different definitions and concepts associated to transport and mobility poverty, in 2011, Markovich and Lucas underlined the “need to establish a lexicon of definitions to ensure a greater degree

of clarity and consistency within and between the academic and policy literature". Lucas et al., (2016) proposed a multidimensional definition of transport poverty including the lack of transport resources, high monetary costs, large distances, low accessibility and exposure to negative externalities of transport.

In this chapter, we use the term "*transport poverty*" to refer to the former, broader problem related to low income and high mobility expenses. Yet, this concept is still often confounded with the associated vulnerabilities. In the words of Adger (2006), "*vulnerability is most often conceptualized as being constituted by components that include exposure and sensitivity to perturbations or external stresses, and the capacity to adapt*". Therefore, being exposed, sensitive and unable to adapt to a situation aforementioned related to mobility constitutes a "*mobility vulnerability*". On the contrary, some households might be exposed to a certain phenomenon, but will not be vulnerable thanks to their capacities to adopt adaptive behaviors. For example, in the event of fuel prices rising, a high-income household will change her financial tradeoff or adopt other transport modes. A low-income household that mainly uses its car for daily travel could fall into mobility precariousness, depending on whether or not it has the possibility of transferring its trips to public transport or active modes. To avoid any confusion, we introduce the concept of "*mobility vulnerability*" as defined above in order to describe the different factors related to mobility issues that might lead to transport poverty. In our case, being unable to adapt to a change is measured by crossing the threshold associated to a phenomenon. These mobility vulnerabilities have been studied in the literature, which mainly explored four dimensions: monetary, work constraints, heavy car use and structural constraints (in particular, accessibility).

If the evaluation of mobility vulnerabilities cannot be limited to economic struggle, the first dimension remains strongly connected to financial issues. This dimension has been widely studied and quantified, by using for example the ratio indicator or LIHC (low-income high costs) (Hills, 2012). By the way, France is currently the only country in the EU with an official indicator of transport affordability. It is estimated that 10% of households need to spend more than 4.5% of their income only for their constrained fuel expenses (Cochez, Durieux, & Levy, 2015). Yet, those indicators are often criticized, as they do not take into account the restrictive and adaptive behaviors, which are central in the evaluation of vulnerabilities. In the housing sector, a restrictive behavior would be to heat your home just enough to keep a livable temperature, while in the transport sector, restrictive behaviors are observed with households trying to limit their trips to the bare minimum, by avoiding leisure activities for instance.

Mobility vulnerabilities are also caused by other factors such as job issues and related constrained trips, and particularly the need to use a car to be able to reach these destinations. Indeed, far from the urban core, households tend to combine low income, high mobility costs and poor access to public transport infrastructure, which makes them particularly car-dependent (Orfeuil, 2004). To assess heavy car use, a very simple indicator, the motorization rate per unit of potential motorization (considering an adult as a potential unit) can be used (Paulo, 2006). Cao and Hickman (2018) also developed a combined indicator to measure Car Dependence and Housing Affordability (CDHA), and evaluate what they call car dependency considering three variables: possession of a motor vehicle, proportion of mandatory trips made by car and the average distance of mandatory trips by car. The car-related economic stress indicator (Mattioli, Wadud, & Lucas, 2018) was designed in order to evaluate both monetary and car dependency issues at the individual level in the UK. It allows identifying the low-income households that spend a large share of their expenses on private vehicles. We see here that the literature approaches the notion of car dependency with variables that reflect the intensity of car use. However, these two notions, car dependency and intensity of car use, should be well distinguished. If some households use the car a lot because of constraints (poor accessibility, work and family commitments...), for others it is a choice based on personal preferences. Bouscasse et al. (2020) show, for example, that in an urban area such as Grenoble, the number of kilometers by car could easily be reduced by 36% through a simple modal shift, given the same infrastructure. Rather than the term "car dependency", we will therefore prefer the term "heavy car use" to reflect a high level of car use, as it stands. This static view of car use

does not prejudice the adaptability of the households concerned but will in any case require substantial changes in the way these households live.

An indicator of heavy car use is still not sufficient to assess mobility vulnerabilities, as it needs to be related to the alternatives available to the households and, more generally, to the accessibility of their dwelling. It is also important to note that the intensity of car use cannot even be applied to some of the most vulnerable households, as they cannot even afford to own a car. For these households, accessibility is even more important.

Being vulnerable is also often associated with a low accessibility. Accessibility can be defined as the possibility of reaching services and activities, and in particular some specific destinations (Preston & Rajé, 2007) and can be measured at the individual level or at the location level. Many transport policies evaluations have been based on this concept of accessibility, as mobility vulnerabilities are highly connected to the idea of social exclusion, that can be favored by a difficulty to move and to have access to opportunities (Lucas, 2012). In general, location-based metrics consider a specific location and associate the number of available destinations based on the travel costs and the transport modes (Geurs & van Wee, 2004). To give some examples, in London, a bus accessibility index was calculated in order to improve access to employment from deprived areas (Transport for London, 2006). Many studies all over the world focused on the access to employment, such as Shen (1998) in Boston or Allen and Farber (2019) in Canada. In France, Hilal et al. (2020) studied the travel times associated to major/intermediate urban centers, while the Regional Council of Ile de France (2014) studied the number of jobs accessible within 60 minutes in public transport in the Paris area. Other works also measured the accessibility provided by the public transport network, using for example the Public Transport Accessibility Level (PTAL) indicator (Kamruzzaman et al., (2014); Recio et al., (2018); Cordhomme (2019)).

When considering the question of measuring mobility poverty, “metrics for estimating their scope and extent remain inconsistent, vary in quality, and are often disharmonized” (Mahoney et al.; 2020) despite the amount of research done about energy and transport poverty. Few multi-dimensional indicators exist to quantify mobility vulnerabilities as most of them only take into account one dimension of the phenomenon, for instance level of income, public transport accessibility, or heavy car use. To our knowledge, only three CIs exist to evaluate vulnerabilities in transport (Lowans, Furszyfer Del Rio, Sovacool, Rooney, & Foley, 2021). In 2007, Dodson and Sipe developed VIPER, based on three variables (household socioeconomic status index, household car ownership, and car use for work trips). They applied this indicator to Australian cities in order to assess average vulnerability to fuel price increase (“oil vulnerability”) at the geographical level, but not at the individual scale. The second indicator, designed to evaluate the risks of transport poverty in England, takes into account the mobility expenses as a share of the income, distance to public transport services and distance to essential services (Sustrans, 2012). The indicator provides a scale from low to high risk of being transport poor, and the results show that half of all local authorities in England have at least one high-risk area. Yet, once again, this indicator was used on the geographical scale and did not allow creating a typology to identify the different profiles of affected households. In order to bridge this gap, Berry et al. (2016) investigated the fuel poverty issue and its measurement and created a CI made of three dimensions: financial resources, mobility practices, and conditions of mobility. The authors defined three levels of exposure to rising fuel prices and then applied this indicator at the individual scale in the Paris region, France. However, in this study, the profiles of vulnerable households were defined *ex ante* and are not specific to the region analyzed. They consider that high monetary expenses are mandatory to characterize a household as vulnerable, while this is not always the case. Moreover, the indicator does not take into account the family structure constraints.

Up to now, the evaluation of mobility vulnerabilities has mostly focused on *ex-post* evaluations of transport policies. Few indicators were developed in order to study the global phenomenon of mobility vulnerabilities, and the ones that exist do not allow mapping the profiles of vulnerable households in a territory while considering the four dimensions of mobility vulnerabilities at once. However, the

definition of these profiles is very interesting in order to provide relevant political recommendations and to facilitate the adaptation of vulnerable households to a shock. With the VulMob indicator, we propose to fill that gap by providing a multi-criteria indicator that takes into account financial resources, work constraints, heavy car use and structural constraints. It can be used to identify transport poor and/or mobility vulnerable households and to conduct *ex-ante* or *ex-post* assessment of any transport policy or shock affecting mobility.

1.3. Methodology: VulMob, a composite indicator to evaluate individual transport poverty and mobility vulnerability

A Composite Indicator (CI) is made of several dimensions, each composed by multiple factors. VulMob follows the OECD and JRC guidelines (Nardo et al., 2005, Nardo et al., 2008) which defines the following steps: 1. definition of theoretical framework, 2. choice of the factors, 3. imputation of missing data, 4. correlation analysis, 5. standardization/normalization, 6. weighting and aggregation, 7. robustness and sensitivity analysis. In this section, we detail the approach we implemented from step 1 to 6. Step 7 is detailed in Appendix A.4.

1.3.1. Construction of the indicator

With this indicator, we can classify the households to identify the most vulnerable profiles in terms of mobility issues. A vulnerability profile corresponds to a combination of different vulnerability factors. Therefore, this indicator has three main objectives: 1. To identify the transport poor households in a territory. 2. To create a typology of mobility vulnerable households in the different sectors of the territory and 3. To evaluate the impacts of public policies and/or shocks on poor and vulnerable households. Our analysis focuses on mobile households and excludes immobile ones, even though some of them are immobile because of mobility vulnerability issues, and not by choice (Tabaka, 2009; Goujon et al., 2011).

We selected 13 individual factors, grouped into four dimensions (see Table 1.1). The definition of dimensions and the selection of the factors come from empirical and theoretical literature (Section 1.2) but are compelled by the availability of the data. All the data used to quantify the factors are available in the local Household Travel Survey¹⁰ (*Enquête Ménage Certifiée CEREMA; EMC²*), a data file from the French tax administration (FIDELI) and the family budget survey.

¹⁰ In France, the local Household Travel Surveys are conducted every 10 years in the major cities. They are carried out according to a standard procedure enabling comparisons between different cities, and between successive surveys (CERTU, 2008). Each survey provides a precise description of each household. Each member of the household aged five and above is surveyed on all his travel during a day of the week (the day prior to the survey, from Mondays to Fridays) and the main characteristics of his motorized and non-motorized vehicle(s) (number, age, motor type etc.).

Table 1.1 Definition of the variable, polarity and threshold associated to individual factors

Dimension	Factor	Variable	Polarity	Threshold (vulnerable if...)
1 - Financial resources	D1F1 - Income per consumption unit ¹¹	<i>income</i>	+	< 13,356€/year
	D1F2 - Mobility expenses	$\frac{mobility\ expenses}{income}$	-	> 18%
2 - Work constraints	D2F1 - Share of mandatory trips	$\frac{N_{mandatory\ trips}}{N_{trips}}$	-	> 75%
	D2F2 - Nighttime job trips	$\frac{N_{night\ trips}}{N_{trips}}$	-	> 1
	D2F3 - Commuting distance	$distance_{home-work}$	-	> 10 km
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	$\max(distance_{car})$	-	> 40 km
	D3F4 - Car efficiency	Crit' Air sticker	-	≥ 3
4 - Structural constraints	D4F1 - Accessibility	PTAL	+	< level 3
	D4F2 - Spatial mismatching	$distance_{avg}$	-	> 10 km
	D4F3 - Car access	$\frac{N_{cars}}{N_{drivers}}$	+	< 0.4
	D4F4 - Household structure (<i>categorical variable – 12 categories</i>)	Categories of structure	/	single pensioners, single-parent families large families (3 and more children)

In order to confirm the importance of each factor and avoid redundant variables, we performed a correlation analysis. The correlation matrix (Pearson's correlation coefficient ρ) shows that ρ never exceeds 0.6. We also conducted a principal component analysis. Seven principal factors explain more than 72% of the variance. These seven principal factors were made of different combinations of the thirteen individual factors as considered in VulMob. It confirms the relevance of the factors selected for the CI.

The normalization step is required prior to any data aggregation as the factors in the dataset have different measurement units. We first define the polarity of each factor. We then define thresholds for each factor. A household is considered as vulnerable to a specific factor if the associated value is below the threshold in case of positive polarity or above the threshold in case of negative polarity, as defined in Table 1.1. This allows us to identify, for each factor the households that can be considered as vulnerable considering each specific issue, as we particularly shed light on HV households. The values of the different thresholds have been defined according to the literature and previous analysis done on the topic, as justified below. One could also use VulMob by studying the distribution of values (median, average, deciles) for each component in the different geographic sectors.

¹¹ 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).

Considering the multidimensional aspect of a CI, the weighting and aggregation step is central. We use linear aggregation with weights equal to 1 (Equal Weights method; Greco et al., 2019; Nardo et al., 2008) for each factor, since we do not wish a priori to give more weight to certain factors. It should be noted that the use of normalization thresholds and therefore the factors taking dichotomous values (0/1) limits the offsetting effect which can be problematic in CIs (Bouyssou, 1986). In the end, the VulMob indicator score is calculated as the sum of mobility vulnerabilities that are faced by each household. We choose to keep a score rather than an index (from 0 to 1) for more readability. Therefore, a household that is not affected by any vulnerability scores 0 while the one affected by the highest number of vulnerabilities scores 13.

1.3.2. Definition of the indicators and associated thresholds

This section defines the selected factors and justifies the associated threshold.

Financial resources

- Low-income per consumption unit: the threshold is defined considering the French poverty line, which has been evaluated for 2020 at €1,128/month per consumption unit, i.e. €13,356 per year (*French Service Public*, 2021).
- Mobility expenses: this factor is expressed as the ratio of mobility expenses and income in order to identify households who dedicate a high share of their income to daily mobility. The associated threshold, which corresponds to two times the French median for mobility expenses, was initially proposed by (Nicolas et al., 2012).

This dimension has a specific role as it allows identifying transport poor households, defined as such if they reach both thresholds.

Work constraints

- The share of mandatory trips is used as a tool to approximate households' restrictive behaviors: if mobility is limited to work trips, we assume that mobility is limited to the bare minimum. We set the threshold associated to mandatory trips at 75%, as some other trips might be constrained even if not included in this category.
- Nighttime jobs highlight the inability to be flexible implied by certain jobs schedules because of PT timetables and safety issues raised by the practice of active modes, which might be dangerous at night. A household is considered vulnerable when at least one person of the household works between 9PM and 7AM (considering the origin time trip).
- The commuting distance factor reflects the spatial constraints associated to a job. The last survey on mobility habits (*Mobilité des personnes*, SDES, 2019) recommends analyzing these trips following the scale 0 to 5, 5 to 10, and above 10 kilometers as this division is coherent with the associated travel times. This justifies our choice of a 10 km threshold.

Heavy car use

- The declared frequency of car use is defined within a work week. The threshold is reached if a household uses the car every day during the workweek.
- The share of car trips underlines the use within a day. The associated threshold is set at 100% to identify people who exclusively travel by car in a day. The combination of these two first factors allows identifying the households that tend to use their car every day and for every trip they make, pointing out their heavy car use for daily mobility.
- The maximum distance travelled by car assesses the extent to which the car is needed, as longer trips may be more difficult to transfer to other modes. The threshold is set at 40 km, which is an

estimation of the Grenoble impact area, Chambéry (the nearest large city) being located 60 km far from Grenoble.

- Car efficiency is measured with the Crit'Air sticker¹² of household's most efficient car. The threshold is set at 3 because entry into the LEZ perimeters (which will be implemented following the Climate and Resilience Law¹³ adopted in 2021 in France) will be prohibited to vehicles with a Crit'Air label higher than 3.

Structural constraints

- Accessibility corresponds to the level of public transport availability that can be calculated at different territorial level. The PTAL is a measure of connectivity by public transport. It has been used in various planning processes for many years. The index is categorized in six levels 6 represents a high level of accessibility and 1 a low level of accessibility. The threshold is set at 3 according to the documentation provided by Transport for London (2010).
- Spatial mismatching reflects the proximity to the most frequented amenities and to households' required activities, as defined in Berry et al. (2016). This indicator assesses the adequacy of the residential location choice and the opportunities and therefore evaluates the potential to use active modes (walk or bicycle). The threshold is set at 10 km distance from basic amenities.
- Car access is a key factor to explain mobility (Van Dülmen, Šimon, & Klärner, 2022) and corresponds to the number of cars available per adult. Two types of households are considered as vulnerable in the literature: those who do not have access to a car and those who do not have enough cars for the whole family (Le Breton, 2005). In this case, we set the threshold at 0.4 car per adult (less than one car for two adults).
- We consider three household structures as more vulnerable to changing mobility conditions: single pensioners, single-parent families and large families (three and more children) (Bernardo, Paleti, Hoklas, & Bhat, 2015).

The structural constraint dimension may be confounded with a preliminary assessment of the adaptability capacities. Yet, this last dimension refers to the constraints associated to the residential location (public transport accessibility and spatial mismatching) and not the individual mobility habits. This dimension is therefore associated to a potential vulnerability related to structural constraints that may be overcome with different adaptation solutions (such as modal shift, a change in destination or the purchase of a new car).

1.4. Application to households in the Grenoble region

The Grenoble region is centered around the Grenoble Alpes Métropole (GAM), a French metropolis that brings together 49 municipalities on a 545-km² area, located in the Auvergne Rhône Alpes Region. This conurbation accounts for approximately 445,000 inhabitants and has the specificity to be in a hemmed zone, surrounded by three mountain ranges. Grenoble is a flat city but with steep slopes when moving away from the center away. It has a monocentric organization around Grenoble, but is very unequal in terms of income distribution within the population. The Grenoble area is commonly described following a seven sectors scheme, defined from existing mountain massifs: the Metropolis is surrounded by Bièvre, Voironnais, Chartreuse, Grésivaudan, Sud-Isère, Vercors and Sud-Grésivaudan (see Figure

¹² The Crit'Air vehicle classification defined by the Decree of June 21, 2016 (Ministère de la Transition Ecologique et Solidaire, 2020), sets out a list of vehicles classified according to their levels of atmospheric pollutant emissions under the Highway Code. The certificates are based on the "Euro" standards, which set pollutant emission thresholds for new vehicles sold and which are periodically made more stringent.

¹³ See <https://www.ecologie.gouv.fr/sites/default/files/DP%20ZFE.pdf> (in French) for more information on the LEZ implementation in France.

1.1). The city of Grenoble was elected “European Green Capital” in 2022 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.

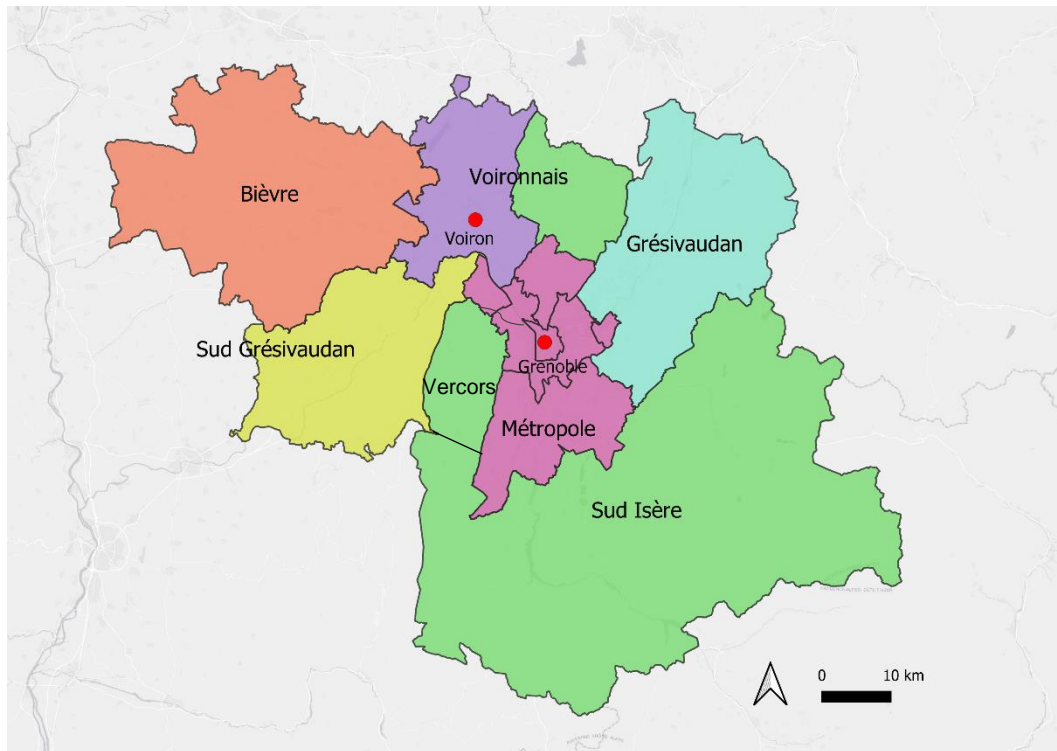


Figure 1.1 Organization of the Grenoble territory by sectors
(Source: Authors' own elaboration)

1.4.1. Data sources

The evaluation of mobility vulnerabilities requires much information on individual travel habits (modes of transport, distances), on the places visited (residential location, workplace...), but also on households' individual characteristics. The local Household Travel Survey (EMC²) provides a precise description of each household: each member aged five and above gives information on all her travel during a day of the week and the main characteristics of the vehicle(s) of the household. For our case study, we use the data from the Grenoble EMC² (2020), a survey submitted to 7,500 households, then weighted to represent the 378,275 households living in the whole area.

We also used:

- Family budget surveys, that are conducted by INSEE every five years to estimate mobility costs (INSEE, 2017). The transportation expenditures of households are included, but we do not have information about the travel that generated the expenses.
- Incomes from the national database FIDELI produced by INSEE and DGFIP. This database is used as a sampling base for official statistics surveys such as the Household Travel Surveys.

Due to some missing data, in particular for the income variable, we removed some households from the EMC² sample. The final dataset is therefore made of 359,427 households.

1.4.2. Computation of the variables

Financial resources include two factors:

- Income per consumption unit: the only accessible information was the income decile associated to each household. We therefore associate a random value of the income per consumption unit based on the income decile thresholds defined in FIDELI (2020).
- Transport effort rate: we estimate the global expenses according to the declared habits, the number and vehicle types as declared in the Grenoble EMC². We take into account all the expenses related to parking costs, fuel costs, car, public transport, taxi and train expenses.

Work constraints are composed of three factors:

- Share of mandatory trips: we assume that mandatory trips have the workplace as an origin or destination. We take into account all the mandatory trips made by a household.
- Nighttime job trips: we consider all the job-related trips made between 9PM and 7AM.
- Commuting distance: we consider the mean home-to-work distance made by the member of a household.

Heavy car use is based on four factors:

- Frequency of using a car is a declarative answer to the question “During the week (Monday to Friday), how often do you travel by car?” Evaluated on the scale: Never/ sometimes/ several days per month/ several days per week/every day.
- Share of car trips: we consider the share of trips made by car in a weekday.
- Car distances: we calculate the mean distance made by car in a weekday.
- Car efficiency: we estimate the Crit’Air sticker¹⁴ associated to the most efficient declared vehicle according to the European standards. To do so, we consider the year of first registration and the fuel type of the car.

Structural constraints are composed of four factors:

- We evaluate accessibility by using the PTAL at the smallest scale provided by the EMC². The indicator takes into account the walking distance, waiting times and frequency of the lines. It can be easily calculated in all conurbations with the available GFTS data.
- Spatial mismatching is defined as the average distance travelled per person in the household, without any restriction on the transport mode and represents a proxy for accessibility to current destinations. We calculate it individually for each household of the sample. It shows to which extend the basic amenities used by the household could be reached by using active modes, for example.
- We estimate car access by calculating the motorization rate. To do so, we divide the number of cars by the number of adults, assuming that an adult constitutes a potential driver.
- The household structure is defined according to the age, current occupation and size of the household.

1.4.3. Descriptive statistics: a spatial characterization

The basic descriptive statistics associated to the sample are provided in Appendix A.1.

A first contribution of VulMob is the spatial characterization of the territories according to their average vulnerability scores (see Table 1.2). This analysis shows the relevance of using a combination of several

¹⁴ See <https://www.certificat-air.gouv.fr/foire-aux-questions?question=tableaux-classification-les-voitures-particulieres> (in French)

factors to characterize mobility vulnerability. On one hand, the accessibility factor and the associated threshold classifies 100% of the households as affected in Sud Isère or Bièvre sectors. Although this result was expected, given the organization of public transport in these sectors, it highlights the importance of taking other factors into account when defining vulnerability profiles in a given sector. On the other hand, despite heavy car use, some territories like Bièvre or the Metropolis have a relatively low share of households concerned by the Maximum distance by car criteria, which may indicate a possible modal shift from car to soft modes.

Table 1.2 Share of households considered as vulnerable according to each factor in each geographical sector (in %).

Note to the reader: the statistics are provided for the seven studied sectors of the global area. The last column describes the global sample, which includes all the sectors.

Dimension	Factor	Grésivaudan	Sud Grésivaudan	Sud Isère	Chartreuse	Voironnais	Bièvre	Métropole	Global sample
Financial resources	Income per consumption unit	10.0	11.1	12.6	11.2	12.9	18.5	17.2	14.1
	Mobility expenses	27.3	25.0	25.3	19.5	31.2	29.3	34.1	29.9
Work constraints	Share of mandatory trips	19.7	19.2	24.7	19.4	20.6	20.3	20.5	20.5
	Nighttime job trips	20.9	25.3	26.0	28.6	16.1	22.3	15.2	18.1
	Commuting distance	11.1	16.0	24.0	12.0	6.9	7.7	9.7	10.5
Heavy car use	Frequency of car use	36.4	34.3	41.4	34.7	33.2	33.5	24.9	29.5
	Share of car trips	33.1	32.4	42.3	45.3	33.3	30.9	24.4	28.9
	Maximum distance by car	16.7	27.1	27.9	19.5	12.6	7.9	11.1	13.5
	Car efficiency	18.7	21.7	23.9	25.7	23.0	27.5	20.0	21.4
Structural constraints	Accessibility	67.8	84.7	100	100	75.6	100	23.1	70.6
	Spatial mismatching	29.6	29.1	32.3	33.1	25.0	23.8	18.6	22.7
	Car access	13.8	21.4	18.8	18.6	17.6	12.3	33.7	25.8
	Household structure	22.4	21.3	25.0	21.1	24.6	25.2	25.2	24.5

A second contribution is to show the heterogeneity in households' vulnerabilities. The distribution of VulMob scores varies among households (see Figure 1.2). More than a half of the sample (57.22% of households) is associated to a score below or equal to three, which means that they face three or less mobility vulnerabilities. On the contrary, we consider as HV those affected by at least six vulnerabilities over 13 (VulMob score greater than or equal to six), which means more than half of the vulnerability factors considered in VulMob. More than 34,000 households (9.64%) in our sample are thus HV. They are designated by the values on the right of the red line in Figure 1.2.

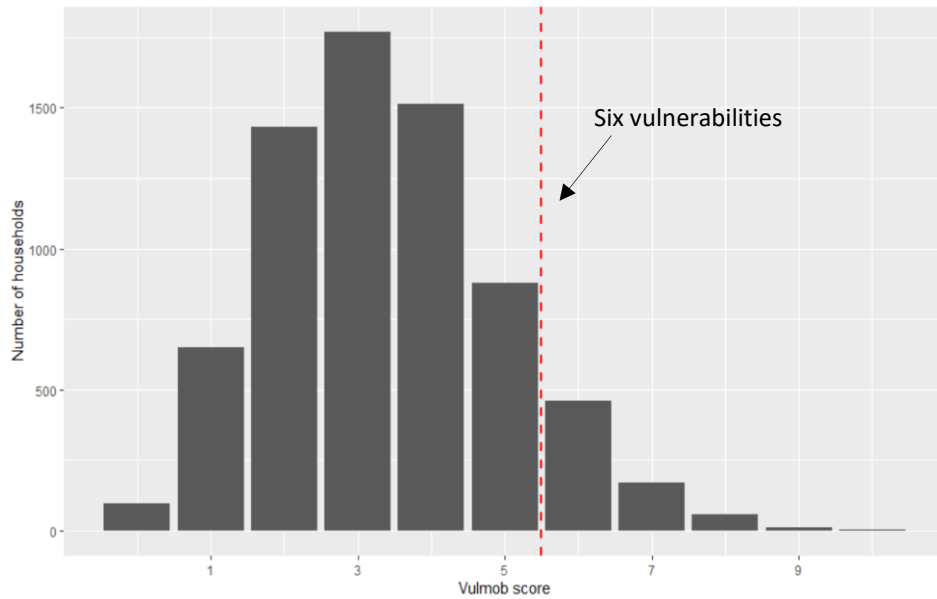


Figure 1.2 Distribution of the VulMob indicator score in the population

Note to the reader: The red line represent the limit to consider a household has highly vulnerable (i.e. affected by at least six vulnerability factors)

A third contribution is to make possible a comparison between the different sectors of the area. The HV and transport poor households are unequally located over the Grenoble area territory (see Figure 1.3). On the one hand, Sud-Isère, Sud-Grésivaudan, Vercors and Grésivaudan (to a lesser extent) tend to concentrate a higher share of HV households. In these geographic sectors, between 12 and 20.3% of households are HV, while they are 7.1% in the Metropole (see Appendix A.2).

Concerning now transport poors, they represent a lowest share of the total population (5.5%) than HV households, which is to be expected as the corresponding factors are a subset of those considered for vulnerability. Indeed, 14.1% of the households in the sample have a low income and 29.9% have high mobility expenses. Transport poor households are also more dispersed across the territory, although we can observe a highest proportion in some municipalities of the Metropole and in certain sectors of Bièvre or Sud Isère (see Figure 1.3b).

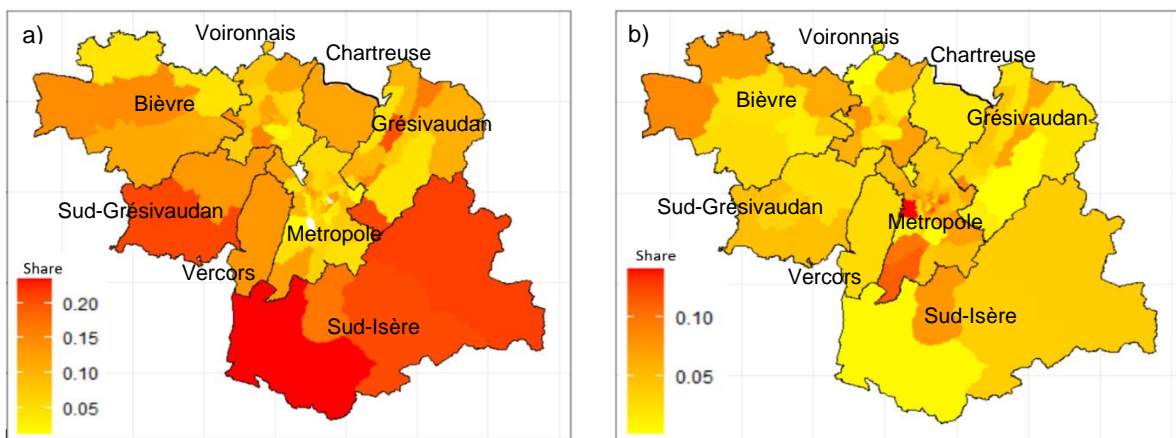


Figure 1.3 Distribution of the highly vulnerable households (a) and transport poors (b) in the territory according to their residential location. (Source: Authors' own elaboration)

Note to the reader: Sectors are delimited with the black lines, while sub-sectors are filled with the different color levels.

1.4.4. Typology of highly vulnerable households

In order to describe the profiles of HV households according to each territory characteristics, we performed a Hierarchical Clustering Analysis (HCA). Clustering is an algorithm technique that involves the grouping of data points, in order to classify each observation into a specific cluster, defined according to similar properties. Here, the clustering method allowed classifying households according to similar vulnerability issues in the different sectors of the Grenoble area. This means that there are clusters specific to each sector and no mixing of clusters across sectors. A strong asset of clustering is to be an unsupervised method, meaning that the clusters are automatically defined according to the characteristics of households in our dataset, without any predefined definition or choice. For each cluster, we analyze for which factors the threshold is exceeded by 80% of the population or more. For example, in the regional cluster G1 in Grésivaudan, at least 80% of HV are vulnerable in the sense that they meet the threshold criteria for factors D1F2, D2F1, D2F3, D3F2, D3F3 and D4F1.

We rely on Ward's linkage method (Ward, 1963). Ward's procedure attempts to generate clusters to minimize the within-cluster variance. For each cluster, we compute the means for all the variables. The results of the HCA allow identifying several clusters of households in each sector (see Table 1.3). The methodology and associated dendrograms are provided in Appendix A.3. Note that the 1,274 households living in Vercors and Chartreuse have been excluded from the analysis because of the small sample sizes.

Table 1.3 Results of the hierarchical clustering analysis

Note to the reader: A cross X in a case means that at least 80% of the vulnerable households in this cluster is above the threshold for the corresponding factor. The “Cluster” column lists all identified clusters by geographical area. The letter corresponds to the sector, the number indicates the cluster within the sector. The “Profile” column classifies each group in the corresponding profile of vulnerability (ex post analysis). The cells highlighted in purple correspond to profile A, which is defined after regrouping different clusters across sectors. Yellow is for profile B. Green for profile C. Blue for profile D. Orange for profile E.

Sector	Cluster	Profile	Factors												
			D1F1	D1F2	D2F1	D2F2	D2F3	D3F1	D3F2	D3F3	D3F4	D4F1	D4F2	D4F3	D4F4
			Income per consumption	Mobility expenses	Share of mandatory	Nighttime job trips	Commuting distance	Frequency of car use	Share of car trips	Maximum distance by	Car efficiency	Accessibility	Spatial mismatching	Car access	Household structure
Grésivaudan N = 4791	G1	E		x	x		x		x	x		x			
	G2	C				x	x	x				x			
	G3	D		x				x	x			x			x
	G4					x						x		x	
	G5	B			x			x				x	x		
Sud Grésivaudan N = 3506	S1	C		x		x	x		x	x		x			
	S2	B				x				x		x	x		
	S3	E		x				x	x			x			
Sud Isère N = 3635	I1	C			x	x	x			x		x			
	I2	C				x	x		x	x		x			
	I3	D		x				x				x			x
	I4	A	x						x			x			
	I5	B			x			x	x			x	x		
Bièvre N = 3765	B1	A	x		x	x						x			
	B2	C				x	x			x	x	x			
	B3	B				x						x	x		
	B4	D		x				x	x			x			x
	B5				x		x		x	x		x			
Voironnais N = 3625	V1	E		x	x	x			x			x			
	V2	C				x	x	x				x			
	V3	A	x									x			
	V4	D		x				x				x	x		x
Métropole N = 13973	M1	C			x	x	x		x						
	M2	E		x	x	x			x	x		x			
	M3	E		x					x			x			
	M4	A	x			x					x	x			
	M5	C				x	x	x		x					
	M6	C				x	x	x					x		
	M7	B		x							x	x	x		x
	M8	D						x					x	x	x
	M9				x			x	x						

In our sample, similarities between clusters lead to the identification of five main profiles of vulnerabilities that are redundant in the six geographic sectors. These profiles are identified by different colors in Table 1.3. These five profiles regroup 30,883 HV households, and we notice that three profiles

face a poor accessibility to public transport. Keeping in mind that all of them also cumulated at least six vulnerabilities issues, the different profiles of HV are characterized as follows:

- ◆ **Profile A** (“monetary constrained”) accounts for $N_A = 3,452$ households. They are characterized by a low income per consumption unit and a bad public transport accessibility.
- ◆ **Profile B** (“without alternative”) regroups $N_B = 5,705$ households affected by spatial mismatching issues and a bad public transport accessibility.
- ◆ **Profile C** (“night worker”) is composed of $N_C = 10,702$ households with night working constraints and living far from their place of work.
- ◆ **Profile D** (“structural heavy car users”) is a group of $N_D = 5,000$ households with constrained family structures who use their car every day and therefore highly depend on it considering their current transport mode choices.
- ◆ **Profile E** (“costly heavy car users”) is made of $N_E = 6,024$ households with high mobility expenses, bad access to public transport and who travel only by car.

Some households do not fit into these main profiles, either because they live within a sector with too few observations in the sample (Vercors and Chartreuse; 1,274) or because their cluster has not been associated to a main profile (2,592 households), yet they are interesting to describe as well:

- ◆ Cluster G4 in the Grésivaudan sector regroups $N = 968$ households that work at night, without access to public transport and with a low access to car. This cluster could be considered similar to profile C.
- ◆ Clusters B5 in the Bièvre sector ($N = 614$ households) and M9 ($N = 1,010$ households) correspond to households that mostly travel for constrained trips and cumulate several car indicators of heavy car use. These two clusters could be defined as heavy car users or car dependent households for some of them (profile D).

Consequently, if some households do not fit with a main profile identified by the spatial clustering method, this does not mean that they are not HV.

Synthesizing Table 1.3, Table 1.4 shows the observed residential locations for the different profiles. Some profiles are specifically located in certain parts of the territory while others are common to the whole area. For instance, there is no cluster corresponding to the monetary constrained profile in Grésivaudan, which is consistent with the high level of income observed in this area (see Table 1.4). The profile of night workers is present in all geographical sectors. On the contrary, some others may correspond to several profiles. Moreover, if a profile does not appear in a sector, it does not mean that nobody living there is affected by the combination of vulnerabilities.

Table 1.4 Residential location of the different identified profiles

Note to the reader: For each profile, a cross indicates if this profile has been identified in the corresponding sector of the territory

Sectors	A monetary constrained	B without alternative	C night worker	D structural heavy car users	E costly heavy car users
Grésivaudan		x	x	x	x
Sud Grésivaudan		x	x		x
Sud Isère	x	x	x	x	
Bièvre	x	x	x	x	
Voironnais	x		x	x	x
Métropole	x	x	x	x	x

1.4.5. Households that are financially constrained and highly vulnerable: a difficult adaptation to mobility changes

Some of the HV households are already poor (without consideration of transport costs), i.e. with low income. These households may find it particularly difficult to adapt to a change in their mobility conditions (LEZ, increase in fuel prices...). 31% of highly HV have low income (see Table 1.5), that corresponds to 3% of the sample. As expected, they are overrepresented in the profile of monetary constrained households but under-represented in the structural heavy car users' profile. This *a priori* means that this last profile (D) could adapt to higher fuel prices (see Blandin et al., 2023) on the contrary of the first one (A), which represents 0.8% of the sample. This profile is certainly under-represented compared with other French cities. Indeed, the mean income per habitant in the Grenoble Metropolis is higher than in France (respectively, 25,801€/year and 20.590 €/year; INSEE, 2022).

Another group of interest are those with a high share of their expenses dedicated to transport. They represent 44.4% of HV households (4% of the sample). Their presence is well balanced in four of the profiles but, as expected, they are over-represented in the profile Costly heavy car use. For these households, any change in the transport system inducing an increase of their transport expenses (be it due to higher fuel prices or the need to buy a new car because of restrictions) will have important consequences if they have a bad access to public transport or long distances to travel (thus restricting the possibility of cycling). This profile concerns 1.5% of the population.

It is interesting to note that none of the main profiles, in the definition of their characteristics, combine both financial factors of vulnerability (low income and high share of expenses; see Table 1.5), which combined define transport poor households. However, a more detailed analysis at the household level shows that 13.8% of HV households are also transport poor. They represent 1.3% of the global sample (4,778 households). Being doubly financially constrained and being HV – they cumulate six vulnerabilities and therefore not only the financial constraints – implies that these households will have even less room to operate than the others to adapt to potential changes in the economic and regulatory conditions of mobility.

Table 1.5 Share of transport poor households among the identified HV profiles

*Note to the reader: % in the first line are calculated among the global sample; In the following lines, the first % are calculated among the considered profile (column), the second one is expressed as a % of the global sample. The first column shows the statistics associated to the global sample. *: p < 0.05 (in comparison with the global sample)*

	Global sample	HV	A monetary constrained	B without alternative	C night worker	D structural heavy car users	E costly heavy car users
Total number of households	359,427 (100%)	34,749 (9.6%)	3,452 (0.96%)	5,705 (1.59%)	10,702 (2.98)	5,000 (1.39%)	6,024 (1.68%)
Low-income (D1F1)	50,614 (14.1%)	10,761* (31.0%; 3%)	2,822* (81.7%; 0.8%)	1,721 (30.1%; 0.5%)	2,403 (22.4%; 0.7%)	978 (19.6%; 0.3%)	2,164* (35.9%; 0.6%)
High mobility expenses (D2F2)	107,572 (29.9%)	15,455 (44.4%; 4.3%)	1,241 (35.9%; 0.3%)	1,922 (33.6%; 0.5%)	3,510 (32.7; 0.1%)	2,188 (43.8%; 0.6%)	5,273* (87.5%; 1.5%)
Transport poors	19,932 (5.5%)	4,778* (13.8%. 1.3%)	825* (23.8%; 0.2%)	788 (13.8%; 0.2%)	1,077 (10.0; 0.3%)	543 (10.8%; 0.2%)	1,046* (17.3%; 0.3%)

In particular, HV households in profiles associated to monetary constrained and costly (respectively A and E) heavy car use households) are, as expected, associated to a high share of transport poor households.

Households that are identified as both transport poor and HV constitute a group of the population that is particularly at stake when implementing a public policy that would constrain or modify mobility habits. Indeed, financial resources often constitute the main lever for adaptation, but this lever is particularly complicated to action when households are already monetary poor and dedicate a high share of their expenses to car, thus having few resources left and also face a combination of other constraints such as a poor accessibility or structural constraints.

1.5. Discussion and conclusion

In this work, we developed a methodology to identify the households affected by mobility vulnerabilities and transport poverty issues. We created VulMob, a multi-criteria indicator based on four dimensions: financial issues, work constraints, heavy car use and spatial and personal constraints. It relies on individual mobility and sociodemographic data. Using a hierarchical clustering method, the indicator scores can be used to create a typology of HV households at regional level. We have applied this methodology to the Grenoble area in France, in order to identify the areas that policy makers should target more specifically in order to implement compensatory policies in the event of a major change in mobility conditions. We have drawn three major conclusions from this analysis.

The first lesson is that there is a significant proportion of HV households (9.6%) in the Grenoble region and/or transport poor households (5,5%). 1.3% of households are both HV and transport poors. Transport poors are spread over all the territory while HV households are concentrated in Sud Isère and Sud-Grésivaudan. Public policies must consider this; otherwise, they will be unfair and socially unacceptable. What is true of the Grenoble area is likely to be even more marked in other areas, which either have lower average incomes – Grenoble area has a higher standard of living than the national average- or less good access from outlying areas to the city center.

The second lesson is that the typology makes it possible to draw up profiles to identify at-risk populations and help public policy to define efficient levers and target households for whom changes to the transport system will have a greater impact. Our analysis allowed us to identify almost 10% of HV households distributed according to five different profiles. The most populated profile of vulnerable households in the area is made of households with night work constraints. Three first profiles are approximately made of the same population size: a profile centered on the lack of alternatives to the car, one characterized by a structural heavy car use and a third one on costly and heavy car use. The two last profiles refers to monetary difficulties and heavy car use. They are the smallest in terms of population, which may be a particularity of the Grenoble area, which has a higher standard of living than the national average. For each household in a considered profile, the socio-economic characteristics makes it possible to evaluate the impact of a shock on their mobility habits. For instance, considering a household described as “monetary constrained” living in Sud Isère, a fuel price increase might be hard to face, as car use is useful in this area, which is poorly connected to public transport infrastructures.

The third lesson is that there is a recurring problem of accessibility for several profiles. It is therefore necessary to act on this lever. There are three avenues to explore in this area, depending on the profiles concerned. First, for the profile of “night workers”, it could be (partially) solved by extended public transport schedules if there are lines (for instance in the Metropolis or Voironnais) or adapt the public policy. For example, in the case of the LEZs, a large number of households in the profile “night-workers” would justify special exemptions such as limiting restrictions to the daytime. Second, among the “heavy car users” profile, a consequent part of households may shift to active transport modes in some territories (for instance, the Metropolis or the Bièvre). Third, for the “Without alternative” profile, accessibility can also be improved for the most remote areas (e.g. Grésivaudan or Voironnais) by inter-urban transport, by coach and train, combined with active modes such as walking and cycling. Here we have an illustration of the usefulness of profiles for analyzing public policy and target the most efficient measures and target areas.

The indicator identifies vulnerable profiles from a dynamic perspective. These households are those for whom changes in the mobility system (transport infrastructure, fuel costs, etc.) will have a significant impact on their mobility practices, whether these practices are imposed or chosen. Once the HV households and profiles have been identified, it is necessary to consider, for each planned change in the mobility system, those who can adapt by changing their individual mobility practices and those for whom compensatory measures need to be envisaged because they remain without a solution (Blandin et al., 2023). Among the individual adaptation strategies, active mobility is central, sometimes in combination with less accessible public transport modes. In addition to walking and the conventional bicycle, electric bicycles now offer an opportunity to increase the distances travelled by bicycle on a daily basis, particularly in the context of commuting to work. Bouscasse et al (2022) have shown that the potential for modal shift in the Grenoble conurbation, particularly towards active modes, is significant and is likely to generate additional health benefits to those associated with pollution reduction through increased physical activity (almost threefold increase in health benefits). These health benefits are important individual determinants of transport mode choice and can be used to promote active mobility (Bouscasse et al., 2023). For households without the individual capacity to adapt, public compensatory measures will have to be taken. We have already mentioned the expansion of intercity transport or the extension of the timetable of existing networks. In urban areas, increasing the number of public transport services can be complicated and expensive, especially if these services are already dense. However, it is still possible to facilitate the use of active transport modes by supporting the purchase of electric bicycles, including cargo bicycles, and by providing the appropriate infrastructure so that they can be used safely over longer distances or at night. Rolling stock, stops and stations can also be adapted to facilitate multimodality. Regarding these compensatory public measures, a detailed spatial analysis of the HV profiles for a given change in the mobility system should make it possible to target shared transport lines and priority developments. In addition to transport policy, 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, Talandier, Tabaka, & André-Poyaud, 2017).

To implement public policies aimed at restricting car use, targeting and helping the households most affected by changes to the mobility system with VulMob is the key to minimizing the number of households unable to adapt, and thereby reducing social impacts and promoting social acceptance of public action to reduce car use. The acceptability of such public policies, analyzed for example by Rejeb et al. (2023) in the case of LEZs, is an essential condition for their proper implementation and therefore for their effectiveness. It should be noted that public policies can also support households with the individual capacity to adapt to measures restricting car use, by providing them with better information on the individual benefits they derive from them. In this respect, Rejeb et al. (2023) emphasize the importance of playing on individuals' intrinsic motivation and perceptions through positive messages about the benefits of active modes to encourage their adoption, rather than making them feel guilty about using polluting modes.

A final lesson from this chapter concerns data, which are essential for the construction of such an indicator. However, there are still urban areas that are required by law to implement policies to reduce car use (e.g. LEZ) and which do not have recent and/or reliable data on the daily mobility of their inhabitants. Under these conditions, regardless of the indicator or tool used, it is difficult to anticipate the consequences of public policies, especially for the most vulnerable households. It is therefore necessary to recommend the use of a reliable and regular tool for measuring travel in urban areas. This measurement should systematically include information on income - at least at the decile level, if possible, from an external source such as taxes, in order to ensure the reliability of the data.

The approach developed in this work has some limitations. First, the aim of this chapter is to identify typical vulnerability profiles and to spatialize them, adopting a compensatory approach for aggregating the indicators. This means that very specific cases of households affected by a change in the mobility system even if they only have two or three vulnerabilities will not be identified. Indeed, the hierarchical clustering methods we used to get a typology of vulnerable households does not capture all the problematic combinations, as some factors affect more households than others. For instance, households cumulating low income, using their car every day and having an inefficient car may be very vulnerable to a LEZ implementation. However, this is not the purpose of this chapter, which seeks to identify trends, some of them fairly detailed, in the types of households that are vulnerable to changes in the mobility system.

Second, the accessibility indicator is based on a description of the transport supply for each sector. Therefore, it does not take into account a number of alternatives to the car, such as active transport or multimodality (e.g. car or cycle and public transport). Such combinations would make areas with little or no public transport more accessible. They can also be considered from the point of view of adapting to changing mobility conditions, as discussed in the previous section.

Third, for each household, we know the income decile to which it belongs, based on French tax data. The income level is a proxy based on this decile, but without knowing the precise level within the decile. On the one hand, this approximation can be seen as a limitation, as the exact level of income is not known for each household. On the other hand, knowing the decile from a reliable source (rather than an income reported by the household without verification) is data that is sometimes difficult to access, but which we hope can be reproduced.

Nevertheless, although VulMob cannot precisely describe the strongest vulnerabilities at the individual level, it has the advantage of being able to be elaborated on a territory and is based on usually collected

data. From this point of view, it has a strong potential of replicability and support to fair territorial policies.

Chapter 2

Assessing the ex-ante impacts of a low-emission zone on vulnerable households in Grenoble, France

Abstract

More than 250 Low Emission Zones (LEZs), which ban the most polluting vehicles from city centers, have been implemented across Europe to improve air quality and reduce car use. Until now, fears that the most vulnerable households would be disproportionately affected by LEZs have slowed their adoption generally in Europe and more particularly in France. The objective of this chapter is to objectify and discuss the impacts of a LEZ on vulnerable or poor households in order to inform the public debate. To do so, we use the VulMob indicator, which allows the identification and characterization of vulnerable and transport poor households in an area (Blandin, Bouscasse, & Mathy, 2023). First, we assess the impact of LEZs on vulnerable and transport poor households. Second, we assess the adaptive capacity of affected households in terms of modal shift options. Third, for households without modal shift options, we assess the extent to which affected trips can be modified according to their destination. We apply this methodology to the Grenoble area (France), using data from the Local Household Travel Survey (*Enquête Ménage Certifiée CEREMA; EMC² 2020*). Results show that among the households affected by the LEZ (8.0% of the global population), some are highly vulnerable (11.6% of them; that is 1% of the Grenoble population), of which 56.5% remain without a modal shift solution (0.6% of the population). The impacts and the possibility of using various solutions to adapt to the LEZ vary greatly depending on the vulnerability profile. More generally, this work can guide decision-makers in the definition of preventive and/or compensatory policies, taking into account the profiles of vulnerability, the specificities of the territory, including where the impact of the LEZ is higher due to a lower supply of cycling and public transport infrastructure.

Keywords: vulnerability, transport poverty, public policy evaluation, low-emission zone, modal shift

2.1. Introduction

The transport sector is a major environmental and health issue, responsible for almost a quarter of Europe's greenhouse gas emissions and the main source of urban air pollution (European Commission, 2023). Air pollution has major and proven effects on mortality and morbidity, mainly through cardiovascular and respiratory health: each year, exposure to ambient PM_{2.5} causes approximately 4.2 million deaths worldwide and 417,000 in Europe (European Environment Agency, 2020). In 2019, around the world, nine out of ten people in urban areas are exposed to levels of fine particulate matter (PM_{2.5}) from outdoor air pollution above the 2005 World Health Organization (WHO) guideline value (average annual PM_{2.5} concentration of 10 µg/m³), and even more so at the current guideline value of 5 µg/m³ set in 2021. In Europe, air quality standards values are much higher. According to the European Commission, the mean annual exposure must be lower than 25 µg/m³ for PM_{2.5} and 40 µg/m³ for NO₂. Where levels are higher than these values, governments should prepare an air quality plan to address emission sources responsible and so ensure compliance with the limit value (see Appendix B.1 for examples of average concentrations in European cities with an existing LEZ) (Lenschow, Becker, & Mehl, 2017). It is to these challenges that the 250 LEZs currently implemented in Europe are attempting to respond. LEZs 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.

The first country to have implemented a LEZ in its current conventional meaning was Sweden, in 1996. Then, LEZs became very common, particularly in Germany, Italy or the Netherlands. 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. Moreover, LEZs can also be combined with other public policies such as congestion charge (CC) zones (see Appendix B.1). Empirical research generally found LEZs to be successful in reducing the concentration rates of local air pollutants after implementation, with positive implications for health. For instance, evaluation of the London LEZ conducted in 2010 estimated a 35% PM₁₀ reduction and a 19% NO_x emission reduction (Ezeah, Finney, & Nnajide, 2015). In Germany, Margaryan (2021) also showed that the implementation of LEZs reduced the number of patients diagnosed with a cardiovascular disease by 2–3% in large cities. Similar positive effects were observed in other cities such as Rome (Cesaroni et al., 2012), Lisbon (Ferreira et al., 2015) or Madrid (Lebrusán & Toutouh, 2021). Other evaluations have also been carried out in Denmark (Jensen, Ketzell, Nøjgaard, & Becker, 2011), Netherlands (Boogaard et al., 2012), Sweden (Flanagan, Malmqvist, Gustafsson, & Oudin, 2022) or more generally in Europe (Holman et al., 2015; Ku et al., 2020).

In France, the fear that the most fragile households would be the most affected by LEZs keeps on slowing their adoption. In 2012, it is for this reason in particular that the implementation of a priority action area for air quality (*in French, 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 exceeded¹⁵. 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 published in June 2023 (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 NO₂ 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. However, these conclusions are based on an online consultation only, and the methodology is neither scientifically rigorous nor based on mobility data for the different population categories that could be affected by these LEZs.

¹⁵ Greater Paris, Lyon, Aix-Marseille, Toulouse, Nice, Montpellier, Strasbourg, Grenoble, Rouen, Reims and Saint-Étienne.

Given these governmental hesitations and fears that the LEZs will affect vulnerable households, and lead to an increase in socio-spatial inequalities, robust ex-ante assessments of the impact of LEZs on mobility vulnerability and poverty are needed, taking particular account of households' ability to adapt to the constraints imposed by an LEZ. This evaluation is particularly important to define compensatory measures to facilitate the LEZ acceptability and implementation.

The objective of this article is therefore to propose an *ex-ante* evaluation of the impacts of the LEZ implementation on mobility vulnerabilities and poverty. To do so, we first rely on the VulMob composite indicator developed by Blandin et al., (2023), to assess mobility vulnerabilities and poverty along four dimensions and identify typical profiles of vulnerable households. Second, we evaluate the potential impacts on households for two different LEZ perimeters and two time schedules. Then, we explore the potential for adaptation considering different possibilities: modal shift, modification of the trips' destination and purchase of a new car. Our field of application is the Grenoble region, located in the French Alps.

This chapter is organized as follows. Section 2.2 presents the literature related to the social impacts of LEZs. Section 2.3 describes the data, the Grenoble context, transport poor criteria and the profiles of highly vulnerable households identified with VulMob. Our methodology is developed in section 2.4 and the LEZ impacts and potential for adaptation are exposed in Section 2.5. These results lead to political recommendations in section 2.6, while section 2.7 concludes.

2.2. Literature on social impacts of LEZs

Many studies have been conducted in Europe to evaluate the global environmental and health benefits associated to LEZ implementation. Yet, few studies particularly draw attention on the social aspects at the individual level (Van Brussel & Huyse, 2019). These impacts are multidimensional and related to the distribution of health impacts of the LEZ and to the distribution of mobility impacts across the population.

Considering health impacts, LEZs are supposed to benefit people living both inside and outside of the restriction's perimeter for two reasons. First, the decrease in pollutant emissions within the perimeter of the LEZ will induce lower pollutant concentrations also beyond the perimeter. Second, the population living outside but near the perimeter of the LEZ will also be encouraged to comply with the regulations and thus to stop using polluting vehicles. Concerning the Grand Paris LEZ, Poulhès and Proulhac (2021) evaluate the distribution of health benefits among the population: the wealthiest residents - who are currently the most affected by pollution - would benefit the most, while the youngest and oldest would benefit the least. According to the scenario, between 13 and 43% of households living outside the LEZ perimeter that are currently exposed to high NO₂ concentrations should fall below the legal threshold of 40 µg/m³. Nevertheless, other studies underline that the implementation of a LEZ could in fact have the opposite effect and increase the pre-existing health inequalities. Indeed, the most vulnerable households - who are more likely to live in the most polluted areas (Schweitzer & Valenzuela, 2004) – will not receive the same distribution of costs and benefits. Several studies in Rome (Cesaroni et al., 2012) or in Paris (Host et al., 2020) concluded that a LEZ was effective in reducing traffic-related air pollution and health impacts (such as premature deaths or asthma) but most of these health gains were deviated towards wealthier residents. In particular, Host et al., (2020) recommend to extend the perimeter of implementation in order to allow a more equitable distribution of the benefits to the inhabitants.

Moreover, a LEZ implementation may have important consequences on mobility habits. Few studies evaluate the impacts on individual mobility behaviors, focusing more specifically on the different socio-economic categories of population. In Grenoble, Charleux, (2014) used the Household Travel Survey data to evaluate the potential impacts of a LEZ on mobility, specifically focusing on whether the impacts would be socially differentiated and could therefore constitute social injustice. Results of the logistic regressions show that the likelihood of being affected by the LEZ is related to the social group. Therefore, 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 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. More recently, a study of the Madrid Central LEZ showed that high-income households are more likely to switch to private parking garages and have a lower likelihood of shifting to cleaner modes in order to avoid modifying their mobility habits. Of course, low-income residents cannot afford such an option and have therefore to find other solutions for their daily mobility (Gonzalez, Gomez, & Vassallo, 2022).

Studying social issues related to LEZs raises many debates, which clearly highlights the tension between social and environmental justice issues. It has been proved that low-income drivers are more likely to own the oldest vehicles subject to charges or ban (Parkhurst, 2017). This is why the social justice argument is often put forward to justify that LEZs will primarily affect the heavy car users, which are potentially car-dependent households. Indeed, the LEZ not only affects households living in the delimited perimeter and therefore increase the risk of social exclusion (Lucas, 2012; Mattioli, 2014) for those who cannot afford to buy a cleaner, more expensive vehicle, as seen for instance in Antwerp (Van der Vlugt et al., 2019). Considering social justice when implementing transport public policies is therefore necessary and decision makers need to implement compensatory measures such as progressive public transport pricing, alternative services or subsidies in particular for the most precarious households (Fandio et al., 2020).

Public acceptability is fundamental in order to implement an ambitious and efficient policy. Yet, in France, LEZs are often described as unfair and are less popular than in other European countries (ADEME et al., 2020, p.123). In Grenoble, seven years earlier (in 2015), policy makers projected to implement a priority action area for air quality (*Zone d'actions prioritaires pour l'Air*) in order to reduce air pollution in the city. Yet, the project was finally cancelled due to fears that the most vulnerable households would be particularly affected (La Branche and Charles, 2012; Charleux, 2014). More recently, surveys highlighted that people living outside the urban core are less likely to stick to this policy as they consider that the LEZ will mostly improve the air quality in the restriction perimeter, while the most affected by the mobility restrictions are living outside (Rejeb et al., 2023).

2.3. The Grenoble case study

In this section, we first describe the territorial organization of the Grenoble region, mobility flows and related data, and then the profiles of highly vulnerable households as identified with the VulMob indicator by Blandin et al. (2023).

2.3.1. Settings and data

Grenoble Alps Metropolis (GAM) is a French metropolis that brings together 49 municipalities on a 545-km² area, located in the French Alps in the Auvergne Rhône-Alpes region. This conurbation (see “Métropole” in Figure 2.1) 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 mobility LEZ under the 2021 law. Despite the government's retreat, this LEZ was implemented in July 2023.

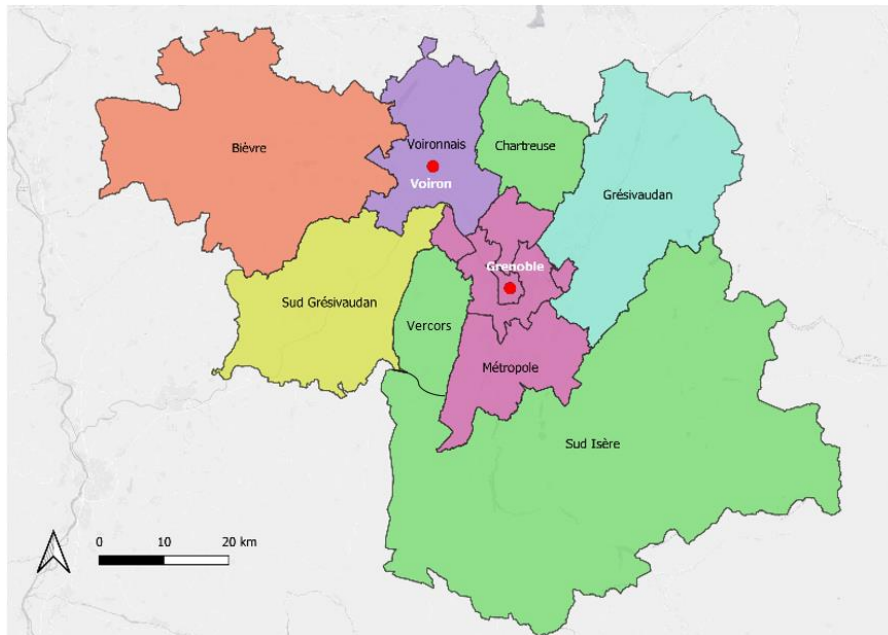


Figure 2.1 Organization of the Grenoble territory by sectors (Source: Authors' own elaboration)

The Grenoble area (defined as the Metropolis and the connected peripheral areas) hosts more than 820,000 inhabitants from 359 municipalities. This territory is often divided in eight sectors corresponding to the economic and structural organization of the region (see Figure 2.1). Almost 55% of them are living 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 conurbations 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 others such as Sud Isère or Bièvre (see Figure 2.2).

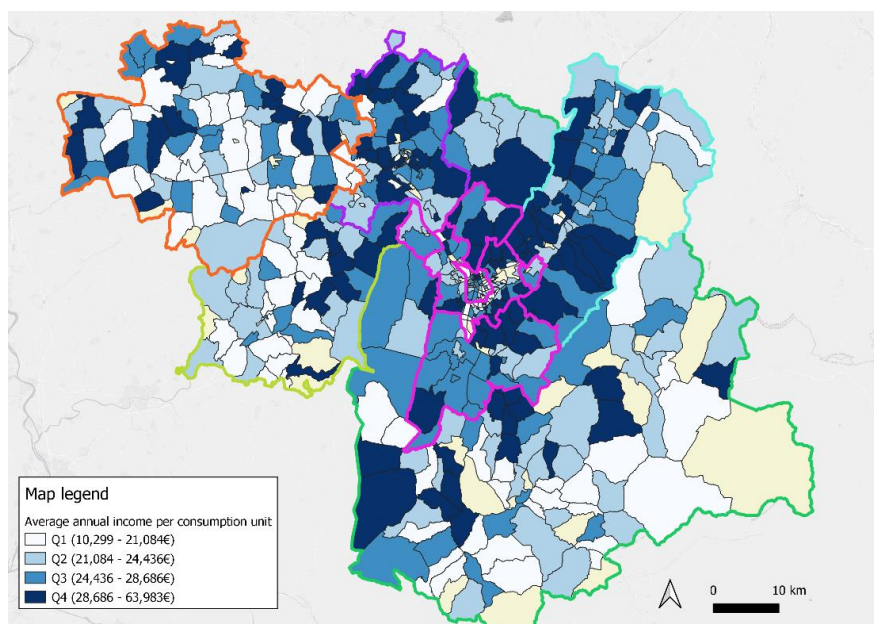


Figure 2.2 Distribution of incomes per consumption unit in the Grenoble area. (Source: Authors' own elaboration)

Note to the reader: 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, many 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. To do so, the CEREMA (*Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement*), follows a standard procedure enabling comparisons between different cities, and between successive surveys (CERTU, 2008). These surveys provide a precise description of households, all the family members and associated mobility habits. We find information on the travel habits during a day of the week (the day prior to the survey, from Mondays to Fridays) and the main characteristics of households' vehicle(s) (number, age, motor type etc.). For our case study, we use the data from EMC² Grenoble (2020), a survey of 7,500 typical households living in 359 municipalities. These observations are then weighted to represent the 378,275 households living in the whole area. The data processing leads us 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 B.2). 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 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 double, and walking habits increased as well, while the modal share of car decreased by 6.3 points (see Appendix B.3). At the metropolitan level, the attractiveness of active modes (walking and biking) is becoming even more important.

2.3.2. The highly vulnerable and transport poor households in the Grenoble area

In Blandin et al. (2023), we present the elaboration and design of VulMob, a composite indicator that enables to identify transport poor households and vulnerable households, allowing to elaborate a typology of Highly Vulnerable (HV) households. 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 2.1. It provides a multifactorial evaluation of the mobility vulnerabilities at the individual level but also allows identifying transport poor households.

Table 2.1 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	$income$	+	< 13,356€/year
	D1F2 - Mobility expenses	$\frac{mobility\ expenses}{income}$	-	> 18%
2 - Work constraints	D2F1 - Share of mandatory trips	$\frac{N_{mandatory\ trips}}{N_{trips}}$	-	> 75%
	D2F2 - Nighttime job trips	$\frac{N_{night\ trips}}{N_{trips}}$	-	> 1
	D2F3 - Commuting distance	$distance_{home-work}$	-	> 10 km
3 - Heavy car use	D3F1 - Frequency of car use	/	-	“Everyday”
	D3F2 - Share of car trips	$\frac{N_{car\ trips}}{N_{trips}}$	-	$\geq 100\%$
	D3F3 - Maximum distance by car	$\max(distance_{car})$	-	> 40 km
	D3F4 - Car efficiency	Crit' Air sticker	-	≥ 3
4 - Structural constraints	D4F1 - Accessibility	PTAL	+	< level 3
	D4F2 - Spatial mismatching	$distance_{avg}$	-	> 10 km
	D4F3 - Car access	$\frac{N_{cars}}{N_{drivers}}$	+	< 0.4
	D4F4 - Household structure (<i>categorical variable – 12 categories</i>)	Categories of structure	/	single pensioners, single-parent families large families (3 and more children)

We also define transport-poor households as households combining low-income and high mobility costs (i.e. households crossing the threshold associated to factors D1F1 and D1F2, see Table 2.1). Moreover, households cumulating at least six mobility vulnerabilities over 13 with the VulMob indicator are considered as HV. We applied this methodology to the Local Household Travel Survey data in order to define a typology of HV households in the Grenoble area.

Table 2.2 Typology of the HV households in the Grenoble area

Profiles of HV households						
	Transport poors	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	- Spatial mismatching - 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		

VulMob allows identifying 19,932 (5.5%) transport poor households in the Grenoble area. We also characterized 34,749 households (9.6%) as HV. The hierarchical clustering analysis (HCA) conducted in the six most populated sectors¹⁶ (Grésivaudan, Sud Grésivaudan, Bièvre, Voironnais, Sud-Isère and the Metropolis) gave the following typology, composed of five main profiles of combined vulnerabilities (see Table 2.2). Households in the same profile have some similitudes and share common vulnerability patterns. Yet, according to the residential location, we observe, within the same profile, an important heterogeneity among households, considering their specific socio-demographic characteristics.

2.4. Methods

In this section, we describe the LEZ scenarios, including perimeters and schedules and then the adaptation assumptions, focusing in particular on modal shift, destination constraints and potential for buying a new car.

¹⁶ The Chartreuse and Vercors sectors have been excluded from the analysis because the size of the sample was too small for such statistical analysis.

2.4.1. LEZ scenarios

Our methodology to evaluate the LEZ impacts (see Figure 2.3) relies on individual mobility data from the Local Household Travel Surveys. First, 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 car¹⁷, we check whether it would be forbidden by the LEZ.



Figure 2.3 Step-by-step identification of trips prohibited under the LEZ

Legal framework

Circulation restrictions are introduced following a standardized classification of the vehicles in six categories using Crit'Air stickers "Certificats Qualité de l'Air", that are evaluated considering the age and the type of fuel used (see the classification in Appendix B.4). We focus on evaluating the impacts of the scenario that was mandatory in the Loi Climat et Résilience which establishes a regulatory timetable (see Figure 2.4).



Figure 2.4 Schedule of Crit'Air labels affected by the ban in a LEZ in France, as defined in the Loi Climat et Résilience (2021)

Perimeters

In Grenoble, policy makers study two LEZ perimeter scenarios. The first one (A, in orange in Figure 2.5) is limited to the center of the Metropolis, i.e. Grenoble inner ring, while a larger perimeter (B, in yellow in Figure 2.5) is extended to 12 other cities from the first ring.

¹⁷ This study focuses only on car ban and exclude motorbikes and scooters, as they only account for 0.3% of the total number of trips identified in the survey.

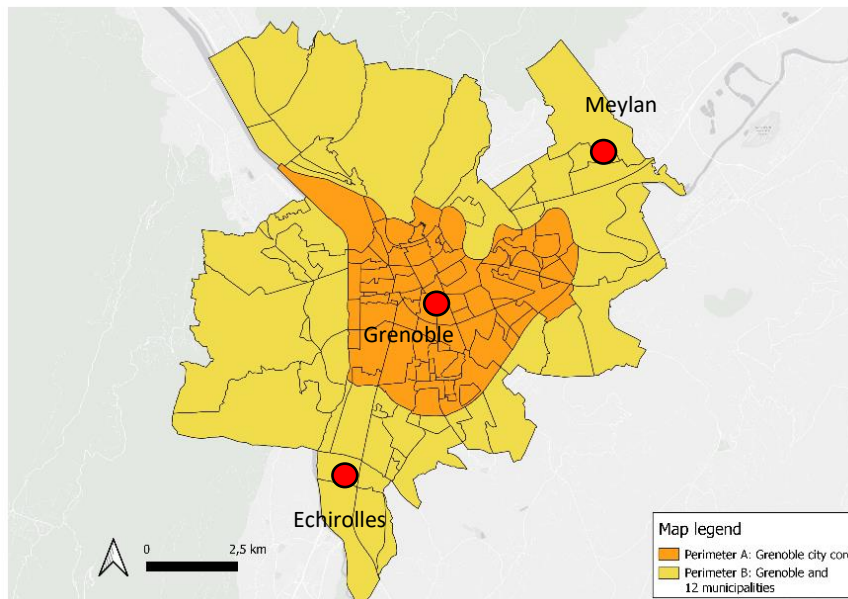


Figure 2.5 Studied perimeters for the implementation of a LEZ

Time schedule

For each scenario, 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 B.5. Table 2.3 provides a quick summary of the two studied scenarios.

Table 2.3 Summary of the two studied scenarios

	Scenario A	Scenario B
Perimeter	Grenoble	Grenoble + 12 municipalities ¹⁸
Number of car trips for a typical day	250,000	430,000
Temporality	7/7 days a week	7/7 days a week

2.4.2. Adaptation hypothesis

In order to adapt to the LEZ ban, we consider households have different solutions according to the following logical chain:

1. Is the car trip transferable to other modes of transportation (considering the existing public transport system)?
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?

The order of these steps has been defined to explore the different possibilities for adaptation. Modal shift allows to keep the same travel pattern, while a modification of the trip may ask for more adaptation efforts. Then, buying a new car would solve all adaptation issues but should be the last one to consider if one aim of LEZs is to promote modal shift. Indeed, the LEZ should be seen as an opportunity to reduce

¹⁸ 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

the importance and the use of cars in urban centers, and to develop active mobility which presents many individual and collective advantages, such as positive health impacts. Moreover, buying a LEZ-compatible car raises many issues: the financial cost, the environmental and resource impacts of new cars or the gap between Crit'Air stickers' classification and the actual emissions of vehicles.

2.4.3. 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).

To define the modalities associated to a mode, Bouscasse et al., (2022) considered that the maximum distance people usually travel by bike is 3km and by e-bike 7.8km in the Grenoble area (based on the median behaviors observed in the EMD data (2010))¹⁹. Hence, in this study, we set the limit for modal shift to e-bikes at the average value of 8km, which is consistent with this work.

Our main hypothesis are defined under the following assumptions:





1. A loop is a combination of successive trips having “home” as an origin and destination. A trip is shiftable to another mode if all the trips in the corresponding loop are also shiftable to the same transportation mode;
2. The priority order for choosing a mode is the following: 1. walk, 2. bike, 3. e-bike and then 4. public transport;
3. Walking is possible if the whole loop length is less than 4km, if each trip length is less than 1km and if the maximum ascending elevation does not exceed 6%;
4. Biking is possible if the whole loop distance is lower than 12km, if each trip distance is lower than 3km and if the maximum ascending elevation does not exceed 6% (CEREMA's technical recommendation for cycle facilities in France);
5. Using an e-bike is possible if the whole loop length is inferior to 20km, if each trip length is less than 8km and if the maximum ascending elevation does not exceed 10%;
6. Finally, for the loops of more than 20km, for all the loops with an ascending elevation above 6% and/or trips of more than 8km, shifting to public transport is possible in two cases:
 - a) If the journey time by public transport is less than three times the journey time by car for journeys initially of less than 10 minutes by car.
 - b) If the journey time by public transport is less than double for journeys of more than 10 minutes by car (Bouscasse et al., 2022).

We apply this modal shift assumptions (Table 2.4) to the data from the “trips” Table of the Local Travel Households Survey, which describes, for each respondent all the trips made the day before (purpose, hour, origin/destination and transport mode). For each car trip, we identify the corresponding loop, calculate the total distance and the maximum ascending elevation of the loop, and estimate for each trip the duration time by car and by public transport using the OpenTripPlanner API²⁰ based on Google Maps.

¹⁹ In 2021, we conducted a survey for the Grenoble Metropolis (unpublished). The results showed that 83% of the respondents might be disposed to travel more than 6km with an e-bike, and more than 10km for 42% of them.

²⁰ See <https://docs.ropensci.org/opentripplanner/articles/opentripplanner.html> for more information

Table 2.4 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%	

2.4.4. Trip purposes

We draw attention to the importance of the trip purpose, as some trips are more constrained than others: commuting trips are constrained by the destination, whereas trips for leisure activities can be modified, particularly in terms of destination. For example, one might consider that going to shopping in the city center (where a LEZ is implemented) while living in a periurban area could be avoided whether by changing the destination or cancelling the trip. Of course, this argument raises important economic issues that deal with the attractiveness of the urban core. Yet, we assume that the only destinations that cannot be modified are workplaces, places of study and health places. If these destinations are included in a loop, the loop is therefore considered as “constrained”.

2.4.5. Car purchase

The potential for purchasing a new car is studied focusing on the incomes and existing subsidies for households that remain without modal shift solutions and trips with constrained destination. We therefore consider the purchase of a LEZ-compliant vehicle to be the solution of last resort. 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 take into account for the analysis.

2.5. 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.

2.5.1. 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 3), 4.8% by 2024 (Crit’Air 4) and 19.3% by 2025 (Crit’Air 5 and non-classified vehicles). Low-income households are the most likely to hold the most polluting cars (see Appendix B.6). 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 2.5), Scenario A would affect 20,225 households in total between 2023 and 2025 (i.e. 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 highly vulnerable under Scenario A (resp. 11.6% under Scenario B) and represent 0.6% of the global population (resp. 0.9%).

Table 2.5 Global impacts of the LEZ according to the considered scenario

Note to the reader: All % are expressed as a share of the global sample.

Scenario A	Affected by the LEZ	Not affected by the LEZ	Total	Scenario B	Affected by the LEZ	Not affected by the LEZ	Total
Not HV	18,074 (5.0%)	306,604 (85.4%)	324,678 (90.4%)	Not HV	25,516 (7.1%)	299,162 (85.8%)	324,678 (90.4%)
HV	2,151 (0.6%)	32,598 (9.0%)	34,749 (9.6%)	HV	3,338 (0.9%)	31,411 (8.7%)	34,749 (9.6%)
Total	20,225 (5.6%)	339,202 (94.4%)	359,427 (100.0%)	Total	28,854 (8.0%)	330,573 (92.0%)	359,427 (100.0%)

The spatial impacts of the LEZ will be heterogeneous. An important share of affected households lives in the perimeter of the LEZ (33% in Scenario A; see Figure 2.6). The LEZ also affects households living in other parts of the area of study, in particular in Voironnais and Grésivaudan. If we consider the largest perimeter (Scenario B), the map highlights that the additional affected households are mainly located in the Metropolis, which means that increasing the size of the perimeter may particularly affect households living in or close to Grenoble.

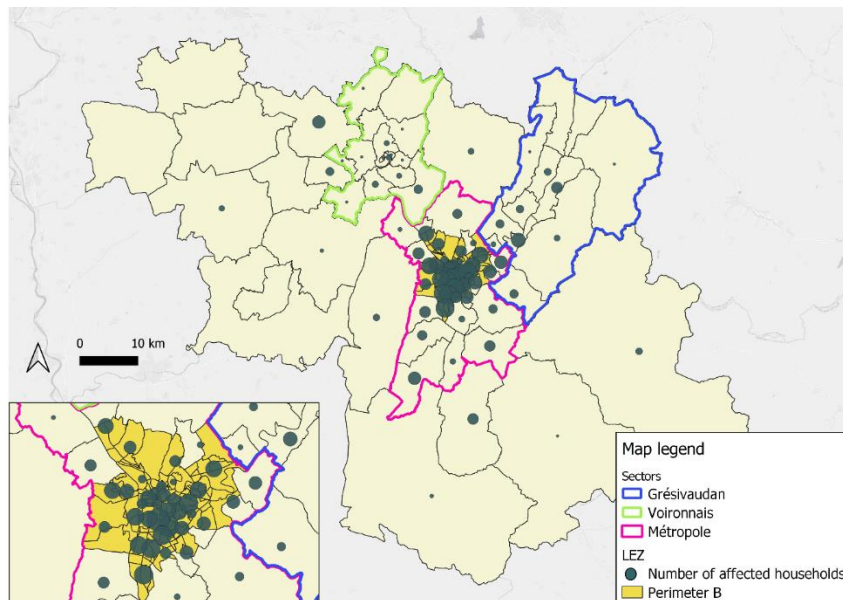


Figure 2.6 Residential location of the affected households in scenario B

2.5.2. What capacity to adapt to the LEZ?

In this section, 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, while results associated to scenario A are described in Appendix B.7. Tables 2.6 and 2.7 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 2.2) and more generally HV households that are affected by the LEZ have more trips within the LEZ perimeter. Indeed, the car trips made in the LEZ perimeter represent 20.8% of the car trips made by the global sample of households affected by the LEZ, while this figure that rises to 48.3% for HV households.

Table 2.6 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	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
<i>% of all households (Total - 1)</i>	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*
<i>% of all households (Total - 1)</i>	8,03%	7,10%	0,93%	0,16%	0,15%	0,18%	0,15%	0,16%
<i>% of all, non-HV and HV households (Total, non-HV, HV - 2)</i>	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 *
<i>% of all households (Total - 1)</i>	3,45%	2,93%	0,52%	0,10%	0,12%	0,09%	0,04%	0,13%
<i>% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)</i>	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*
<i>% of all households (Total - 1)</i>	2,42%	2,00%	0,43%	0,09%	0,04%	0,09%	0,04%	0,13%
<i>% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)</i>	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 (transport poor)	1 607	1 312	295	112 *	7	21	8	140*
<i>% of all households (Total - 1)</i>	0,45%	0,37%	0,08%	0,03%	0,02%	0,61%	0,14%	1,31%
<i>% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)</i>	5,6%	5,1%	8,8%	19,2%	1,3%	3,2%	1,5%	23,7%

Note to the reader:

- 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).

Table 2.7 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
<i>% of all trips (Total - 1)</i>	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 *
<i>% of all trips (Total - 1)</i>	9,5%	8,2%	1,3%	0,3%	0,1%	0,2%	0,3%	0,2%
<i>% of all, HV and non-HV trips (Total, HV, Non-HV - 2)</i>	9,5%	8,9%	17,0%					
<i>% of affected trips with a modal shift solution</i>	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*
<i>% of all trips (Total - 1)</i>	3,8%	3,2%	0,6%	0,2%	0,1%	0,1%	0,0%	0,2%
<i>% of all, HV and non-HV affected trips (Total, HV, Non-HV - 2)</i>	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*
<i>% of all households (Total - 1)</i>	2,3%	1,9%	0,4%	0,1%	0,0%	0,1%	0,0%	0,1%
<i>% of all, HV and non-HV households (Total, HV, Non-HV - 2)</i>	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 (transport poor)	2 940	2 024	916	331	29	102	40	379*
<i>% of all households (Total - 1)</i>	0,3%	0,2%	0,1%	0,0%	0,0%	0,0%	0,0%	0,0%
<i>% of all, HV and non-HV households (Total, HV, Non-HV - 2)</i>	3,2%	2,6%	7,5%	11,4%	2,1%	4,5%	1,5%	18,1%

Note to the reader:

- 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 shift solution (third column, situation 3).

Analysis of the adaptation solutions

First, modal shift (line 3 in Table 2.6) 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. Overall, 0.5% of the population is HV, affected by the LEZ and with no modal shift solution. Considering trips (Table 2.7), 60.4% of car trips find a modal shift solution. If we focus on HV households, 52.9% of their journeys can be transferred to another mode of transport, forcing them to find another solution for almost half of their journeys. For non-HV households, 61.6% of their trips have a modal shift solution.

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% for non-HV affected households. The gap is therefore widening between the two population categories. At the level of the trips, 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 possibility of modal shift, compared with 22.7% of trips by non-HV households. This indicates that 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 transport poors (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 which will require special assistance from the public authorities. Among them, some suffer from a combination of financial vulnerability and other vulnerabilities: 0.1% of the population is highly vulnerable, poor and has no solution to modal shift or change of destination.

Analysis by highly vulnerable profiles – households' level

The LEZ has differentiated impacts on the different HV profiles (Table 2.6). 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, such that, 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.

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

Table 2.7 proposes an analysis by vulnerability profile at trip level, which also makes it possible to look at the alternatives to the car that can be used by each category of population.

Conventional cycling and public transport are two alternatives that, in similar proportions, 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, because 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 very 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 (profile A), and e-bikes appear as a great solution for "*structural heavy car users*" (profile D). On the contrary, households "*without alternatives*" and "*costly heavy car*

users” (profiles B and E) have no possibility to report their trips to conventional bikes (0%) and a low access to e-bike (respectively 10.4% and 5.7%), which is due to their residential location (see Appendix B.8). As a result, these two profiles will respectively see 77.8% and 85.1% of their affected trips remaining without modal shift solution. The specificity of the profile E (“*costly heavy car users*”) is also that 77.1% of the affected trips have a constrained destination. Although this profile only concerns 1.68% of the population, it should be noted that these journeys would be particularly affected by the LEZ.

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

- 1- Comparing the results of scenario A (smaller perimeter; Appendix B.7) 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 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 B.5) 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, i.e. a reduction of respectively 3.5% and 1.8% of affected households in each scenario.

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

In order to face the consequences of a LEZ implementation, the last solution is to buy a vehicle compatible with the restrictions. This purchase has budgetary consequences that might be important despite the existing subsidies for new cars (Mattioli, 2017). Moreover, 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 & Vanoutrive, 2022). Recent press articles concerning cities where a LEZ has been implemented estimate that it is complicated to find a LEZ-compatible second-hand car (Crit’Air 2 or less) under 6,000€ (20minutes, 2023). Moreover, the additional cost for new electric vehicles compared to a conventional car is still very high, around 45 to 50% according to Tabarrot, (2023).

In this sense, we evaluate the potential for buying a new car for the households without any modal shift solution and with constrained trip purposes (identified in Table 2.6 – line situation 4). If we consider households below the median income (21.5k€/year/cu) may not afford to buy a car compatible with the LEZ, this represents 51% of households without other solution in scenario B and 41% in scenario A (Figure 2.7). The situation is particularly complicated for the 295 transport poor households in scenario B and 190 in scenario A that would definitely need a subsidy to afford to modify their mobility habits.

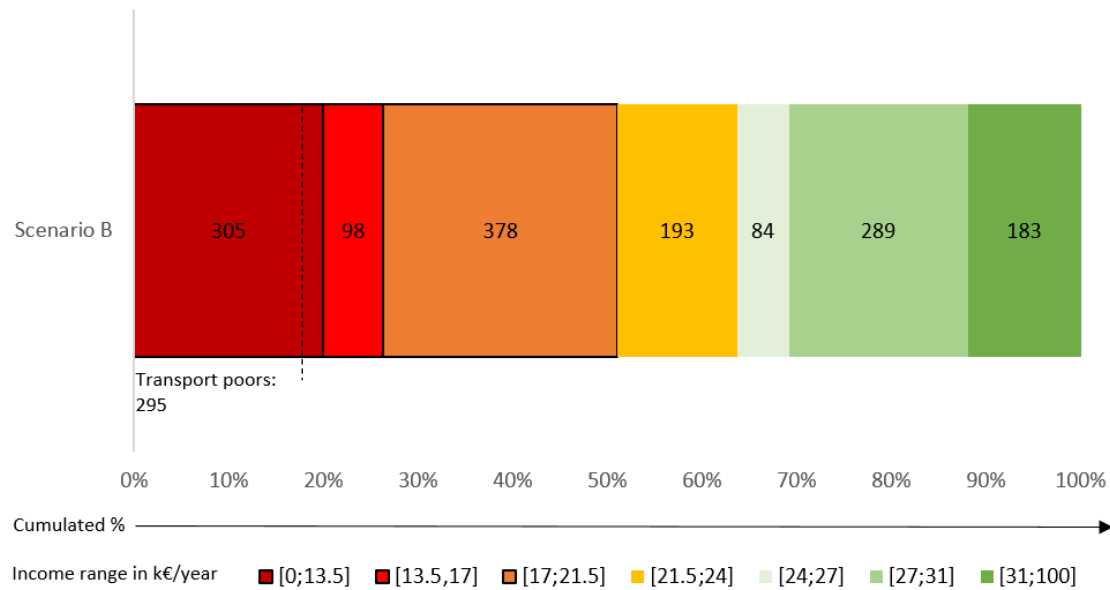


Figure 2.7 Income shares associated to the households without modal shift solution and constrained by their destination

Note to the reader: The income ranges are defined according to the deciles in the EMC2 data, 21.5k€ corresponding 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.

2.6. Political recommendations

Our results show that HV households are over-represented among households affected by the EPZ and that they have fewer adaptation solutions available to them overall. The implementation of preventive and/or compensatory policies are thus necessary in order to avoid increasing mobility vulnerabilities and transport poverty in the Grenoble area. Yet, as a one-size-fits-all solution does not exist, results help providing recommendations according to the households' profiles and their residential locations and focusing in particular on HV households affected by the LEZ.

First, modal shift is a major solution to adapt to the constraints imposed by the LEZ. For that purpose, local authorities have to be proactive in organizing this modal shift. At the local area, the Grenoble metropolis is committed in personalized advice for households to ensure that modal shift is favored as part of the implementation of the LEZ, so that the purchase of a new vehicle is the solution of last resort. Indeed, even a Crit'Air 2, 1 or electric car is polluting (cars also emit particles during braking and re-suspension and these emission levels are far from being negligible). Moreover, there is an important gap between the emission standards introduced in the Euro standards and the actual emissions (ICTT, 2017).

Modal shift has also to be achieved by working on the security of active modes, infrastructures for public transport and active modes as well as financial assistance to invest in efficient bicycles, including e-bikes. For instance, in France, there is a €1,500 bonus for buying 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. In the light of our results, support for the purchase of a bicycle, whether electric or not, is all the more important as it is a solution that is widely accessible to HV households, just as much as to non-HV households.

Second, our results highlight the great potential of modal shift towards conventional and e-bikes. Bouscasse et al. (submitted) 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. Policymakers should therefore focus their active mobility promotion campaigns on these levers. 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, Bouscasse, Chalabaev, & Mathy, submitted). Free test days to try the use of a conventional bike or an e-bike could also encourage changes in mentalities and habits. 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.

Third, for households living in areas where the public transport system is efficient enough to catch their needs, our recommendation is to increase their accessibility. To do so, incentive measures such as a price reduction and/or gratuity may encourage people to switch to public transport. Indeed, in the survey on LEZ acceptability conducted in Grenoble, Rejeb et al. (2023) showed that the question of accessibility to public transports was strongly requested as an accompanying measure following the LEZ implementation. Results show that only a limited share of the current affected trips are actually potentially switchable to this solution, so the current infrastructures might be able to handle this shock if the frequency is increased.

Fourth, in the sectors particularly poorly served by public transport (such as Sud Isère and Bièvre), the first objective would be to improve the public transport system provision; as this project 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. For instance, in Grenoble area, the Citiz service (self-service cars) might offer an option for those who occasionally need to use a car. On longer-term, another solution might be to roll out new economic activities in those sectors, and therefore reduce the mobility needs and/or dependence to the urban core (Chardonnel et al., 2017).

Fifth, in order to deal with night workers issues, implementing a temporary LEZ instead of a permanent LEZ in order to allow more flexibility would not significantly affect the environmental efficiency (see Appendix B.5). This measure would increase public acceptability towards the LEZ implementation. This is one of the reasons why decision-makers have chosen to set up a temporary LEZ²¹ in the Grenoble Metropolis.

Finally, for those who do not have access to public transport, cannot switch to active modes and cannot modify their destination, the last solution remains buying a LEZ-compatible car. Yet, considering our assumptions, 295 households (0.1% of the global sample) that are both poor and HV would have no alternative but to purchase a car compatible with the constraints of the LEZ. Therefore, a monetary subsidy targeted at these particularly vulnerable and poor households would be needed. Beyond these particular cases of great vulnerability and poverty, subsidies conditioned on income level and possibly on modal shift possibilities will be necessary, especially if we consider the impact of the LEZs on the price of vehicles with a Crit’Air label of 3 or less. 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 (Le Dauphiné Libéré, 2023). In particular, in Grenoble, decision makers consider the LEZ an excellent opportunity to promote active mobility, by providing a bonus subsidy for those who choose to give up their car. Yet, these subsidies are for now limited to households living in the Metropolis, excluding households living in other sectors of the territory that may also be affected by the LEZ.

2.7. Discussion and conclusion

In this chapter, we rely on the VulMob indicator (Blandin et al., 2023) to estimate the *ex-ante* impacts of a LEZ in the Grenoble area. In particular, this work showed that the households that are already highly vulnerable without the LEZ might be the most affected. Therefore, the implementation of this measure clearly adds an additional barrier to mobility for the households that are already vulnerable, with important differences among the five typical profiles of HV households identified in Blandin et al. (2023). In particular, three profiles may have important difficulties to adapt to the LEZ: 1. Monetary

²¹ The Grenoble Metropolis, following our recommendations presented in the expert committee for the LEZ evaluation, has adopted this modality.

constrained households, 2. Households living far from the basic amenities and without access to public transport, and 3. Households with heavy car use, -and potentially car dependency issues- and high mobility costs. Although the number of people affected is low in Grenoble, it may be high in other towns with a different urban layout and poorer public transport and cycle infrastructure.

We showed that the size of the perimeter and the schedule also play an important role in the increase of the number of affected households. We observed many territorial disparities, which make the implementation of compensatory policies more complex. These policies must therefore be decentralized and defined at the local level by local decision-makers who know the territory and the local populations. The contributions of this work can guide decision-makers towards the definition of compensatory measures and the deployment of the required infrastructures, in particular to provide active mobility equipment, which seems to be a powerful tool to shift almost a half of the banned trips that were previously made by car.

Two main issues condition our conclusions. On the one hand, the psychological motivators are at stake in our hypothesis for possible modal shifts. Indeed, switching from the use of a car to active mode can be complicated. It is therefore important to better understand the factors associated with active and sustainable mobility in order to be able to change mobility behaviors towards more active and more sustainable mobility (Bamberg, 2012; Rejeb et al. (submitted)). On the other hand, the question of the acceptability of the LEZ is particularly important, as a rejection from the population could threaten the implementation of ambitious policies. Studies on LEZ acceptability *ex-ante* (Rejeb et al., 2023; Morton et al., 2021) or *ex-post* (Oltra, Sala, López-Asensio, Germán, & Boso, 2021; Tarrío-Ortiz, Soria-Lara, Gómez, & Vassallo, 2021) showed that the main determinants of acceptability are a positive social perception, a high trust in government, political ideology, risk of being affected and environmental awareness while only few socio-demographic characteristics resulted statistically significant.

The approach developed in this article has some limitations.

First, the VulMob indicator cannot capture all the household specificities. Therefore, the observations made on some HV profiles might also be true for other groups of the population that have not been identified as HV, and other specific households' structures affected by vulnerabilities can be particularly affected by the LEZ.

Second, the adaptation hypothesis may be criticized. Considering modal shift, the thresholds for switching to a mode might differ according to the structure and the transport policies of the studied area. Moreover, we do not consider the potential of multi-modality. For instance, individuals could decide to drive until the restriction perimeter and then to use public transport. Lastly, we choose a particular chain of adaptation solutions that considers modal shift as the solution that should be favored and the purchase of a new car as the last solution. This choice can of course be discussed.

The work developed in this article shows that it is possible to assess the *ex-ante* impacts of a LEZ on mobility vulnerabilities and poverty, using a rigorous approach. Such an approach should become more widespread to inform public policy on mobility issues. We have carried out an assessment of the LEZ as envisaged in the Climate and Resilience Act for the Grenoble conurbation, based on Crit'Air stickers, but other LEZ designs or types of policy aimed at restricting car traffic could also be studied if sufficiently robust and detailed data were available to enable mobility to be cross-referenced at individual level with socio-demographic data, particularly income levels. However, this is not currently possible with household travel surveys. In addition, individual mobility data is collected as part of household travel surveys, which are only carried out on average every 10 years. Of the 42 cities that should have introduced a LEZ under the Climate and Resilience Act, 24 had a Local Household Travel Survey, only seven of which dated from after 2015.

However, the results obtained in the Grenoble area cannot be generalized to all other French conurbations, as socio-demographic issues, land constraints, infrastructure and regional planning are specific to each area. In order to answer questions about the potential risks of worsening inequalities and socio-spatial vulnerabilities with the widespread introduction of LEZs, it is therefore necessary to roll out a program to collect individual mobility data.

Chapter 3

Car dependency in the urban margins: the influence of perceived accessibility on mode choice

Abstract

Car dependence is a dimension of transport poverty whose subjective components have been limitedly explored. Research on car dependence highlights the incidence of transport costs, assesses the multidimensional vulnerability of car-dependency and the possibility to access valued opportunities. However, people's perceptions and their perceived ability to access destinations may better reflect the way they move in car dependent settings. In this chapter, we aim to examine what are the determinants of perceived accessibility and to which extent perceived accessibility influences mode choices in such areas. Based on a survey carried out in four peripheral and periurban municipalities in the Metropolitan Region of Santiago de Chile, we examine how subjective perceptions of accessibility contribute to explain modal choice in the outskirts. Results show that perceived accessibility has a negative net impact on the utilities for both car and public transport, which means that a low perceived accessibility increases the likelihood of choosing motorized modes. Moreover, residents from peripheral municipalities tends to perceive a higher accessibility than households from periurban areas, which are excluded from the public transport system. These findings show the importance of providing nearby opportunities and convenient alternatives in order to limit car dependency, especially in periurban areas.

Keywords: discrete choice, mode choice, perceived accessibility, periphery, car dependence, metropolitan areas

3.1. Introduction

Car dependence can be defined as a situation in which there is a lack of both alternative transport modes to the car and opportunities near residential places, implying that cars become essential to access services, jobs and opportunities (Mattioli, 2016). In car dependent contexts, most forms of transport poverty can be related in one way or another to the dominance of cars over other transport modes, making car dependence a particularly important dimension of transport poverty (Mattioli and Colleoni, 2016). The possibility to own and use a car therefore becomes fundamental in places “built on the assumption of near-universal car access” (Mattioli et al., 2020). As a result, in car-dependent areas, those who cannot afford a private vehicle or lack the autonomy to use one may be socially excluded. Others may end up being forced to spend an important share of their income in order to maintain a car (Tiznado-Aitken et al., 2022). The dependence on cars can also determine forms of accessibility poverty, that is, the difficulty to reach key activities: the car in fact becomes fundamental to access opportunities that are located farther away, implying an expansion of activity spaces that determines increased travel times and costs (Mattioli, 2021).

Transport poverty studies go beyond travel distances, times and expenses dimensions. These include travel expenses, with a focus on fuel (Curl et al., 2018); their relationship with energy and housing costs (Mattioli et al., 2017; Ortar, 2018; Sterzer, 2017); the possibility to engage in various compulsory and non-compulsory activities (Morris, Blumenberg et al., 2020; Morris, Ettema et al., 2020); and the strategies required to access opportunities while coping with transport costs (Belton Chevallier et al., 2018; Tiznado-Aitken et al., 2022). These issues also affect the possibility to reach valued places and opportunities, since moving may imply high monetary and time costs that people may be willing to avoid (Mattioli, 2021). To define this broad concept, Lucas et al.(2016) proposed a multidimensional definition of transport poverty based on five sub-dimensions: mobility poverty, accessibility poverty, transport affordability, exposure to transport externalities and time poverty.

Adequate accessibility levels are essential to move towards sustainable mobility patterns (Bertolini, le Clercq, & Kapoen, 2005), especially in the Latin American context (N. Valenzuela-Levi, Echiburru, Correa, Hurtubia, & Muñoz, 2021); (Núñez, Albornoz, Gutiérrez, & Zumelzu, 2022). Accessibility poverty, which reflects the existing difficulties - in terms of time, ease and costs - in reaching key activities, has been broadly studied and led the development of many indicators and methods to measure it (Vecchio, Tiznado-Aitken, & Hurtubia, 2020). In particular, accessibility poverty is often explained through time poverty (i.e. when individuals need to spend too much time travelling, leading them to social exclusion or social isolation). In the Global South, time poverty is a particularly relevant concept, especially in peripheral areas, which are often characterized by long travel times and a limited access to cars (Hernandez & Titheridge, 2016). While accessibility is not the only dimension of transport poverty affected by inequality, as demonstrates the exposure to transport externalities such as air pollution (Gouveia et al., 2021; 2022) it is especially important considering its contribution to the promotion of social inclusion.

While most transport poverty studies focus on objective features (such as travel times or distances), subjective dimensions could also help to explain the forms of accessibility poverty experienced in car dependent settings. As the concept of perceived accessibility explains, how individuals rate their environment and their subjective ability to reach a destination and access opportunities does not necessarily reflect the results of objective accessibility evaluations (Lättman et al., 2016; 2018). For example, people’s perceptions may question the traditional association between cars and freedom (Sheller & Urry, 2000) while in compact urban settings, the possibility to be car-independent may even generate a feeling of freedom (Lagrell, Thulin, & Vilhelmson, 2018). In Sweden, a sample of 2711 Malmö residents showed that bicycle users may also perceive to have better transport accessibility than car drivers or public transport users (Lättman et al., 2018). Yet, subjective dimensions such as perceived accessibility have received less attention, even if they could further confirm – or even question – the findings of objective evaluations.

Additionally, research on car dependence has overlooked settings outside the Global North. Most works in fact focus on “developed countries” and their suburban areas (Mattioli et al., 2020) but these issues may be equally important also in other areas of the world. Latin America is a good example in this sense. The region shows high levels of socioeconomic inequality, determining specific forms of transport poverty that are visible especially in the peripheries of urban areas (Vecchio et al., 2020). Valenzuela-Levi (2018) found in his worldwide study that “more unequal countries, and particularly those in which the rich concentrate income, tend to be more car-dependent” (p. 393). Despite having a smaller car ownership rate compared to Global North areas, motorization rates in the region are growing (Yañez-Pagans, Martínez, Mitnik, Scholl, & Vazquez, 2019), determining an higher importance of cars for everyday trips and activities. Finally, the rapid expansion of Latin American cities has generated significant forms of suburban development, with significant implications for the metropolitan mobility patterns and the everyday choices of their inhabitants (Blanco & Apaolaza, 2018; Cox & Hurtubia, 2016; Guzman et al., 2017; Obregón Biosca et al., 2018; Tiznado-Aitken et al., 2023). Therefore, in the rapidly growing suburban areas of Latin American cities car dependence may be a further dimension of transport poverty.

Drawing on these premises, we aim to examine to what extent perceived accessibility influences modal choices in a car dependent setting. We focus on Santiago de Chile, a Latin American setting in which the issues of transport poverty have been widely examined, but only partially considering their subjective dimensions. In particular, we intend to compare peripheral and periurban settings, which share a functional dependence from zones of the city in which most opportunities (jobs, health, etc.) are concentrated, but have different socioeconomic conditions and different access to public transport (Tiznado-Aitken et al., 2023). To do so, we examine the results of a survey involving 300 households in four peripheral and periurban municipalities of the Metropolitan Region of Santiago.

Until now, most of the studies on mobility issues tend to focus on urban areas in a Global North and urban core settings, while periurban and peripheral tend to receive less attention. This study therefore provides several contributions to the existing literature. Giving the relatively high socioeconomic inequalities in the Global South, individual perceptions might be better suited to measure inequalities than aggregated objective data (J. Ryan & Pereira, 2021). Indeed, current methods based on objective data are not sufficient to identify accessibility poverty in the Global South, in particular in periurban and peripheral areas where transport accessibility indicators are not even available for many municipalities, due to a lack of data in these areas. Therefore, to the best of our knowledge, this work is the first to introduce perceived accessibility as an explanatory variable of the mode choice in the Global South context. These results might be particularly relevant to improve transport planning and policies as perceptions might be complementary to objective measures of accessibility. First, the chapter discusses the existing mismatching between subjective and objective accessibility measures, by identifying the missing features that should be considered for accessibility evaluation in Latin America. Second, it points out how perceived accessibility might be particularly relevant to explain mode choice process in periurban and peripheral areas.

The chapter is structured as follows: section 3.2 gives some highlights on the concept of perceived accessibility, section 3.3 describes our case study, while section 3.4 presents the theoretical framework of our modelling approach. Section 3.5 provides the definition of latent variables and results, while section 3.6 concludes providing key lessons about the role of perceived accessibility and future research.

3.2. Perceived accessibility and mode choice

Accessibility has gained attention as a suitable evaluative approach for assessing the social implications of transport (Lucas, 2012; Martens, 2016; Vecchio et al., 2020), but most studies have mainly focused on “objective” and often aggregate measurements, based on variables such as the total number of opportunities and average observed travel times. These objective features may differently affect the opportunities available to each person, considering diverse individual features, aspirations and choices (Vecchio & Martens, 2021). As a result, subjective features should be considered when dealing with

accessibility, since people living in the same place may take different mobility decisions according to several factors – including perceptions (Van der Vlugt et al., 2019).

The concept of perceived accessibility has recently emerged in the transport literature. Perceptions and subjective metrics are relevant since they relate the way people evaluate the conditions in which they live and move (Pacione, 1982). When considering an objective territorial measure of accessibility, individuals may perceive accessibility of their residential location differently according to their constraints, needs and feelings. Various theoretical frameworks on perceived accessibility have pointed out that perceived accessibility is the actual determinant of human spatial behavior (and thus mode choice) and that calculated 'objective' measures are designed as a proxy for this perception (Pot et al., 2021). Perceived accessibility may therefore influence travel behavior and therefore have impacts on sustainability issues.

If perceived accessibility “is about how people rate the conditions in which they live” (Lättman et al., 2018), it might often be confounded with other related concepts, such as perceived convenience, easiness to move, or proximity. Yet, perceived convenience corresponds to a perceived ease of use and perceived usefulness of a service, and therefore includes the idea of utility. Easiness to move is related to what is the easier way to move and proximity describes the nearness in terms of space and time. If these concepts are close, perceived accessibility has the specificity to not only include the idea of proximity but also the one of being able to reach destinations according to our preferences, which is not necessarily easy.

Comparisons between objective and subjective features showed that the two approaches often identify a low level of agreement and mismatching issues. Different studies have been conducted, focusing on walkability and physical activities (McCormack et al., 2008; Ball et al., 2008; Gebel et al., 2011), access to Metro stations (Shao, Derudder, & Yang, 2022) existing socio-spatial inequalities related to transport (Curl, 2018; Ryan and Pereira, 2021) or mobility accessibility (Lättman et al., 2018). In particular, this mismatching has been explored in relation to different settings. In Australia, Ryan et al., (2016) explored this mismatching in relation with age groups or transport modes. Results showed that older people experienced the lowest accessibility while middle age are associated with the highest. In Sweden, Lättman et al. (2018) showed that levels of objective accessibility do not allow predicting perceived accessibility in a given residential area, but also highlighted that levels of perceived accessibility differ between main transport modes. As a result, perceived accessibility may explain also how people decide to move, but until now, few studies integrated this as an explanatory variable in mode choice modelling. In Hong Kong, Tam et al. (2010) integrated perceived service quality in an airport ground access mode choice model. This variable was defined according to satisfaction level on five selected service attributes related to walking time, distance, reliability, travel costs and travel time. Then, in the Netherlands, Scheepers et al. (2016) introduced perceived accessibility to shops, public natural spaces and sports facilities in their neighborhood by car, bicycle and walk in a mode choice model, exploring more specifically the purpose of the trips. Results showed that when perceived accessibility by car was high, persons were more likely to use the car instead of active transport modes. Yet, these studies were focusing on Global North settings and the latter did not distinguish different residential places.

3.3. Case study and data

3.3.1. Santiago de Chile: an unequal metropolis

The Metropolitan Region of Santiago (SMR), the capital and main city of Chile, hosts more than 7 million inhabitants. The Greater Santiago is composed of 34 autonomous municipalities, but at least 14 outer municipalities are also strongly connected to the urban center and constitute the functional urban area (Fuentes et al., 2018). Santiago and Chile are representative of urban trends that can be found in other Latin American countries and more in general in the Global South, including intense forms of urban growth, expansion of peripheral and periurban areas, and the emergence of segregated urban structures (Cox and Hurtubia, 2021; 2022). In Chile, almost 90% of the population lives in a city, and 60% of the population lives in the SMR. The periurban areas of Santiago experienced intense demographic growth and land use changes (Banzhaf, Reyes-Paecke, Müller, & Kindler, 2013) in the

last few decades, especially outside the urban growth boundaries established in regional plans (Schuster Olbrich, Vich, Miralles-Guasch, & Fuentes, 2022), and highways often acted as a push factor for this suburban growth (Borsdorf et al., 2007; Garreton, 2017).

Nonetheless, the case of Santiago has experienced forms of segregation that are stronger – and more intentional – than elsewhere. Between 1979 and 1985, an eradication policy implemented by the dictatorship displaced families away from the eastside areas that are today occupied by a concentration of high-income residents and the main economic activities (Suazo-Vecino et al., 2020). As a consequence, the poorest households are often living in low accessibility areas with few job or school opportunities (Tiznado-Aitken et al., 2021), making most work-related trips being directed towards the eastern part of the city, with travel expenses representing a high share of the income for many lower income households. Indeed, the highest transport costs (in terms of both time and monetary expenses) are associated to the highly segregated areas of the territory (location, land prices, accessibility), and concentrated in the areas inhabited by the most deprived groups, which tends to reproduce the existing dynamics of socio-spatial inequalities (Iglesias et al., 2019; Moreno Alba et al., 2021; Tiznado-Aitken et al., 2022).

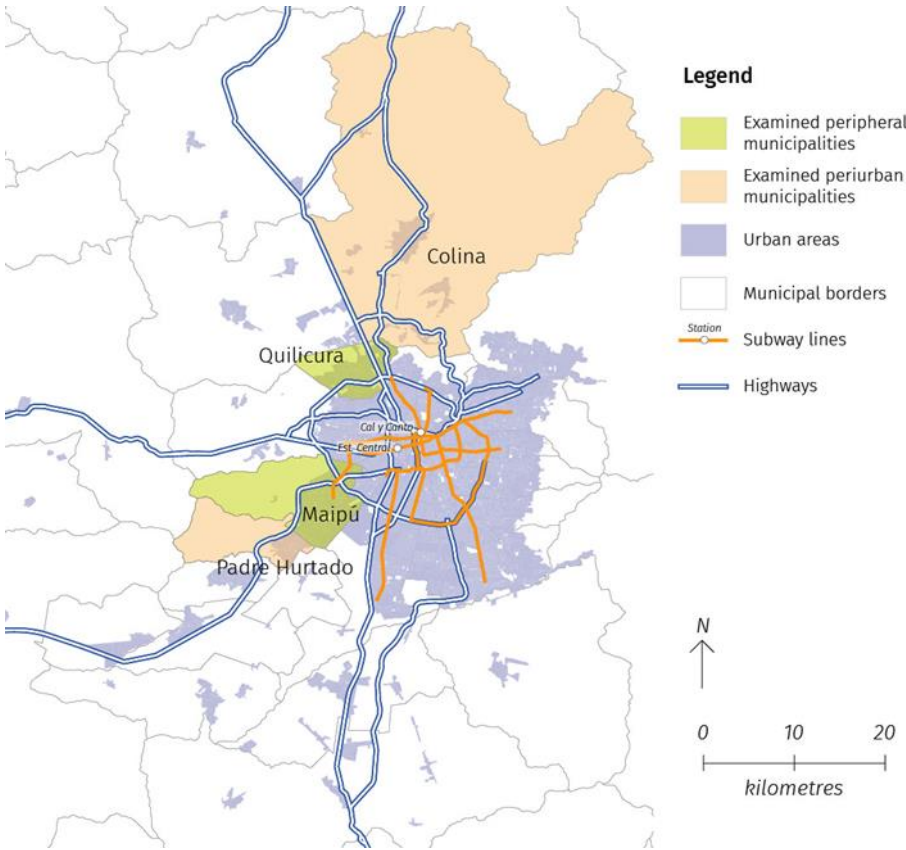


Figure 3.1 Location of the four examined municipalities

The SMR is also affected by governance issues that condition the effectiveness of its transport system. Santiago lacks a metropolitan authority in charge of urban and/or mobility issues, and therefore, the integrated public transport network is available only for the 32 urban municipalities of the city. In our study, we chose to compare four municipalities (see Table 3.1 and Figure 3.1): two peripheral but included in the public transport system perimeter (Quilicura and Maipú) and two contiguous periurban municipalities (Colina and Padre Hurtado) that are located out of the official city borders. In the latter, independent bus lines exist and allow to connect with the integrated system and thus important hubs located in the center of Santiago. Yet, fares are not integrated, the covered distances are huge and so are the travel times; for instance, 32 km separate Colina center from the Costanera Center (approximately the center of mass of the CBD), which represents on average a trip of more than one hour and a half by public transport. Moreover, in peripheral areas, bus stops can be far from residential locations and trips

can also be dangerous, for instance if walking at night or close to a highway is necessary to get home (Jirón & Mansilla, 2013). As a result, despite having integrated and frequent public transport services, some peripheral areas are characterized by equal or even higher travel times than periurban areas, which are spatially further from the economic center though (Tiznado-Aitken et al., 2023).

Table 3.1 Description of the four municipalities of interest

	Quilicura	Maipú	Padre Hurtado	Colina
Type	Peripheral	Peripheral	Periurban	Periurban
Population (2017)	210 410	521 627	63 250	146 207
ICVU (2021) ²²	56.23	53.15	49.38	51.49
ICVU CoMo (2021)	67.56	72.05	58.59	50.79
Area	57.5 km ²	135.5 km ²	80.8 km ²	971.2 km ²

Because of all these cumulated difficulties, car-dependency issues are very important in Santiago. These mobility constraints concern everyone, as the inhabitants have to manage complex and expensive travel chains if they want to use combinations of active and public transport. In Santiago, car use considerably increased in the last few years, especially during the pandemic, therefore increasing travel times associated with the congestion costs (Muñoz et al., 2022). However, not everyone can afford its purchase and use, and low-income population is often captive of public transport, while many mid-income households live in car-oriented peripheral zones, under a very high financial and time stress due to depending on their cars for their daily mobility (Cáceres Seguel, 2015). At the same time, high-income households prefer to use a car, as observed in Buenos Aires (Blanco and Apaolaza, 2018) and Santiago (SECTRA, 2015). The preference for private vehicles is often justified by the comfort and the cheapness of the vehicles, as cars in Chile have a lower relative and real final price than in the rest of the countries of the region (Figueroa & Rodríguez, 2013). For those who can afford it, results show a high inelasticity compared to the direct cost of its use: despite fuel price increases, there is no observed traffic reduction in the short or medium term (Cortés Salinas et al., 2016).

3.3.2. Data collection

We used data from a survey developed within the CODS project. The interviews were conducted by phone in the last months of 2021, when some pandemic-related restrictions were still in place, but most in-person activities had resumed. In Santiago, 304 residents from the four examined municipalities were asked to describe their trips related to work, shopping and health purposes. The panel of respondents is quite representative of the metropolitan population in terms of gender and income (see Table 3.2).

²² The ICVU (Índice de Calidad de Vida Urbana, index for urban life quality) measures and compares several life quality index in 99 Chilean cities, covering more than 79% of the population. In particular, the ICVU has a component dedicated to the measurement of “connectivity and mobility” (ICVU CoMo) according to seven variables. The higher is the component; the best are connectivity and mobility and therefore the most accessible is the municipality. See <http://icvu.observatoriodeciudades.com/> for more information.

Table 3.2 Descriptive statistics of the sample

<i>Observations: 304 households</i>		Share (%)
Gender	Male	41.3
	Female	58.7
Age	18 to 30	16.1
	30 to 40	20.8
	40 to 60	46.6
	60 or older	16.5
Household size	2 or less	16.9
	3	24.1
	4	31.0
	5 or more	28.0
Income (€)	Up to 2 minimal wages	34.5
	2 to 4 minimum wages	29.6
	More than 4 minimum wages	35.9
Number of cars	None	45.5
	One	43.0
	Two	10.2
	Three or more	1.4
Employment status	Regular worker	54.6
	Student	3.8
	Unemployed	19.4
	Housekeeper	12.4
	Pensioner	9.8

Moreover, respondents provided information on their perceptions regarding travel behavior and their environment for a set of 15 psychometrics indicators (available in Appendix C.1) based on 5-levels Likert scale affirmations (see Table 3.3). These affirmations are related to different subjects that may influence mobility, such as monetary expenses, accessibility, easiness to move, pleasantness of environment, quality of sidewalks or feeling of safety. Answers associated to these affirmations were recoded using a 1 to 5 scale.

Table 3.3 Descriptive statistics of psychometrics indicators (shares in %)

I	Description	(Strongly disagree)	Neutral	(Strongly agree)
I1	Getting around the city is cheap	65.4	15.1	19.5
I2	You choose the means of transport you use most often because it is the cheapest	46.1	13.2	40.7
I3	You use your usual means of transport because it is the only one available	26.4	15.3	58.3
I4	The locations where you need to go are close to your home	19.9	19.9	60.3
I5	It is easy for you to get to the places you need to go	19.5	16.1	64.4
I6	If you were living somewhere else, it would be easier for you to get to where you need to go	22.9	20.1	57.0
I7	The environment in which you move is pleasant	14.8	15.1	70.1
I8	The environment in which you move has good quality streets and sidewalks	31.0	14.8	54.2
I9	The environment in which you move has good quality cycling infrastructure	54.4	15.8	29.9
I10	Some of your journeys involve other family members	62.0	7.1	31.0
I11	When you leave home, you usually take the opportunity to do several activities before returning home	13.4	11.1	75.5
I12	Other people depend on you to get around the city	46.0	9.1	45.0
I13	You feel insecure because of possible accidents you may suffer when moving around	25.5	15.8	58.7
I14	You have been injured while driving	65.9	8.4	25.7
I15	In general, you feel satisfied when you move	20.5	23.6	55.9

Then, respondents provided the destinations of their trips and the transport mode they used (see Table 3.4), allowing to calculate the associated travel times and distances. These variables were computed using the OpenTripPlanner API²³ for active modes and car options. For public transport, the API was used only to calculate the trips that can be made with the urban public transport system (n=257 trips), since no GTFS files are available for periurban areas in SMR. For travel originating in or directed to these zones, we estimated a travel time connection to Cal y Canto metro station (45 min) for Colina and to Estación Central metro (59 min) for Padre Hurtado. The choice for these connection places has been conditioned by the destination of the few existing bus lines. These estimations come from the travel times declared by the bus companies. We excluded three outlier observations and all the incomplete answers. Each respondent may be associated with one or two observations depending on their answers for work and health issues (shopping trips were excluded, as the exact destination address was not provided). In the end, the useful database is composed of 399 complete trip observations relating mobility habits, psychometric indicators (perceptions) and socioeconomic attributes.

Table 3.4 Mode share by residential location

	Quilicura (N=119)	Maipú (N=142)	Padre Hurtado (N=62)	Colina (N=76)
Car	48.8%	45.8%	72.6%	78.9%
Public transport	37.0%	41.5%	24.2%	15.8%
Active modes	14.2%	12.7%	3.2%	5.3%

3.4. Methods: defining the integrated choice and latent variable model

To explain mode choice, the majority of the existing models relies on the use of modal attributes and socioeconomic characteristics (Ben-Akiva & Lerman, 1985), but unobserved factors may have relevant effects on travel behavior, such as perceptions of the environment, accessibility, feasibility. In this sense, the framework of modeling choice behavior was extended with the emergence of the Integrated Choice and Latent Variable (ICLV) model (Ben-Akiva et al., 1999; Walker and Ben-Akiva, 2002). In ICLV models, psychometric indicators are used to measure attitudes and/or perceptions, taking the form of affirmations to which respondents are asked about their level of agreement. These indicators are useful to relate the individual's characteristics with unobserved or latent variables, allowing to build structural relations that can be later used to include the latent variable in a choice model.

In the literature, latent variables included in ICLV models focusing on mode choice are related to a wide range of concepts, reflecting the multiple dimensions of the decision process. For instance, these variables may be related to lifestyle and or/trip constraints, as individuals may have to face different types of constraints when travelling, whether in terms of duration, location and timing or the need to travel with children (Redmond, 2000). Other variables may be linked with travel liking: individuals may be characterized by positive feelings and perceptions when travelling, which decreases their value of time. For example, some people enjoy their travel times in order to work or do other activities (Ory & Mokhtarian, 2005). Safety perception when travelling may explain mode choices (Raveau, Álvarez-Daziano, Yáñez, Bolduc, & de Dios Ortúzar, 2010). For example, the fear of accidents when moving and/or and driving-related injuries may show driving avoidance when not necessary and therefore create a preference for other transport modes. Other studies have also included other variables such as comfort, convenience and flexibility (Vredin Johansson, Heldt, & Johansson, 2006), social comparison (Abou-Zeid & Ben-Akiva, 2011), environmental concerns (Atasoy, Glerum, & Bierlaire, 2013), values and attitudes (Paulssen, Temme, Vij, & Walker, 2014) or habitual behaviors (Idris, Habib, Tudela, & Shalaby, 2015).

As defined earlier, perceived accessibility reflects individuals' perceptions and feelings related to the ability to reach a destination considering the whole range of personal opportunities and constraints

²³ See <https://www.opentripplanner.org/> for more information.

associated to their specific mobility behavior. Therefore, it may be useful to explain individual preferences for choosing a transportation mode.

The general structure of the ICLV model is described in Figure 3.2. Rectangles represent observable variables while ovals represent unobservable and latent variables. Red arrows show the structural relations between observable and unobservable variables with the choice model and blue ones represent the relations between observable variables and the latent variable. In this chapter, we use the ICLV model to explain mode choice considering a set of three alternatives considering car, public transport or active modes. In our case, the dependent variable is the transport mode chosen by a respondent. Other variables are related to the socio-economic characteristics of the households, trip attributes and location characteristics. The psychometric indicators allow to define the latent variable of perceived accessibility (which is unobservable but defined from indicators and individual characteristics).

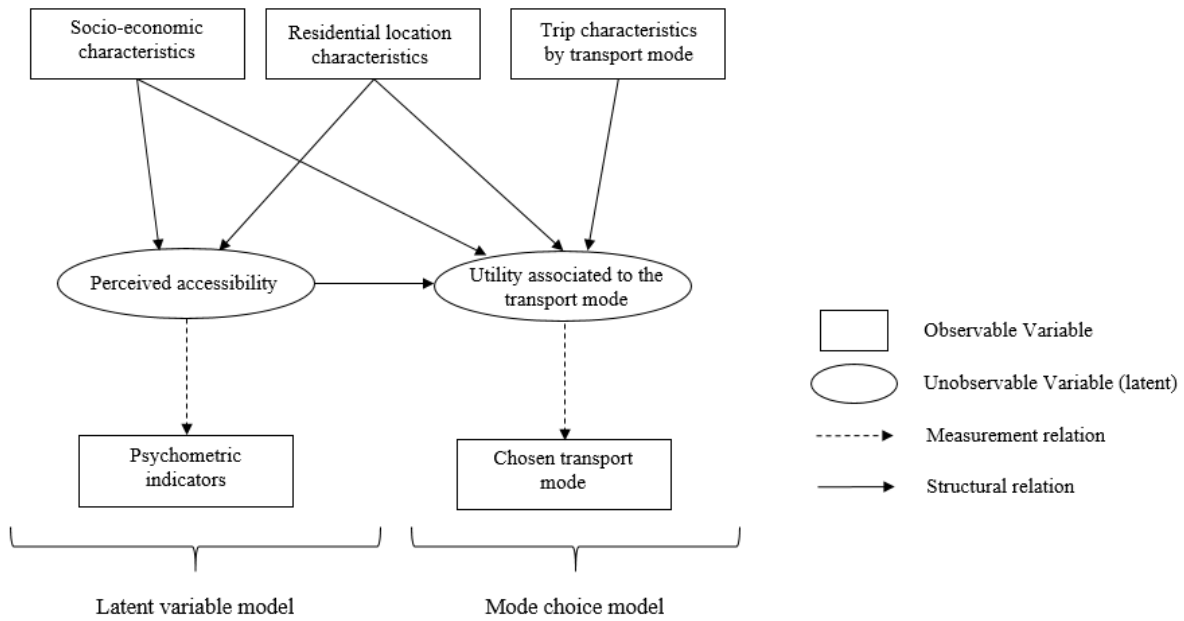


Figure 3.2 Structure of the ICLV model (Source: Authors' own elaboration)

An ICLV model consists in the combination of two components: a structural equation modelling (SEM) and a discrete choice modelling (DCM). For an individual n :

The SEM measurement equations that allow describing the relation between the psychometrics indicator and the latent unobservable variable are:

$$I_n = f(X_n^*; \zeta) + v_n \quad (1)$$

where the indicator I is a function of the latent variable X^* , a set of parameters ζ and an error term (v).

The latent variable can also be related to observable explanatory variables X (the characteristics of the household, the residential location). This relation is described by the SEM structural equation:

$$X_n^* = g(X_n; \gamma) + w_n \quad (2)$$

where γ is a set of parameters and w is an error term.

For each transport mode (described as an alternative i , for an individual n), we write a utility function:

$$U_{in} = V(X_n, X_i, X_n^*; \beta) + \varepsilon_{in} \quad (3)$$

where V is the indirect utility function, β a set of parameters and ε an error term.

In a utility maximization framework, the probability for individual n to choose alternative i in a set of alternative denoted A is:

$$P(i|X_n, X_i, X_n^*; \zeta, \sigma_\varepsilon) = \text{Prob}[U_{in} \geq U_{jn}, \forall j \in A] \quad (4)$$

where σ_ε is a vector of parameters of the error term related to ε .

As the latent variable X^* is not observable, it requires to integrate over the distribution of the latent variable. Using the associated density functions, we obtain:

$$P(i, I_n | X_n, X_i; \beta, \zeta, \lambda, \sigma_\varepsilon, \sigma_v, \sigma_w) = \int_{X^*} P(i|X_n, X_i, X^*; \beta, \sigma_\varepsilon) f(I_n | X^*; \zeta, \sigma_v) f(X^* | X_n; \gamma, \sigma_w) dX^* \quad (5)$$

Estimating the parameters implies maximizing the likelihood function of observable variables and indicators. The likelihood function (L) is:

$$L = \sum_n \sum_{i \in A} \theta_{in} P(i, I_n | X_n, X_i; \beta, \zeta, \lambda, \sigma_\varepsilon, \sigma_v, \sigma_w) \quad (6)$$

In the literature, many researchers used this approach and applied it to the transport field, focusing in different issues such as mode choice (Ben-Akiva and Boccara, 1995; Espino et al., 2006; Hurtubia et al., 2010), car choice (Bolduc, Boucher, & Alvarez-Daziano, 2008), residential location choice (J. L. Walker & Li, 2007) or cycling infrastructures (Rossetti, Guevara, Galilea, & Hurtubia, 2018).

3.5. Results

In this section, we first present the steps followed to identify the latent variable, and then describe our results when applying the model.

3.5.1. Identification of the latent variable

We conducted a factor analysis which generated 5 relevant factors with an eigenvalue greater than 1, that together explain 54.19% of the total variance. We used a varimax rotation to ease the identification of each variable with a single factor. We did not conduct a previous cluster analysis of the data, as the size of the dataset was not large enough for this purpose. The set of results detailed in Table 3.5 are limited to indicators associated with an absolute value greater than 0.2 and a 95% significant level.

Table 3.5 Loading factors associated to the psychometric indicators

I	Description	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
I1	Getting around the city is cheap					0.366
I2	You choose the means of transport you use most often because it is the cheapest			0.277		0.519
I3	You use your usual means of transport because it is the only one available			0.363	0.247	
I4	The locations where you need to go are close to your home	0.775				
I5	It is easy for you to get to the places you need to go	0.558			0.367	
I6	If you were living somewhere else, it would be easier for you to get to where you need to go	-0.285		0.246		
I7	The environment in which you move is pleasant		0.351		0.275	
I8	The environment in which you move has good quality streets and sidewalks		0.564			
I9	The environment in which you move has good quality cycling infrastructure		0.764			
I10	Some of your journeys involve other family members			0.346		
I11	When you leave home, you usually take the opportunity to do several activities before returning home				0.453	
I12	Other people depend on you to get around the city			0.228		-0.375
I13	You feel insecure because of possible accidents you may suffer when moving around		-0.202	0.440		

I14	You have been injured while driving		0.534	-0.201	0.212
I15	In general, you feel satisfied when you move	0.291		0.429	

By analyzing the corresponding indicators and their signs, it is possible to infer the latent variable associated with each factor. Focusing on factor 1, we observe that a high level of agreement with affirmation 4, 5 or 15 demonstrates a feeling of having easy access to opportunities, few difficulties reaching the needed destinations and a positive perception of moving. On the contrary, factor 1 is associated to a disagreement with affirmation 6, meaning that the current residential place appears to be satisfying considering mobility purposes. This shows that factor 1 can be identified as the individual “perceived accessibility” latent variable, defined as “how easy it is to live a satisfactory life with the help of the transport system” (Lättman et al., 2016).

A similar analysis performed with factors 2 to 5 allowed to identify other latent variables such as amenities (factor 2), safety (factor 3), and utilitarian travel (factor 5) while factor 4 is not easily identifiable. Yet, we decided to restrict our analysis to the effect of one latent variable in order to focus on the analysis of the potential for perceived accessibility to explain mode choice.

3.5.2. Definition of the ‘perceived accessibility’ variable

Before going any further, we underline that perceived accessibility is a complex issue, which is often mixed up with other similar concepts such as perceived convenience, easiness to move or proximity. Consequently, areas that might objectively be described as having low accessibility can still be attractive for residents who perceive it more positively. Despite not being very accessible in terms of travel times and distances, people seem to value the environment in which they live; other elements may therefore explain their residential choices. For instance, some areas may be objectively described as having low accessibility considering all available opportunities, but in reality, households might need a limited amount of close or reachable services to have a high-perceived accessibility.

In our specific case, perceived accessibility appears to be particularly related to the close environment. Moreover, the inclusion of a satisfaction item in the definition of our perceived accessibility variable goes further from the definition provided by Lättman (2016). In this sense, exploring in detail the different factors leading to the construction of the perceived latent variable might offer great insights on the differences observed with the Global North context and highlight what is missing in the current accessibility evaluations.

Table 3.6 Indicators and factor loadings associated with factor 1 (perceived accessibility)

Indicator	Value	Sign	Description
I1	0.159	+	Getting around the city is cheap
I3	-0.197	-	You use your usual means of transport because it is the only one available
I4	0.775	+	The locations where you need to go are close to your home
I5	0.558	+	It is easy for you to get to the places you need to go
I6	-0.285	-	If you were living somewhere else, it would be easier for you to get to where you need to go
I7	0.146	+	The environment in which you move is pleasant
I9	0.142		The environment in which you move has good quality cycling infrastructure
I15	0.291	+	In general, you feel satisfied when you move

Table 3.6 gives a detailed description of all the factors that are actually significant to explain perceived accessibility in our dataset, without any threshold restriction. These results show that other dimensions also play a role in the measure of perceived accessibility. Indeed, perceived accessibility appears to be associated to a perceived relatively low-cost of travelling (I1, positive), but also to the availability of different transport modes (I3, negative). At the same time, a pleasant environment (I7, positive) and good quality cycling infrastructures (I9, positive) also appear to increase perceived accessibility.

These observations, that appear to be specific to the Latin America context, underline the importance of considering different subjective features when studying accessibility. In particular, perceived monetary costs, which, in fact, reveal the share of expenses that households would like to dedicate to mobility, are relevant to explain perceived accessibility. Moreover, the quality of the environment and the existence of active mobility infrastructures – that translates the potential for multimodality and flexibility – are also of interest.

3.5.3. Model specification

We specified a logit model including latent variables as defined in section 3.2. Here, the choice is the transport mode that is used for a trip, considering a set of three alternatives: car, public transport or active modes (bicycle, walk). For each alternative, we defined a utility function:

$$V_{car} = ASC_{car} + \beta_{tt_{car}} TT_{car} + \beta_{cost_{car}} cost_{car} + \lambda_{car} access + \beta_{income_{car}} * income + \beta_{peripheral_{car}} * MQ + \sum_k \beta_{k_{car}} \delta_k \quad (7.1)$$

$$V_{pt} = ASC_{pt} + \beta_{tt_{pt}} TT_{pt} + \beta_{cost_{pt}} cost_{pt} + \lambda_{pt} access + \sum_k \beta_{k_{pt}} \delta_k \quad (7.2)$$

$$V_{active} = ASC_{active} + \beta_{tt_{active}} TT_{active} \quad (7.3)$$

Where TT variables represent travel times in minutes, $income$ is the monthly income described as the number of minimal wages earned monthly, and MQ indicates if the household lives in peripheral municipalities (Maipú or Quilicura). δ_k is a vector of socio-economic characteristics, which includes dummy variables for number of cars, gender, presence of children, trip purpose (work or health), and educational level. The latent variable, denoted $access$, represents the perceived accessibility.

The SEM measurement equations are estimated using ordered logit with four thresholds as our psychometrics indicators follow a 5-levels Likert scale. The thresholds are denoted τ_{ij} with i within a range from 1 to 4 and $j = 4, 5, 6$ and 15, corresponding to the 4 most relevant psychometrics indicators (equation (8)).

$$I_j = \begin{cases} 1 & \text{if } I_j^* < \tau_{1j} \\ 2 & \text{if } \tau_{1j} < I_j^* < \tau_{2j} \\ 3 & \text{if } \tau_{2j} < I_j^* < \tau_{3j} \\ 4 & \text{if } \tau_{3j} < I_j^* < \tau_{4j} \\ 5 & \text{if } I_j^* > \tau_{4j} \end{cases} \quad \forall j = 4, 5, 6, 15 \quad (8)$$

The latent variable is composed by two variables, corresponding to education and declared travel time. For an individual n , the structural relation between the latent variable perceived accessibility, denoted $access$, and the socio-economic characteristics is given by:

$$access_n = \gamma_{time} (1 + \gamma_{MQ} MQ_n) time_n + \gamma_{educ} EDUC_n + w \quad (9)$$

Where $time$ corresponds to the average declared travel time, without distinction on trip purposes or transport mode. It is an approximation of the perceived travel time and is not necessarily realistic, but sufficient to explain perceived accessibility. MQ_n is a dummy variable equals to 1 if the respondent lives in Maipú or Quilicura (the peripheral municipalities) and $EDUC_n$ is a dummy variable that indicates if individual n has a university degree.

3.5.4. Perceived accessibility in the model

Results are obtained by using the Apollo package in R (Hess & Palma, 2019). Table 3.7 provides the estimation results of the ICLV model and a comparison with a logit (MNL) model.

Table 3.7 Estimation results of the ICLV and MNL models

	Affected utility			ICLV model		MNL model	
	V_{car}	V_{pt}	V_{active}	Value	t-test	Value	t-test
ASC_{car}	x			0.005	0.08	0.153	0.29
ASC_{pt}		x		-0.359	-0.46	0.273	0.44
ASC_{bike}			x	0	-	-	-
$\beta_{tt_{car}}$	x			-0.053*	-1.70	-0.055*	-1.82
$\beta_{tt_{pt}}$		x		-0.017*	-1.70	-0.015	-1.57
$\beta_{tt_{bike}}$			x	-0.054***	-3.95	-0.056***	-4.33
$\beta_{cost_{car}}$	x			-6.97e-5	-0.60	-5.03e-5	1.1e-4
$\beta_{cost_{pt}}$		x		-1.57e-4	-0.26	-2.86e-5	5.0e-4
$\beta_{income_{car}}$	x			0.214***	3.29	0.203***	3.21
$\beta_{peripheral_{car}}$	x			-0.711*	-1.74	-0.523	-1.24
$\beta_{nvh_{car}}$	x			1.386***	4.59	1.362***	4.62
$\beta_{educ_{car}}$	x			0.720***	2.54	0.714***	2.70
$\beta_{female_{car}}$	x			-0.590***	-2.26	-0.560***	-2.21
$\beta_{child_{pt}}$		x		-0.607***	-2.25	-0.506***	-2.00
$\beta_{work_{pt}}$		x		0.833***	3.09	0.814***	3.14
λ_{car}	x			-1.220***	-2.79	-	-
λ_{pt}		x		-1.560***	-3.45	-	-
γ_{time}	x	x		-0.021***	-4.30	-	-
$\gamma_{time_{MQ}}$	x	x		-0.321***	-2.04	-	-
γ_{educ}	x	x		-0.540***	-2.79	-	-
LL(final) ²⁴				-266.23		-278.15	

*** p < 0.01, ** p < 0.05, * p < 0.10

The ICLV model allows for the identification of structural relationships between observable and latent variables, which would not be possible using the reduced form choice model. In comparison with the logit model, the latent variable approach allows to remove some endogeneity bias and identify additional relevant parameters to explain mode choice (Vij & Walker, 2016).

All the parameters have the expected signs. We observe that a higher travel time has a negative impact on the utility function of all modes ($\beta_{tt} < 0$). Moreover, earning a high income, having more than a car ($\beta_{nvh_{car}}$) and having a university degree ($\beta_{educ_{car}}$) has a positive effect on the utility for car, while being a woman or living in peripheral municipalities has a negative effect. In particular, the utility of car is lower in peripheral municipalities, which is consistent with the better overall objective accessibility observed in this area (as indicated by the ICVU CoMo indicator, see Table 3.1). This distinction between peripheral and periurban areas was also tested for other modes but was insignificant and therefore removed from the model. Concerning public transport utility, having children has a negative effect while travelling for work purposes ($\beta_{work_{pt}}$) has a positive effect on utility.

We tested the influence of the monetary travel costs on the utility of both motorized modes, which had no significant explanatory power. This could be interpreted as people in this context assuming travel costs as sunken, or unavoidable. In our case, this observation is particularly relevant and can be interpreted as a consequence of the lack of options to travel from periurban and peripheral areas, which strongly affects and conditions the choice of a transport mode. Moreover, the purpose of the trip had not significant explanatory power in the car utility function and was excluded from the analysis. When considering the utility function for public transport, the (objective) public transport accessibility of the municipality and the residential location were also insignificant.

²⁴ Final likelihood estimated for each model.

The latent variable has a negative impact on the utilities for both car and public transport, which means that a lower perceived accessibility increases the likelihood of choosing these modes, with a slightly more important effect on public transport ($|\lambda_{pt}| > |\lambda_{car}|$). Therefore, a low perceived accessibility increases the probability of choosing to travel by car and even more by public transport. This result is particularly important in terms of transport planning and underlines not only the necessity to provide new mobility options in these territories, but to also explore mechanisms to increase perceived accessibility.

Considering the specification of the latent variable, having a university degree has a negative impact on perceived accessibility, which was expected, as a high-level education is generally associated with higher income and a greater value of time. Then, we observe that subjective (or declared) travel times (γ_{time}) have a negative impact on perceived accessibility (i.e. the longer the trip is perceived, the lower is the perceived accessibility), and therefore, declared travel times have an indirect net positive impact on utilities (opposed to the effect of objective travel times).

Other socio-economic characteristics such as gender, family size, number of cars, or the objective travel times were not significant to explain the latent variable. In particular, the insignificance of objective travel times in explaining perceived accessibility reinforces the idea that there is no clear correlation between perceived and "objective" accessibility, as existing literature shows (Ryan et al., 2016; Lättman et al., 2018).

Finally, households living in peripheral municipalities (Maipú and Quilicura) tend to perceive a higher accessibility, which is consistent with the existing transport supply in these areas. In particular, when comparing the average perceived accessibility in the four municipalities – computed by considering the average value for the responses in the sample – we observe that Padre Hurtado is perceived as the least accessible ($access = -1.31$), while Quilicura is seen as the most accessible (-0.60), followed by Maipú (-0.82) and Colina (-0.91). Yet, objective indicators, such as the mobility component of the ICVU indicator (Table 3.1), classify Maipú as the most and Colina as the less accessible municipalities, indicating again the existing mismatching between objective and subjective measures of accessibility.

3.6. Discussion and conclusion

In this chapter, we investigated the influence of perceived accessibility on modal choices realized in an unequal, car-dependent setting such as the Santiago Metropolitan Region. In particular, we identified a relevant latent variable to explain the observed mode choice in peripheral and periurban areas.

First, based on the fact that perceptions appear to better explain individuals' behaviors than objective features, it is particularly relevant to integrate subjective indicators when studying mode choice (J. Ryan & Pereira, 2021). In this sense, our results showed that the introduction of perceived accessibility as an explanatory variable in our mode choice model provided a better understanding of the mode choice in peripheral and periurban areas. In particular, our analysis revealed that perceived accessibility is not only a question of perceived access potential to services and needed destinations but also integrates other subjective features such as the perceived quality of the environment and/or availability of different transport modes and especially active modes, in line with other studies led in suburban settings (Chowdhury, Zhai, & Khan, 2016). Therefore, integrating these new dimensions in future evaluations of accessibility in Latin America may be particularly useful to identify more precisely accessibility poverty.

Second, these results are particularly useful for policymakers to tackle car dependency issues by designing equitable public policies and transport planning at the local scale depending on individuals' characteristics and perceptions of their environment. While car dependence is of concern from environmental, externalities and climate change standpoints, the consequences are strengthened for those who are forced to use a car, having to bear costs that may lead to debt or a lower quality of life as they spend less on other dimensions of life. The interplay of environmental and social concerns requires adopting an intersectional approach, focusing on providing affordable and convenient transportation

alternatives as well as opportunities and services in their neighborhoods, especially for those at risk of transport poverty. In this context, our results showed that a low perceived accessibility increases the likelihood of choosing to travel by car and even more by public transport in both periurban and peripheral areas. Therefore, increasing residents' (perceived) accessibility is at stake to limit car dependence in these areas. Based on these results, providing near opportunities, improving the moving environment and/or developing active mobility infrastructures may have a positive influence on perceived accessibility and may encourage choosing non-motorized modes. This may be especially important in the post-pandemic era, which has shown car dependency intensification as the pandemic spread (S. Kim et al., 2023) and long-lasting effects remain to be studied.

Third, in a Global South context marked by strong socioeconomic inequalities and poor transport planning, the study of perceived accessibility is particularly relevant. In particular, perceived accessibility may improve the current measures of accessibility in peripheral and periurban areas, where objective accessibility is globally low. In Santiago de Chile, periurban areas experienced high levels of urban growth in the last decades, with both high- and middle-income urban inhabitants relocating there looking for features that the city could not offer (Cáceres Seguel, 2015; Cox and Hurtubia, 2021). The increasing motorization rates and the relatively recent growth of periurban areas configure car dependency as a newer phenomenon in comparison to Global North countries, as demonstrated also by the scarcity of data and analysis involving settings outside Europe or North America (Saeidizand, Fransen, & Boussauw, 2022). Instead, the inhabitants of peripheral areas often did not decide to live in these places and many of them were relocated to the periphery a long time ago, after the eradication of informal settlements located in the eastern affluent areas of the city. Such relocations had important consequences also for their everyday mobility, increasing greatly travel times (Suazo-Vecino et al., 2019). Our analysis showed that perceived accessibility reveals that the attractiveness of periurban and peripheral municipalities differs from what could be expected with objective measures. This creates a mismatch between expectations and reality that influences the gap between objective and perceived accessibility. In particular, municipalities that are objectively described as the most accessible, such as Maipú, are perceived as less accessible by residents, who might consider that reaching their destinations considering the current available transport modes set is too complicated, in comparison with Quilicura residents.

Fourth, the observations made for mobility costs, which have a neglectable influence on mode choice for every single mode, are interesting and show that mobility choices are based on different concerns in such periurban areas. Undeniably, in these areas people develop residential and mobility choices having other concerns in mind in comparison to other contexts; moreover, specific differences in terms of low carbon behaviors emerge when comparing urban and suburban residents (Neo et al., 2017; Du et al., 2020). In the case of Santiago de Chile, it has been observed that the people who relocate to periurban areas look for bigger houses and neighborhoods safer than those of the central city, and in doing so, they are willing to internalize the increased costs of mobility and access to opportunities (Cáceres Seguel, 2015). This may explain the high car dependency in periurban areas, which may be the only available option for traveling large distances given the inadequate level of service offered by public transport. On the contrary, it could be imagined that people who remain in peripheral areas and have access to the integrated public transport network may expect to have higher levels of accessibility than those actually available to them, also in comparison to other, more central municipalities of the same city. These attitudes have strong implications in terms of urban planning, underlining the necessity to work not only to make existing modal choices more sustainable, but rather adopting a broader definition of accessibility that may include the attitudes, perceptions and feelings of residents regarding mobility environment (R. Zhang et al., 2021).

Yet, this work has some limitations that could lead to future research avenues.

The use of a more extensive dataset, including also other peripheral and periurban municipalities should be explored, as it would allow conducting a cluster analysis before modelling and therefore understanding better the existing differences between peripheral and periurban areas. Moreover, the size of our dataset is limited to 304 respondents. The exclusion of some trip purposes such as shopping is also a limit of this work as it would be of interest to study local mobility habits.

Then, the use of complementary psychometrics indicators may also improve the definition and the results associated to the latent variable. However, we are aware that this would have increased the survey time, which makes data collection more difficult and therefore demanded decisions about which purposes to prioritize.

Finally, few information is available to assess objective accessibility in periurban municipalities and particularly in Colina, which is a limit of the analysis. Complementary work on objective accessibility in these specific areas that are poorly documented may be enlightening in order to better understand the differences between objective and subjective measures of accessibility.

Chapter 4

Did you care about environmental risks and natural areas when choosing where to live? A discrete choice analysis in France

Abstract

The choice of residential location is conditioned by many factors, the main one being a trade-off between land price and transport costs. Among these factors, environmental features have been limitedly explored. Yet, in a global warming context, with increasing environmental risks, it is particularly relevant to understand if households also care about natural amenities and potential environmental risks that may affect their residence. This chapter aims to discuss the influence of effective environmental risks and attributes and of their perception on housing choices for French buyers and renters. We examine housing preferences and analyze residential location choices using discrete choice models (multinomial logit -MNL and latent class - LC). The research is based on revealed preference data from the PERL survey (Perception of the Environment related to Residential Location) conducted in 2023 in France. Results highlight that effective exposure to environmental risks (flood risks and clay swelling risks) and environmental attributes (natural areas) indeed influence preferences. However, the MNL results give few insights on the importance of environmental perceptions, given that a limited share of the population actually considers these risks. The possible heterogeneous effects among the population are explored with a LC model, which reveals that low-income retired households tend to value living in municipalities with a better air quality and limited clay swelling risks.

Keywords: residential location, environmental risks, mixed logit model, latent class analysis, discrete choice

4.1. Introduction

Choosing for a residential location is a complex process, but mainly results in a trade-off between land prices and transport costs (in terms of money and time) (Alonso, 1964; Muth, 1969; Mills, 1972; Fujita, 1989; Duranton et al., 2015). However, various other parameters may considerably influence individual residential choices. These parameters are closely related to the characteristics of households and their preferences for spatial and social opportunities. When choosing among a set of alternatives, households seek to maximize space, accessibility to specific destinations, neighborhood characteristics, given constraints of time and financial resources. One of the most important factors driving households' choices within urban regions is access to jobs (Waddell, 1993) and in particular commuting times (Schirmer, van Eggermond, & Axhausen, 2014). People also frequently prioritize other characteristics besides job proximity. Such factors include the presence of environmental amenities (Rouwendaal and Meijer, 2001; Wales, 1978), nature (Hörnsten and Fredman, 2000; Tyrväinen, 2001) air quality (Palmquist and Israngkura, 1999; Gawande et al., 2001; Tyrväinen and Väänänen, 1998) and recreational areas (Colwell et al., 2002; Greenberg and Lewis, 2000).

In the current global warming context, characterized by increasing environmental risks and disasters for humans and buildings, the presence of environmental risks is therefore of particular interest. Indeed, France is one of the European countries most threatened by floods. Because of climate change, a 40% increase of 100-year floods risks is expected by 2050 in Paris according to the Paris Climate Agency (APC, 2021). Moreover, 48% of France mainland is located in an area characterized by moderate or high exposure to clay shrinkage and swelling (Georisques, 2021). Then, between 2015 and 2019, heatwaves caused 7,309 excess deaths, representing more than 100,000 life years lost in France (Adélaïde, Chanel, & Pascal, 2022). Therefore, adaptation solutions relying on green spaces and natural areas are particularly important. In this sense, considering environmental attributes and risks when choosing a new residential location becomes a central issue.

Even if these risks are precisely studied and objectively quantified by scientists and local authorities (risk prevention plans), they are not always well known by the general public, who do not necessarily take them into account when choosing for a home or, more generally, a residential location. Added to this is the fact that the public's perception of exposure to risk is not always consistent with the objective exposure to risk calculated scientifically. In France, since the 2003 law, it is mandatory to inform future buyers and renters of the risks to which the property is exposed in an official risk report (*in French, Information Acquéreurs et Locataires sur l'état des risques et pollutions*). This report includes, among others, flood risks, seismic risks, soil pollution, and radon pollution. Clay swelling risks have been added to this list through the 2018 law on the evolution of housing, development and digital (ELAN).

While effective exposure indicators statistically describe the environment in which people live, subjective indicators intend to reflect the personal perceptions and feelings of the existing conditions and amenities as observed by individuals (Lee and Marans, 1978). In particular, the importance of environmental perceptions in residential choice has been explained by different theoretical models such as the expectancy (EV) model (Vroom, 1964) or the protective action decision theory (Lindell & Perry, 2012). Moreover, self-protective behavior theories suggest that personal experience affects responses to hazards risk, and in particular, perceptions constitute one important antecedent of homebuyers' response to environmental hazards (Weinstein, 1989). These theoretical models found different empirical applications, for instance in windy areas (Ewing, Kruse, & Wang, 2007) or multi-hazard environments (Y. Zhang, 2010).

Despite the importance of environmental perceptions, housing research remains mostly based on objective environmental indicators, while perceptions of the exposure to environmental risks are less studied. Indeed, empirical applications are largely based on data supplied by systems for observing and measuring the environment, such as a number of decibels or an average concentration of pollutants (Gueymard, 2006). Nevertheless, we do not know whether households really take these risks and

attributes into account when choosing where to live. Moreover, the impacts of environmental features on residential choices are often studied individually, or without looking at the interactions between both risks and environmental attributes, which may improve life quality, in a same model.

To bridge this gap, this chapter aims to discuss to what extent buyers and renters consider the existing environmental risks and attributes when choosing for a residential place at the municipality scale in Metropolitan France. Our study simultaneously includes three environmental risks: air pollution, flood risks, clay-swelling risks; and one environmental attribute: the presence of natural areas, which are particularly important to limit heatwaves issues. A major objective of the study is to examine the role of households' subjective consideration of environmental attributes and risks in the choice of a residence municipality. In order to explain housing choices and preferences at the individual level, we use discrete choice modelling (DCM) methods. We develop a multinomial logit (MNL) and a latent class (LC) model to explain the residential choices of 1,871 French households.

The chapter is organized as follows. Section 4.2 is a literature review on residential location choices and environmental risks and perceptions. Section 4.3 describes the case study and data. Section 4.4 presents the models and their specifications, while results are detailed in Section 4.5. Section 4.6 concludes, describes the limits of this work and gives some future research avenues.

4.2. Environmental attributes and risks in residential location choice models: a literature review

In this section, we outline the methods developed in the literature to study the effects of environmental risks and natural areas on residential choices. We also describe residential choices models and discrete choice models. Last, we briefly sum up the existing literature involving environmental attributes and risks in residential choice processes.

4.2.1. A variety of approaches and methods

A large amount of research has been carried out to evaluate the impact of environmental features on residential choices. The literature distinguishes different approaches that can be based on the observation of behaviors (revealed preferences) or through the analysis of declared preferences (stated preferences).

Most empirical studies use hedonic price modelling. This approach uses residents' actual choices to develop models based on revealed preferences. These methods have been particularly developed for evaluating the impacts of floods (Shultz and Fridgen, 2001; Eves, 2002; Bin and Kruse, 2006), air quality (Nelson, 1978; Chiarazzo et al. 2014), noise (Nelson, 1982; Fietelson, 1996; Lindgren, 2021), view (Baranzini & Schaerer, 2011) or green spaces (Panduro, 2013; Abildtrup et al. 2013; Tu et al., 2016; Trojanek, 2018; Piaggio, 2021) on housing prices. Most of these hedonic studies show the positive impacts of environmental amenities (such as natural areas) and the negative impacts of environmental risks (such as air pollution, noise) on housing prices.

Few applications of the hedonic price method integrate perceptions of the environment, except for Berezansky et al. (2010) and Chasco and Le Gallo (2013) who compare the influence of objective exposure indicators and perceptions related to air pollution and noise on real estate prices respectively in Haifa and Madrid, but at an aggregated level. Chasco and Le Gallo found a positive counterintuitive sign for the effect of objective measures of pollutants on housing prices, which gives the wrong impression that they are positive amenities, rather than negative ones. They therefore conclude that a model based on perceptions could outperform the models based on measures of objective attributes. In Haifa, results also showed that subjective evaluations of local air quality performed significantly better in explaining the variation of apartment prices than objective pollution indicators. These results are consistent with the findings Adamowicz et al. (1997) concerning recreational areas.

An alternative to this approach is to directly question households about their perceived personal preferences (stated preferences) to understand how environmental perceptions affect their residential choices (Palm, 1981; Burby et al., 1988; Adriaanse, 2007; Zrobek et al., 2015). To do so, they answer to a survey to collect detailed information about residents' knowledge and perceptions of environmental hazards. The advantage of this method relies on the possibility to integrate individual perceptions in the analysis. Yet, the validity of survey methods has been questioned, as the respondents' answers may not exactly correspond with their perception of hazards at the moment of the purchase of the home (W. Adamowicz, Louviere, & Williams, 1994).

4.2.2. Residential location choices models

The question of location choices was first addressed by urban microeconomics theories as a problem of utility maximization under budgetary constraints in a monocentric urban environment (Alonso, 1964). This standard model of urban microeconomics has given rise to several extensions by successively relaxing the initial assumptions. For instance, Anas (1990) relaxed Alonso's hypothesis on monocentric spatial organization, absence of amenities and unicity of the transport mode.

In parallel, Lowry (1964) developed operational models based on the spatial interaction approach to understand the links between location decisions and transport demand. In particular, this work includes two location models integrating spatial interaction: a residential model and a service location model. He considers that accessibility to employment (respectively accessibility to potential customers) is the only element that guides the residential choices.

These two approaches have their limits. The theoretical framework of urban microeconomics has reduced the household decision to a simple trade-off between property price and transport cost, while models based on the spatial interaction approach have focused on the principle of generalized accessibility to simulate residential location choices.

Discrete choice models (DCMs) propose a different theoretical framework, based on random utility, for more realistic empiric applications in the field of household location choices at the individual level. McFadden (1978) developed the first model of residential choices using a random utility approach, which makes it possible to overcome these complexities. The strength of these models is their ability to integrate other determinants of residential location choice, such as accessibility, preferences for spatial and social amenities or households' specificities (Pagliara, Preston, & Simmonds, 2010). They also make it possible to quantify the effect of different characteristics of the area of location, of the dwelling and their interactions with household characteristics. The random utility approach is nowadays the most appropriate solution to bridge the gap between the theory of urban economics and the operational tools of the spatial interaction approach.

If MNL models are the most popular in the literature, researchers also employed more flexible discrete choice models such as the mixed logit (Hoshino, 2011) and latent class models to estimate preference heterogeneity. In particular, latent class approaches (LCs), assuming a finite mixture of preference heterogeneity, have attracted greater attention in recent studies (Olaru et al., 2011; Rid and Profeta, 2011; Walker and Li, 2007; Liao et al., 2015). For instance, Olaru et al. (2011) evaluate to what extent households consider transit-oriented development characteristics in their location choices in Perth, Australia, while Walker and Li (2007) study how lifestyle influences residential location decisions in Portland, USA.

4.2.3. The integration of environmental risks and attributes in DCMs

Many residential location models based on DCMs actually integrate environmental attributes, with a particular focus on atmospheric pollution and open areas.

Air quality is one of the main environmental attributes studied to explain residential choices. In the US, several studies attempted to evaluate the willingness to pay (WTP) for a better air quality in thirteen

American metropolises with hedonic and discrete choice models (Palmquist and Israngkura, 1999; Chay and Greenstone, 2005). A stated preference ranking experiment, conducted in Santiago de Chile, showed that the WTP for reducing the amount of atmospheric pollution came out 60% higher than estimated in Edmonton, in Canada, where the PM₁₀ concentration is six times lower (Ortúzar & Rodríguez, 2002). More recently, a two-step residential location and transport choice model showed that a concern for air pollution exposure at the residential location tends to increase population dispersion to suburban areas, especially with access to public transport; whereas concern of exposure during the commute tends to concentrate population closer to the central business district (CBD) (Schindler, Wang, & Connors, 2021).

Green spaces and open areas have also been integrated to a significant part of the literature on residential choices. A study in Toronto developed a reference-dependent model for residential location choice, allowing to capture asymmetric responses toward gains and losses in making location choice decisions. Results showed that a loss aversion attitude is observed for the percentage of open areas (Habib & Miller, 2009), which is consistent with the results obtained in Seattle (Chen, Gong, & Paaswell, 2008). In the Netherlands, Zondag and Pieters (2005) used a nested logit to study the role of accessibility in residential choices and found that open areas always have a positive impact on residential utility while water amenities (proximity to a river, a lake) have a positive impact for employed persons in particular. These results were completed by a study that showed that highly educated singles value higher inner-city waterfront areas, while the natural living environment is more important to larger households, elderly people and double earners (Van Duijn and Rouwendal, 2013).

Over time, some studies attempted to explore the effects of a wide range of combined environmental attributes on residential choices. For instance, a recent choice experiment conducted in Beijing study the link between air quality and WTP for greenspaces. Results showed that respondents exposed to higher pollution levels have higher WTP for new neighborhood parks (Liu, Hanley, & Campbell, 2020). A study in the US uses stated and revealed preference data, separately and jointly, to examine housing choices in Fairfield. The MNL model includes structural, neighbor and environmental variables; more specifically rivers, forests, open fields, lakes, flooding risk and air quality. Air quality has no significant effect on choices due to minimally variations in the study area, but the risk of 100-year flooding negatively affected utilities (Earnhart, 2002). More recently, in France, Schaeffer et al. (2016) studied the metropolises of Grenoble and Marseille to explore natural amenity-driven segregation based on a MNL residential location choice model. They highlighted significant effects of natural amenities on location choices and showed that preferences for natural amenities systematically differ according to the household's size and socio-professional status. In particular, they found significant results related to environmental variables such as forests, green spaces, water amenities, mountains and coastal areas.

In this study, we use DCM methods to model residential choices at the individual level in order to better assess the determinants of residential choices in France. Yet, to our knowledge, all of the existing studies focus on residential choices within a city, urban area or region. In our case, we take a different perspective by looking at the choice of a municipality of residence at national level.

4.3. Models and methods

In this section, we present the general model formulation of DCMs, then detail the challenges related to the definition of the choice set and finally explain our models' specifications.

4.3.1. Model formulation

Choosing the most adapted model requires to find a balance between computational complexity and restrictions of the hypothesis (Aissaoui, 2016).

In discrete choice models in general, a household n chooses the alternative i , from a set of mutually exclusive alternatives I , which maximizes its utility function. The utility associated with a residential location U_{in} can be expressed as follows:

$$U_{in} = V_{in}(\mathbf{X}_{in}; \beta) + \gamma_n + \varepsilon_{in} \quad (1)$$

Where V_{in} is the deterministic part of the utility, \mathbf{X}_{in} is a vector of the explanatory variables associated with alternative i and individual n , β a set of parameters, γ_n is the individual fixed effect for respondent n and ε_{in} is the random error term associated to the utility, assumed to be independently, identically distributed (McFadden, 1974).

4.3.2. Choice set for the estimation problem

A major difficulty with residential location models is the large number of alternatives available (size of I_n). Indeed, in reality, households select one specific dwelling from a large number of houses and apartments in different municipalities. Yet, this large number of choices, combined with a large sample of respondents is not adapted to the discrete choice analysis. Therefore, the construction of a feasible choice set for the discrete choice analysis requires making some hypothesis in order to reduce the set to a relevant sample that might represent the actual set of choices. This step is particularly challenging because in reality, personal constraints (such as job or school proximity) may strongly modify the size of the set. Therefore, it is necessary to find a balance between households who may be very flexible and open to live in many different municipalities, and those who may restrict their research to a single municipality.

To reduce the size of possibilities, different methods consisting in defining a set of available choices have been developed. In particular McFadden (1978) provides a sampling rule to randomly select a small subset of the available alternatives for each household, which contains the actual choice and some others that were not selected (Chattopadhyay, 2000). Moreover, Zolfaghari et al. (2013) developed a method to form the set of location areas available to households, by considering a threshold of commuting distance and defining the set of choices based on areas that do not exceed this distance. The results showed that the estimation of a multinomial model with the alternatives formed using this new method is equivalent to the estimation of a MNL estimated with a random sample of alternatives.

In our empirical analysis, we attempt to explain residential choices at the municipality scale, which means that one alternative corresponds to one municipality. As we work on the French territory and considering the availability of data for each alternative, we have a global sample of 30,302 municipalities that could potentially be selected by each respondent. Working at the national scale is an originality of our work – as most other similar studies using discrete choice modelling focus on an urban area – but also a difficulty, as the study area is particularly heterogeneous.

Given the large size of the sample of alternatives (30,302 municipalities), there is a trade-off between the number of households, the size of the alternatives set and the number of explanatory variables that can be used for estimating the model. For this specific case, we define a set of 20 alternatives for each household, based on a criterion that considers the minimum distance to the actual choice. Therefore, each set is made up of the actual choice and the 19 closest other municipalities.

4.3.3. Model specifications

Within the choice set of a decision maker, values of these sociodemographic attributes are constant among different alternatives in the choice set. Variables describing alternative locations that are expected to have a similar influence on the utility of all types of households are entered with no interactions, whereas all household's characteristics included in the specification are entered only through interactions with characteristics of alternatives, as households' characteristics do not vary over alternatives. Therefore, "including a household characteristic individually would not allow the

maximum likelihood estimation algorithm to converge, since there is no way to estimate a parameter on a variable that is constant across all alternatives” (de Palma et al., 2007, p.217).

The deterministic part of the utility function for the residential location choice is defined the following way:

$$V_{in} = \sum \beta'_1 \mathbf{household}_n + \beta'_2 \mathbf{municipality}_i + \beta'_3 \mathbf{env}_n + \beta'_4 \mathbf{env}_{perc}_{in} \quad (2)$$

Where β_k are vectors of parameters, **household** is a vector of socio-demographic variables, **municipality** is a vector of variables related to the residential place, **env** is a vector made of variables related to environmental risks and attributes and **env_{perc}** is a vector which components are the product between effective environmental risks and environmental perceptions (defined in vector **perc**).

$$\mathbf{env}_{perc}_j = \mathbf{env}_j * \mathbf{perc}_j \quad (3)$$

\mathbf{X}_{in} defined in Equation (1) contains the vectors **household**, **municipality**, **env** and **env_perc**.

This definition of utility functions is particularly interesting to sum objective effects and perceived effects, and thus obtain an overall net effect associated for each environmental attribute and risk, given a considered level of the perception variable. Studying the net effect therefore requires fixing the perception parameter to a given level (between 0 and 1).

The net effect of environmental risks and attributes can be expressed as:

$$\text{net effect}_j = \mathbf{env}_j (\beta'_{3j} + \beta'_{4j} * \mathbf{perc}_j) \quad j \in \{1 \dots 4\} \quad (4)$$

Where \mathbf{env}_j corresponds to attribute j of the vector **env** and \mathbf{perc}_j to the corresponding perception j from vector **perc**.

a) *Multinomial logit (MNL) model*

In this chapter, we developed two different types of models. First, we tried to explain residential choices using a MNL model. The structure of this model is detailed in Figure 4.1. The detailed list of the variables used in this model is given in Table 4.4.

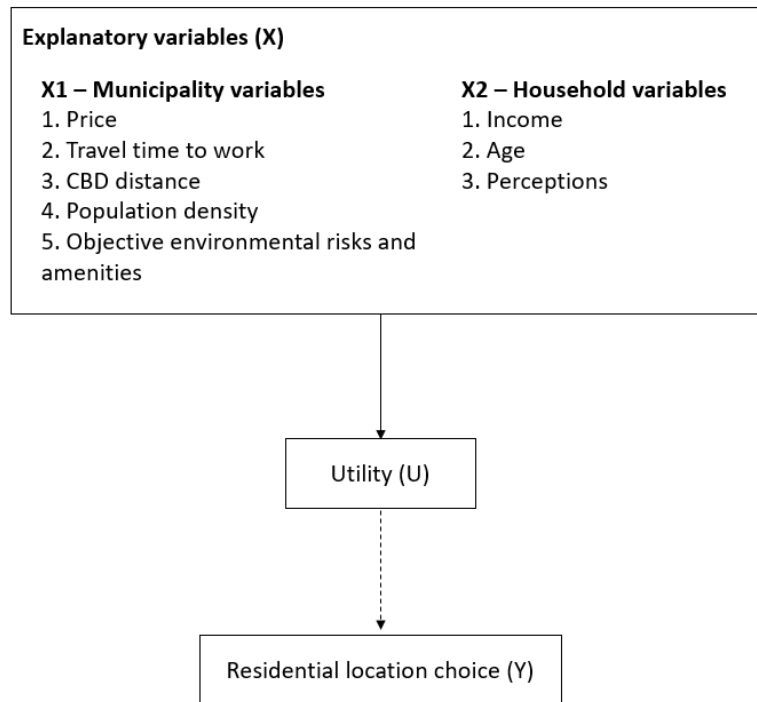


Figure 4.1 Structure of the MNL model (Source: Authors' own elaboration)

The probability P of choosing alternative i is (Train, 2009):

$$P(Y_n = i) = \frac{e^{U_{in}}}{\sum_{k \in I_n} e^{U_{kn}}} \quad (5)$$

where Y_n is the decision taken by individual n , U_{in} is the utility of individual n for choosing alternative i , and I_n the set of alternatives.

b) Latent class (LC) model

Second, considering that residential preferences are heterogeneous in nature, we developed a LC model. Through the application of discrete choice analysis, researchers have also employed rigorous modelling techniques, particularly LC analysis to estimate preference heterogeneity in residential choice behaviors. In particular, the LC analysis is a statistical procedure used to identify qualitatively different subgroups within populations who often share certain outward characteristics. LC models work on the assumption that the observed distribution of the variables is the result of a finite latent (unobserved) mixture of underlying distributions. In this model, the heterogeneity in sensitivities across individuals is measured by making use of separate classes with different values for the vector of taste coefficients β in each class.

First, an adequate number of classes has to be discussed in order to get relevant results. As we see in Table 4.1, the 3-class model outperforms all others according to the Akaike information criterion (AIC), but the 2-class model is preferable based on the Bayesian information criterion (BIC). We also determined that the 2-class model was most appropriate for further examination, based on its fit statistics, degree of interpretability and the size of classes. Indeed, the 3-classes model produces a class that is excessively small to be interpreted (associated to an allocation probability equals to 5.8%).

Table 4.1 Exploration of the adequate number of classes in the LC model

	No classes	2 classes	3 classes
Parameters	11	30	55
Log likelihood	-4663	-4555	-4527
AIC	9348	9162	9136
BIC	9407	9303	9357
Adjusted R2	0.0416	0.0607	0.0634

Then, LC models require estimating two different probabilities: first, the probability to be a part of a class, and second, the probability of choosing for each residential location. In our case, the latent class model structure is summed up in Figure 4.2.

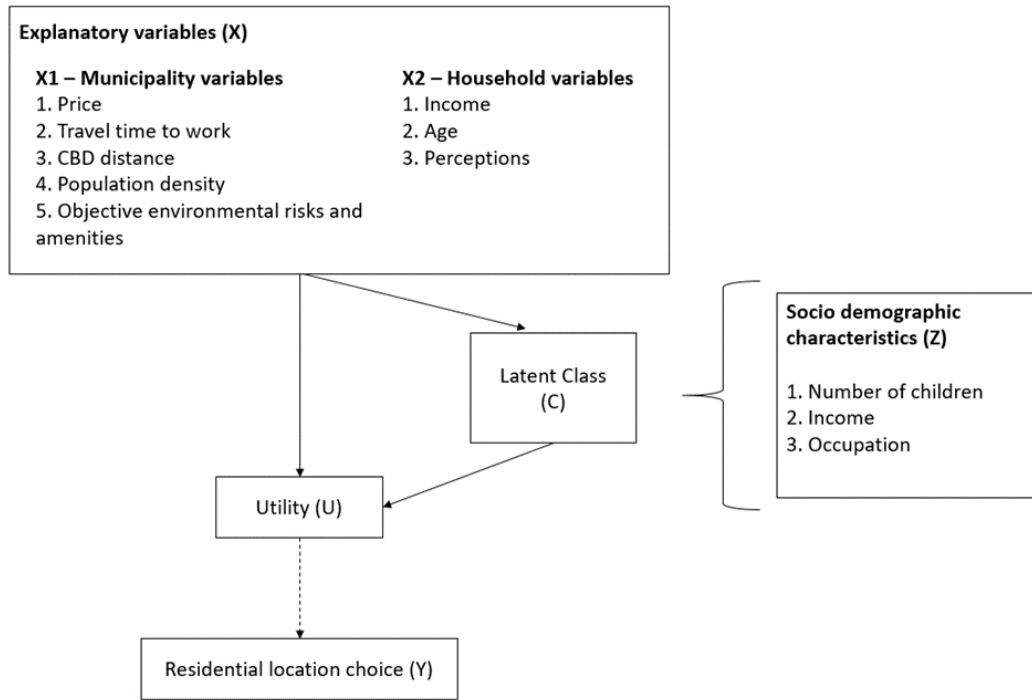


Figure 4.2 Structure of the LC model (Source: Authors' own elaboration, adapted from Liao et al. (2015))

To define the utility of belonging to a class, the literature shows that residential preferences are closely associated with individuals' demographic characteristics, such as educational attainment or income (Lewis & Baldassare, 2010) and important events in a life cycle, particularly childbirth (Chen and Lin, 2011; Smith and Olaru, 2013). We therefore based our class membership model on three binary socio-demographic variables: having children, having a job and earning a high income. These variables were chosen based on existing literature, but we also tested other variables such as density, low income or socio-professional category.

Utilities associated to belonging to class c are defined as:

$$\vartheta_c = K_c + \gamma'_{1c} \sigma_{working} + \gamma'_{2c} \sigma_{children} + \gamma'_{3c} \sigma_{high\ income} \quad (6)$$

With $c \in \{1;2\}$, K a constant, and γ a vector of parameters. The three σ variables are dummies. $\sigma_{working}$ equals to 1 if the respondent has a job, $\sigma_{children}$ equals to 1 if the respondent has children, and $\sigma_{high\ income}$ equals to 1 if the respondent has a monthly average income per consumption unit higher than 3000€.

The class membership of a household is unknown, but a probability can be estimated using observable household characteristics formed by a set of socio-demographic variables: The probability that respondent n belongs to class c . P_{nc} is also a general logit choice function of the form:

$$P_{nc} = \frac{e^{\theta_c z_n}}{\sum_{c \in \{1,2\}} e^{\theta_c z_c}} \quad (7)$$

where θ is a vector of parameters capturing the influence of the vector of individual characteristics z_n on the class allocation probabilities. In our case z corresponds to the following individual socio-demographic characteristics: $\sigma_{working}$, $\sigma_{children}$ and $\sigma_{high\ income}$.

The probability that the respondent n chooses alternative i from a choice-set I_n conditional on belonging to class c is:

$$P(Y_n = i)|_c = \frac{e^{U_{in}}}{\sum_{j \in J_n} e^{U_{jn}}} \quad (8)$$

The detailed list of the variables used in this model is given in Table 4.4. However, in the LC model, the household vector is limited to the tt_{job} variable and the municipality vector to the price and tt_{CBD} variables.

4.4. Case study and data

In this section, we detail the existing environmental risks and associated impacts in France. Then, we present the data collection used in this study.

4.4.1. Environmental risks in France: levels of exposure and health impacts

a) *Air quality*

Atmospheric pollution is a major public health problem: each year, exposure to ambient $PM_{2.5}$ causes approximately 4.2 million deaths worldwide, 467,000 in Europe and approximately 40,000 in France because of particles exposure (WHO, 2022). Indeed, particulate matter is particularly harmful to health. They cause irritation and respiratory problems in sensitive individuals, and are associated with increased mortality (respiratory ailments, cardiovascular disease, cancer...). In France, the cost of air pollution is estimated at 70 to 100 billion euros a year by the Senate's Commission (2015 report).

At the national level, different public policies have been implemented in order to improve air quality and aims to tackle pollution issues associated to road transport and wood heating, the main sources of PM emissions. These policies are most often the national transcription of European policies such as low-emission zones, classification of vehicles according to their emissions of atmospheric pollutants, subsidies for the installation of electric vehicle charging stations, bonuses for the purchase of electric vehicles or subsidies for the replacement of wood-burning appliances.

b) *Floods*

As a consequence of climate change, floods are expected to become more frequent all over the world (Jongman, Koks, Husby, & Ward, 2014). In France, 16.8 million permanent residents exposed to the various consequences of flooding from overflowing rivers (Ministère de l'écologie, 2023). Until now, more than 40% of the 36,500 French communes have been affected by floods (both coastal and river), and flooding is responsible for 80% of the damage attributable to French natural disasters (N. Pottier, Penning-Rowsell, Tunstall, & Hubert, 2005).

Floods can have human (danger of being swept away, drowned, electrocuted, injured), economic (many businesses are built in flood-prone areas) and environmental consequences, but they can also affect transport, energy and telecommunications networks. In this context, France has adopted a strategy that requires a proactive approach to flood prevention in all areas at risk. Thus, the Flood Risk Prevention Plan (*In French: Plan de Prévention des Risques d'inondation - PPRI*) maps the areas exposed to risks and regulates them according to hazards and land use.

c) Clay swelling

Clay soils can vary in volume because of changes in their water content, linked to weather conditions. They "shrink" during periods of drought and swell when the rain returns. These variations can reach an amplitude large enough to damage buildings located on these soils. Ground movements induced by clay shrinkage and swelling constitute a major risk as they affect buildings' structures. As a natural hazard of climate origin, climate change directly influences the phenomenon of clay swelling.

In France, the phenomenon of clay shrinkage and swelling has gained ground since it was highlighted during the exceptional drought during the summer of 1976. The latest national zoning of clay swelling shows that more than 10.4 million individual houses are potentially highly exposed to the phenomenon of clay soil shrinkage and swelling (RGA), half of which were built after 1976 (SDES, 2021). The 2018 law on the evolution of housing, development and digital (ELAN) changed the prevention of risks of land movement related to the shrinkage and swelling of clays during the construction of residential buildings.

d) Natural areas and urban heat islands (UHIs)

The presence of natural areas in the neighborhood, such as parks and public gardens that are easily accessible, is constantly mentioned among the required criteria for a good quality of life (Boutefeu, 2007). The importance of accessing natural areas has been particularly important during the COVID-19 pandemic. Indeed, the Urban Green Spaces Taskforce (2002) recommends that a natural green space of at least 2ha in size should be available within 300m of a residential location. The distance of one kilometer is also often used to evaluate access to green spaces, as it corresponds to a distance people are willing to walk to reach a nearby destination (Dygryn et al., 2010; Troped et al., 2010).

In France, 38.0% of the territory are covered by natural areas, including 28.6% by forests. These natural spaces play an essential role in regulating heat and noise, improving air quality, contributing to the well-being of residents and fostering the development of biodiversity (Yusof & Johari, 2013). Taking into account natural areas in such study about environmental risks is therefore particularly relevant as they constitute a mitigation tool to limit the intensity of heatwaves or UHIs (see Shishegar (2014) for a review).

4.4.2. Data collection

Our study is based on different data sources: the PERL survey gives information on environmental perceptions, while other datasets have been used for objective exposure indicators and control variables.

1.1.1. The PERL survey

The dataset analyzed in this chapter is based on the results of the PERL (Environmental Perceptions related to Residential Location) survey. This questionnaire aims to assess respondents' perceptions related to different environmental risks and attributes, but also to characterize their current residential location and socio-demographic attributes. It was designed to be completed in 15 to 20 minutes. The main constraint of this survey is that we were limited to data collection at the municipality level, due to confidentiality issues. Indeed, it would have taken much longer to obtain the General Data Protection Regulation authorization to request addresses and would have been difficult and costly to obtain a

sufficiently large sample given the reservations respondents may have about giving out their personal addresses.

We launched two waves of data collection, employing two different strategies to recruit respondents. First, we collaborated with Meilleurs Agents²⁵, an online French platform offering services for selling, buying or renting houses or apartments. They selected more than 160,000 households that consulted the platform for their home-buying or renting projects in the last 24 months and sent them an invitation to fill in the questionnaire. Participants were surveyed by email, from January to March 2023. 406 complete answers were collected. As we considered that the sample size was too small for the analysis, we completed the sampling with an email recruitment conducted by a polling organization, with the quotas method based on the 2022 French population by regions to complete the answers collected with Meilleurs Agents. This second method allowed collecting 1,465 complete answers from March to April 2023.

The questionnaire is structured in five categories (see Appendix D.1).

Firstly, we asked questions about the characteristics of the property, such as occupancy status, floor area, soil, purchase or rental price, heating system, number of rooms, and whether it has a garden, terrace, swimming pool, car park and garage. We also asked for the criteria that led to the choice of this residential location (general criteria and environmental criteria).

Second, psychometric indicators related to environmental perceptions were assessed for the six studied attributes: air pollution, noise, flooding, shrinkage and swelling of clays, UHIs and access to natural areas. For each environmental risk, we tried to follow the same logic by defining similar affirmations as detailed in Table 4.2, while natural areas were associated to different affirmations.

Table 4.2 Survey affirmations associated to environmental perceptions

Variable	Goal	Survey affirmation
A	Consideration	When choosing for my residential place, I paid attention to <i>[environmental risk or attribute]</i> in my neighborhood
B	Exposure	I think I am exposed to <i>[risk]</i> in and/or around my dwelling
C	Concerned	I feel concerned by <i>[risk]</i> issues in my neighborhood
D	Worry	I think that <i>[risk]</i> constitutes a risk to my health / I am worried about the risk
E	Feeling	Since I have been living in this dwelling, I have already felt the effects of / being exposed to <i>[risk]</i>

We started by asking if they consider they are currently affected by the phenomena (affirmation A), and if they believed that they would be affected when choosing this home (affirmation B). Then, we asked questions about the knowledge, the importance, the risks sources and the previous experiences of these risks (having already been affected in the past, for instance). This part also includes 5-levels Likert scale questions to assess individual attitudes and perceptions (see Appendix D.2).

²⁵ See <https://www.meilleursagents.com/>

Third, we asked for the current and previous residential location address (municipality and postal code), as well as the move-in date. We also invited respondents to mention their current housing projects (planning to move, when, and where) for future studies.

Fourth, the socio-demographic questions concern gender, age, household size, family composition, income level, education level, occupation, job characteristics, job location and personal assessment of health. For comparability purposes and to make the reading of the results easier, we created categories for some of these variables.

Fifth, the sensitivity to environmental issues was evaluated with different questions about general concerns, most important society subjects, fears of climate change impacts on well-being and environmental sensitivity based on a reduced NEP (New Environmental Paradigm) scale (Dunlap et al., 2000).

The final sample is composed of 1,871 complete observations described in Table 4.3.

Table 4.3 Sample characteristics

<i>Observations: 1,871</i>		Share (%)
Gender	Male	54.0
	Female	46.0
Age	18 to 24	1.0
	25 to 44	18.2
	45 to 64	45.7
	65 or older	35.1
Household size	1	22.4
	2	47.6
	3	15.7
	4 or more	14.3
Income per uc ²⁶ (€)	1000 or less	5.6
	1001 – 1500	12.8
	1501 – 2000	20.1
	2001 – 3000	33.5
	3001 – 4000	19.2
	4001 or more	8.8
Tenure status	Owner	76.4
	Renter	19.8
	Other	3.8
Duration	0 to 5 years	25.6
	6 to 10 years	14.2
	11 to 20 years	20.9
	21 to 30 years	20.6
	More than 30 years	18.7
Dwelling type	Apartment	33.1
	House	66.9
Occupation	Farmer	0.4
	Craftsman or Shopkeeper	5.0
	Executives and higher intellectual profession	25.4
	Intermediate profession	7.7
	Employee	13.9

²⁶ The income per consumption unit (or standard of living) is equal to the disposable income of the household divided by the number of consumption units (uc). The number of uc 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, 2019).

Table 4.3 shows that more than a third of our respondent is aged of more than 65 years old, meaning that many respondents are retired. 25.4% of the respondents are executives, which is significantly higher than in the general population (19.0%). 76.4% of our sample is made of owners (while they actually represented 64% of the population in France in 2020). The distribution of respondents within the sample is representative of the regional distribution of the metropolitan population (see Appendix D.3).

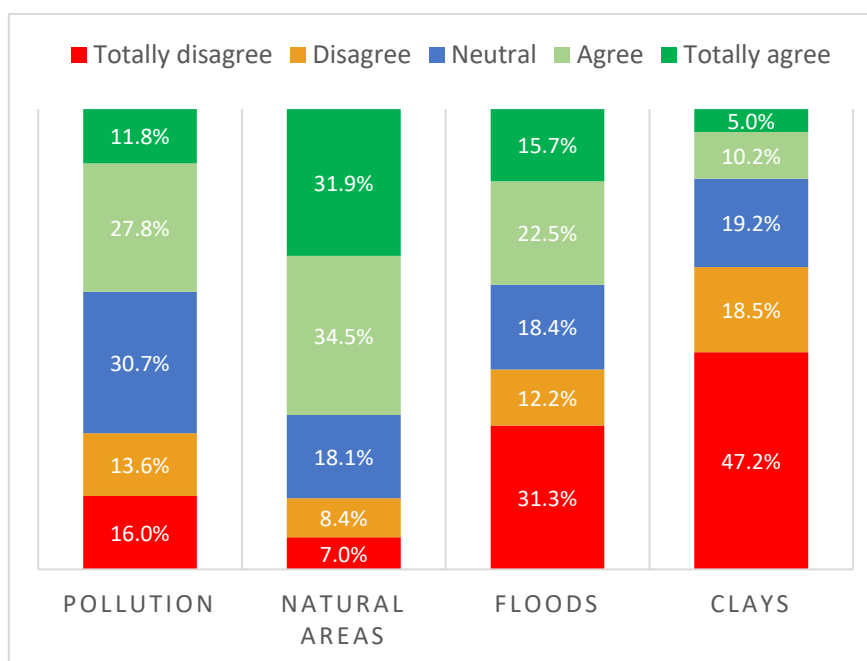


Figure 4.3 – Descriptive statistics associated to affirmation A (When choosing for my residential place, I paid attention to [environmental risk or attribute] in my neighborhood) for each environmental feature

In this study, we mainly used affirmation A that reflects the fact that an environmental attribute or risk was taken into account when choosing for the given residential place. This variable is coded as a scale variable based on the answer obtained to the 5 Likert-scale affirmation and takes the values of 0 if the risk was absolutely not considered when choosing the residential location (totally disagree), 0.25 (disagree), 0.5 (neutral), 0.75 (agree) or 1 (totally agree)²⁷. Descriptive statistics associated to affirmation A are provided in Figure 4.3. We observe that natural areas are very often considered when choosing a residential place (66.4% of the respondents), while clay swelling risks are considered by only 15.2% of our respondents. Pollution risks and flood risks are respectively considered by 39.6% and 38.2% of the respondents. Descriptive statistics associated to other affirmations are detailed in Appendix D.4.

1.1.2. Objective exposure indicators

Due to the limited availability of objective exposure indicators, our analysis had to be restricted to four main environmental risks and attributes. Indeed, noise and UHIs objective exposure indicators were not available for all the French territory. Moreover, as most of the data was only available at the municipality

²⁷ We tested different coding methods to integrate this variable, such as between -1 and +1 or -2 and +2, in 5 points or 3 points. The selected definition was the most significant in all models.

scale, our analysis had to be limited to this level. Therefore, we calculated four objective exposure indicators for environmental attributes and risks at the municipality level:

- Air pollution is approximated by the particulate matter (PM_{2.5}) concentrations (in µg/m³), which are considered the best proxy for the “ideal” measure of air pollution exposure (OECD, 2011). The mean annual level of PM_{2.5} exposure is available at the municipality scale (INERIS, 2021) and provides a direct estimate of air quality based on the reported value.
- Flood risks²⁸ are described in the Territoires à Risques important d'Inondation (TRI) data (GeoRisques, 2020). This database is used to calculate the share of population subject to a medium risk of flooding (100-year flood) in a given municipality. The variable therefore takes a value between 0 and 1.
- Natural areas have been explored on the most recent CORINE Land Cover data (2018), which provides surfaces of different land use types such as forests, natural fields, agricultural areas, but also artificialized areas. The variable takes a value between 0 and 1 that corresponds to the share of the municipality surface covered by natural areas.
- Clay swelling risks⁴ have been estimated from the GeoRisques data (2021). First, we estimated which share of the population would be affected by a high, medium or low risk at the municipality level. Then, we created a variable that indicates the risk level of the municipality based on the number of inhabitants exposed to a level of risk. The variables take a value between 0 and 1 that corresponds the weighted share of the municipality inhabitants respectively affected by a low, medium or high risk as defined in Equation 11.

$$clay_{risk} = (1 * high_{risk} + 0.5 * medium_{risk} + 0.1 * low_{risk}) \quad (11)$$

1.1.3. Control variables

Control variables have been selected based on the existing literature. In particular, the main identified control variables to elaborate a residential choice models are housing prices, distance to CBD and commuting time (e.g. Guo and Bhat, 2007; Habib and Miller, 2009; Zolfaghari et al., 2012). Several studies used income groups as explaining variable in their residential location choice models, and proved it significant (Weisbrod et al., 1980; de Palma et al., 2007). A limited number of studies includes households' previous location and showed that households tend to stay in the same city or even district (e.g. Axhausen et al., 2004; Zondag and Pieters, 2005; de Palma et al., 2007). Then, population density is an attribute used in most residential choice models.

The following control variables are used in the model:

- Housing prices are proxied by mean prices based on housing sales in each municipality. The geolocated DVF (Demande de Valeur Foncière, 2019) database, published by the French government, give information on real estate sales. It provides the average Price per Square Meter in almost all French municipalities (where at least five transactions were done) except some located in Moselle, Lorraine and Alsace.
- Commuting time (tt_{job}) is a major driver of location choice (Schirmer et al., 2014). The PERL survey provides information on the municipality of residence and of work, which allows us to calculate distances between the different municipalities and the workplaces.

²⁸ Flood and clay swelling risks were calculated for all French municipalities and are now available at <https://doi.org/10.57745/W9N5Z9>

- The average travel time to the main urban centers (tt_{CBD}) have been calculated using the data and methodology from Hilal et al., 2020²⁹.
- Average income by consumption unit at the municipal level proxies for the socio-economic level of the population (socio-eco level), based on the Filosofi data (2022) that provides the median annual income at the municipality level.
- The migration cost, estimated as the distance between current and previous residential place, has been easily computed for all available alternatives since the previous municipality of residence was collected in the PERL survey.
- Other control variables, such as population density and housing stocks, have been calculated using the last population census (INSEE, 2019) at the municipality level.

Basic descriptive statistics of all the previously defined variables are provided in Table 4.4.

²⁹ The data is available at: https://hal.archives-ouvertes.fr/hal-03064655/file/202009_Data_EtudesCentralit%C3%A9s_INRAE_ANCT.xlsx"

Table 4.4 Variables used in the utility functions

Note to the reader: these statistics are calculated for a sample of 30,302 municipalities for which we have complete information. Travel times equal to 0 reflect that the two places are located in the same municipality.

	Variable	Description	Min	1 st qu	Median	Mean	3 rd qu	Max
<i>household</i>	age (years)	Age of the respondent	19	49	60	58	68	91
	income (€/month)	Declared income per consumption unit	314	1,674	2,270	2,204	3,048	7,989
	migration cost (km)	Distance between the current and previous residential loc.	0	0	9	112	98	1,279
	tt_{job} (min)	Travel time to workplace	0	0	5	18	9	110
	duration (years)	Length of residence in the dwelling	0	4	14	17	26	74
<i>municipality</i>	price (€/m ²)	Housing price per m ²	300	1,104	1,453	1,467	1,927	11,965
	tt_{CBD} (min)	Travel time to main urban center	1	25	34	32	44	137
	density (pop/km ²)	Population density of the municipality	0.88	23	47	207	108	27,419
	socio-eco level (€/year)	Average income (as a proxy for the socio-economic level)	11,780	20,570	21,990	22,428	23,790	51,340
	housing stock	Number of available dwellings in the municipality	33	157	306	380	715	1,389,375
<i>env</i>	PM2.5 _{avg} (µg/m ³)	Objective average pollution level	6.3	8.5	9.1	9.2	9.8	12.4
	flood _{risk} (%)	Objective 100-years flood risks	0	0	0	0.08	0.05	1
	natural areas (%)	Calculated share of natural areas	0	0.54	0.83	0.72	0.95	1
	clay _{risk} (%)	Objective clay risks	0	0.17	0.43	0.43	0.65	1
<i>perc</i>	$\delta_{pollution}$	Consideration of air pollution	0	0.25	0.50	0.53	0.75	1
	δ_{flood}	Consideration of flood risks	0	0	0.50	0.47	0.75	1
	$\delta_{natural\ areas}$	Consideration of natural areas	0	0.50	0.75	0.70	1	1
	δ_{clay}	Consideration of clay risks	0	0	0.25	0.28	0.50	1

4.5. Results

We estimated two models: MNL and LC, using the maximum likelihood estimation technique with the R package Apollo (Hess & Palma, 2019). Estimation results are detailed in Table 4.5.

With a pseudo-R2 (McFadden's likelihood ratio index) of 8.18%, the MNL model has a low explanatory power at the individual level. To obtain this pseudo-R2, we had to add many control variables to ensure the validity of our model. However, these variables tend to hide the small effect of subjective environmental variables. Therefore, we decided to use a LC model to better capture a possible heterogeneity, and increase the explanatory power without erasing the effect of environmental attributes and risks.

In the LC model, we reduced the control variables to the bare minimum in order to avoid erasing the subjective environmental effects on utilities. The adjusted R2 associated to the LC model is equal to 6.1%, which is still low but much higher than what was obtained with the MNL model using the same number of control variables (1.9%).

Table 4.5 Estimation results for MNL and LC models

	MNL model		LC model – Class 1		LC model – Class 2	
	Coef	t-stat	Coef	t-stat	Coef	t-stat
Residential choice model						
log(price)	-3.541*	-1.78	0.613***	4.58	-4.259***	-2.59
log(price) * (age-18)/10	-0.163*	-1.75				
log(price) * log (income)	0.598***	2.17				
density	-0.019	-0.93				
log(tt_{CBD})	-0.146***	-2.46	-0.284***	-4.95	5.774***	2.76
migration cost	-0.105***	-16.25				
tt_{job}	-0.156***	-13.06	-0.087***	-12.93	-24.500***	-3.22
socio-eco level	0.529***	5.16				
log(housing stock)	0.069*	1.87				
PM2.5 _{avg}	-0.259	-0.84	-0.684***	-2.68	23.540***	4.41
flood _{risk}	-0.665***	-2.03	-0.602***	-2.04	-2.024	-0.77
natural areas	1.035***	2.36	0.996***	2.27	-39.220***	-2.71
natural areas * density	0.361***	3.35				
clay _{risk}	-0.258***	-2.10	-0.170	-0.71	-7.98*	-1.65
PM2.5 _{avg} * $\delta_{pollution}$	-0.044	-0.12	0.310	0.80	-24.489***	-2.60
flood _{risk} * δ_{flood}	0.912***	2.24	0.971***	2.20	-2.207	-0.45
natural areas * $\delta_{natural\ areas}$	-0.419	-0.86	-0.577	-1.04	36.712***	2.17
clay _{risk} * δ_{clay}	0.165	0.83	0.564	1.04	-29.899*	-1.82
log(price) * $\delta_{pollution}$	0.567	1.29				
log(price) * δ_{flood}	0.311	0.84				
log(price) * $\delta_{natural\ areas}$	-0.791*	-1.74				
log(price) * δ_{clay}	-0.223	-0.54				
PM2.5 _{avg} * duration/10	-0.071	-0.78				
flood _{risk} * duration/10	0.007	0.07				
natural areas * duration/10	-0.222**	-1.97				
clay _{risk} * duration/10	-0.003	-0.08				
Class membership model						
K			2.535***	10.15		
σ_{worker}			-1.707***	-6.23		
$\sigma_{children}$			1.055***	3.79		
$\sigma_{high\ income}$			0.462***	1.91		
Class allocation probability			0.857		0.143	

* Significant at the 10% level.

** Significant at the 5% level.

*** Significant at the 1% level.

Net effects of environmental risks and attributes should be assessed analyzing the cumulative effect of the objective and perceived effects. Indeed, assessing the net effect associated with each environmental risk and attribute allows understanding the global and combined role of actual exposure and the associated perception. These net effects could be distinguished according to the perceptions levels. As we are interested on the effect of perceptions on residential choices, this section focuses on the analysis of the effect of environmental risks and attributes on residential choices when totally considered by the respondent (i.e. $perc_j = 1$) in Equation (4). In this case, the net effect corresponds to the global effect related to the combination of objective exposure indicators and perceptions.

4.5.1. Overall evaluation of preferences using a MNL model

The first model assesses the extent to which households take into account environmental risks and attributes when choosing a residential place. The variables used in the definition of Equation (2) for this model are listed in Table 4.4.

a) Socio-demographic variables and municipality description

As expected, price has a negative effect on utilities. Price effect increases with the age of the household referent and decreases as the household income increases. Older households are more price-sensitive and wealthier households less so. The average price effect as well as the age and income interactions all have expected signs (de Palma et al., 2007). Since price is entered using three variables to capture average effects as well as interactions with age and income, the combined effects are complex. However, for a small subset of the population (very young and wealthy respondents) the net price effect shows a positive preference for higher prices according to the interaction of these three coefficients. This is likely be due to some amenities that are not included in the model, rather than an actual preference for a higher price.

The effect of density on preferences is unclear and insignificant, which is relevant considering that our study focuses on a whole country, meaning that some people will prefer to live in dense areas while others will prefer more rural municipalities. Moreover, the model reveals that an increase of the average travel time by car to CBD also decreases the preference of households for a municipality. The coefficient corresponding to the travel time to the workplace has the same effect. We also observe a significant migration cost effect, which reveals that households prefer to move close to their previous location. Moreover, they tend to choose municipalities with higher socio-economic level and important housing stocks.

b) Impacts of environmental perceptions on preferences

We observe that, when considered by the respondent, environmental risks and natural areas affect the residential choice through three channels:

First, if objective flood risk negatively influences preferences, considering this risk at the moment of the choice increases the likelihood of choosing a municipality which is exposed ($-0.665+0.912 = 0.247$). This result is counter intuitive. However, one explanation could be that people who took into account this risk is the one that had access to this information precisely because there is a risk in the considered municipality. It is because there is a risk in the municipality, they have chosen that they pay attention to it, not because they have paid attention to it that they have avoided this risk.

Second, taking into account the presence of natural areas when choosing for a residential place tends to reinforce the decreasing effect of price on preferences. Indeed, in this context, the natural areas variable represents the share of the municipality covered by natural areas. Therefore, a municipality with many forests and/or natural fields may have fewer services, jobs or other uncaptured features that may conduct to this observed effect.

Third, the longer the household stays in the municipality, the less they tend to value natural areas, decreasing the positive effect initially observed. This could mean that people tend to value these natural amenities at the moment of the choice, but the positive effect is limited over time, as people get used to live in the considered municipality. This result is confirmed by a recent study conducted in European cities that shows that green spaces are a determinant of residential choices for new residents, while longtime residents need an improvement (a variation) in green spaces availability to be satisfied (Chapel & Legras, 2023).

Globally, the integration of environmental perceptions in the MNL model gives few insights, which may reflect whether that only a small share of the population takes these attributes and risks into account or that preference is heterogeneous among the population. This is why we focus on the exploration of the LC model results.

4.5.2. Identification of heterogeneous preferences using a LC model

Considering the class membership model, we observe that households' socio-demographic characteristics are associated with preference heterogeneity. In particular, class 1 refers to families with more children younger than 18 years old and more high-income respondents. Class 2 contains more households that are inactive (in particular, retired). The only point of vigilance that we want to underline here is that the probability of belonging to class 2 is almost equal to 15%, which is low compared to class 1 (see Table 4.5).

a) Socio-demographic variables and municipality description

Results of the LC model reveal that prices have a slightly positive impact on class 1 households' preferences, while they have as strong negative impacts on class 2. This appears to be consistent with the fact that class 1 is composed of more high-income households. Moreover, class 1 tends to value the proximity to major urban centers (distance to CBD has a negative impact on their utilities), while class 2 prefers being out of urban centers (distance to CBD has a positive impact on their utilities). Then, preferences of both classes are negatively affected by the working distance, as expected.

b) Impacts of environmental perceptions on preferences

Each environmental perception is significant for only one of the two classes in the LC model: flood risks are significant for class 1 while air pollution, natural areas and clay swelling risks are significant for class 2. The facts that class 2 is associated to more significant perceptions and that the probability to belong to this class is equal to 14.3% appear to be in line with our previous hypothesis, as we assumed that only a limited share of the population actually took into account environmental risks and natural areas for their residential choices.

Table 4.6 sums up the net effects associating a high consideration of environmental risks and attributes (i.e. $perc_j = 1$).

Table 4.6 Summary of the cumulated effects of environmental attributes and risks in the LC model when $perc = 1$

Note to the reader: Obj = objective effect; Perc = perceived effect; Net = net effect

		Class 1	Effect on utility	Class 2	Effect on utility
Air pollution	Obj	-0.684***		23.540***	
	Perc	0.310		-24.489***	
	Net	-0.374*	Negative, significant	-0.949**	Negative, significant
Flood risk	Obj	-0.602***		-2.024	
	Perc	0.971***		-2.207	
	Net	0.369*	Positive, significant	-4.231	Negative, insignificant
Natural areas	Obj	0.996***		-39.220***	
	Perc	-0.577		36.712***	
	Net	0.419	Positive, insignificant	-2.508*	Negative, significant
Clay swelling risk	Obj	-0.170		-7.98*	
	Perc	0.564		-29.899*	
	Net	0.394	Positive, insignificant	-37.879*	Negative, significant

The net effect of air pollution is negative and significant for both classes, with a slightly more important effect on class 2. This result reflects that households globally tend to choose less polluted municipalities for their residential places. As class 2 is made of low-income and retired households, we may assume that these households tend to live in peripheries of urban centers, which corresponds in theory to less-polluted municipalities.

If flood risks objective exposure has a negative impact for both classes, the cumulated effect becomes positive and significant for class 1. For class 1, which is made of high-income working families, the perceived effect is significant and reverses the negative effect of actual exposure. This means that households that considered flood risks when choosing for their residential location tended to finally choose a municipality where they are more likely to be exposed. As underlined earlier, people who consider these risks may do so because they already know that they want to settle in municipalities at risk, and knowing that there is a risk does not change their minds. This result raises the question of the efficiency of the public information provided and the public awareness of flood risks.

A similar result is observed for clay swelling risks for class 2. Clay risks have a strong significant and negative impact on utilities for class 2 residents, meaning that taking into account clay risks when choosing for the residential location considerably decreases the probability of choosing a municipality that is affected. Therefore, this means that retired, low-income households tend to particularly consider these risks when choosing for their residential place.

Natural areas have a negative and significant impact on class 2 respondents' utilities. This means that retired, low-income households prefer municipalities with limited natural spaces, or said differently, they tend to devalue less compact municipalities with fewer services and opportunities. By analyzing this result in relation to the distance to the CBD, we understand that class 1 households prefer to live close or in a large urban center and therefore value more the natural areas that may be scarce in these municipalities, while class 2 households prefer to live further away from the urban center but not in rural municipalities. These results therefore appear to be consistent with the MNL model.

If our results are not fully operable given the limited explanatory power of estimates, this work shows the relevance of studying different risks and environmental attributes at the same time, in particular in a context of climate change adaptation. Future analysis could be based on the use of different types of models, such as for instance the mixed multinomial logit, introduced by Boyd and Mellman (1980) and Cardell and Dunbar (1980), and defined as a MNL model with random coefficients (McFadden & Train, 2000). These models would be particularly useful to explain the existing heterogeneity among classes. Moreover, interactions could be envisaged between some environmental features that often influence each other as observed in other existing studies, such as air pollution and green spaces (e.g. Liu et al., 2020). It would be particularly interesting to characterize these interactions in order to take into account the potential compensability between high levels of air pollution and benefits from greenspaces, for instance.

These findings show the existing heterogeneous preferences for environmental risks and attributes in different subgroups of the population.

4.6. Discussion and conclusion

In this chapter, we investigate to what extent actual exposures influence residential choices and to what extent individuals take into account the perceived environmental risks and attributes when choosing where to live. To do so, we used an original dataset made of 1,871 households surveyed in 2023 in France and we developed two different discrete choices models. The originalities of this work rely on the simultaneous study of several environmental risks and natural areas, and the scale of the analysis that includes a whole country, while other studies often focus on an urban area.

This work gives insights on the importance of environmental features for residential choices. Indeed, the MNL model shows that actual environmental risks and attributes influence residential choices. In particular, environmental risks such as flood risks and clay risks have negative significant effects on preferences while natural areas are globally positively evaluated, which is in line with the existing results

in the literature. Therefore, this work shows that actual exposures have an influence on households' preferences. The MNL model gives few significant insights related to environmental perceptions, which reveals the necessity to introduce heterogeneity in our study. In this sense, we assumed that residents have a heterogeneous vision of environmental risks and natural areas and take them into account differently. We therefore try to model it using a LC model.

The LC model confirms that respondents have heterogeneous ways to consider environmental risks and natural areas for residential choices. When considering perceptions, results show that all residents tend to choose a municipality that is less exposed to air pollution. At the same time, a small share of the population, mostly composed of retired households, appears to prefer municipalities with limited natural areas and less clay swelling risks. Thus, studying together both objective and subjective effects of environmental risks appears to be particularly relevant to fully understanding residential choices.

We observe that considering the combined effects of risks and positive attributes such as natural areas is particularly relevant in a context of adaptation to climate change. Indeed, air pollution appears to have a negative impact on utilities while natural areas have a positive impact for high-income working families. In this sense, this gives an important key on how valuating access to natural areas can be particularly relevant to compensate for environmental risks and limit the climate change impacts at the local level.

If this work offers preliminary results that open interesting research avenues, the realization of this study has been limited to data-related difficulties that are worth mentioning, as they can offer useful insights for futures studies of this kind.

First, getting access to actual measures about environmental attributes and risks at the local level is an important challenge. At first, we wanted to integrate noise pollution and urban heat islands (UHIs) in the study. However, actual noise levels at the national level were only available for roads, and some metropolises did not even have any noise map. UHIs have been mapped in the MApUCE project³⁰ (coordinated by J. Hidalgo, Laboratoire Interdisciplinaire Solidarités Sociétés Territoires - LISST) but some important metropolises - such as Aix-Marseille - have been excluded from the analysis.

Second, given the available data, we explored the possibility of defining objective variables in different ways. For instance, we tried to define the clay swelling risks as a dummy variable or a share of the population affected by different levels of risk. For natural areas, we tried to define the variable using only the forests surface or to add a "green spaces" variable using the parks surface as defined in the Corine Land Cover database. In the end, the definition of these variables remains complicated and not fully adapted. For instance, what is important for a household is not necessarily the surface of natural areas in his municipality but above all the proximity between these natural areas and their dwelling.

Third, the psychometrics indicators we used in order to capture respondents' perceptions are limited. In this work, we tried to explore the use of another psychometric indicator related to the 5-level Likert scale affirmation: "I think that my home is exposed to [risk]" in the MNL model.

As explained earlier, the MNL model gave few interesting insights related to subjective features, and when integrating this psychometric indicator to the LC model, results were unsuccessful. The only significant insights we obtained from the MNL model is that the feeling of being exposed to air pollution tends to decrease the preference for the municipality. This observation shows the existing mismatching between objective and subjective exposure to air pollution, which has already been observed in other contexts and at different scales (Chasco and Le Gallo, 2013; Chiarini et al., 2021; Shi et al., 2022). On the contrary, the feeling of being exposed to clay swelling risks increases the likelihood of living in a municipality affected by clay swelling. The subjective perception even almost cancels the negative effect

³⁰ See <https://www.umr-cnrm.fr/ville.climat/spip.php?rubrique120> for more information on the project UHI maps are available at <https://github.com/orbisgis/mapuce.orbisgis.org/tree/gh-pages/data/icu>

observed with the exposure indicator. Given the few research on the topic of clay swelling risks, it appears relevant that residents that feel exposed have indeed chosen a municipality that is actually exposed. All the results related to the use of this affirmation in the MNL model are detailed in Appendix D.5. For now, the other psychometric indicators related to the worry or effects on health have not been explored yet.

Forth, the data we have collected has a number of limitations. The first relates to the geographical level (municipal scale), which has been restricted for reasons of confidentiality. It would have taken much longer (given the time constraints of the thesis) to obtain General Data Protection Regulation authorization to deploy a survey in which respondents' addresses were requested and would have been difficult and costly to obtain a sufficiently large sample given the reservations respondents may have about giving out their personal addresses. Therefore, this has considerably restricted our explanatory potential. Indeed, rather than being able to choose between a set of streets or neighborhoods, our respondents expressed their preferences at the scale of a municipality. However, these municipalities can be very different; in particular for big cities that are often heterogeneous (e.g. Paris has more than 2 million inhabitants, while other rural municipalities have less than 500 inhabitants) and exposure to environmental risks also varies among the cities.

Moreover, another limit of the data we collected relies on the fact that respondents may have lived in their current residential place for a long time. Therefore, their perceptions may have changed over time, and environmental risks evolved too. In some cases, respondents also indicated that they had not been in a position to choose their place of residence (in the case of legacy, for instance). Ideally, it would therefore be necessary to collect data from respondents that chose their residential location for less than a year. If we explored this idea at first, it was too complicated – given time and money constraints – to get a sufficient sample size.

Fifth, this work makes it possible to formulate methodological recommendations for tackling the issue of the impact of environmental perceptions and exposure on residential location choices: such an analysis should be carried out at the level of an urban area or a region. Indeed, the diversity of residential locations in a country complicates the analysis process. On the one hand, the challenge is to define the size of the appropriate set of alternatives. In rural areas, the ideal set of alternatives might be equal to 20 or even 30 municipalities, while in metropolises, it should be reduced to 1 to 5 (for instance, in Paris, some people only search for a new residential location only in Paris, which is already a huge research area). On the other hand, when searching for significant control variables, working at the scale of the country is once again more complicated. As the set size is already not adapted for all respondents, some control variables appear not to be significant for a share of the population. Taking again an example, the price variable may appear to have a positive impact on utility for those who want to live in the urban core, while this same variable has negative impacts for respondents in rural areas.

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General conclusion

1. Main results

This thesis contributes to a better understanding of residential and mobility choices through the prism of existing vulnerabilities by considering the impacts of individual perceptions and environmental policies. These results are particularly important in the current ecological transition context, given the social issues raised by the ecological transition policies, made essential by the negative effects of motorized transport modes on health and the extension of distances caused by the suburbanization process. In particular, this thesis answers the following question: How do public policies and individual perceptions influence mobility and housing decisions, and subsequent vulnerabilities?

We answer this question with two case studies: France, and more specifically Grenoble, and Chile with a focus on Santiago de Chile, two cities surrounded by mountains ranges. On the one hand, Grenoble constituted a relevant study area as the city is affected by high level of pollutants despite a strong willingness to develop active mobility and to ensure environmental and social equity at the city level. On the other hand, Chile is in the throes of change, characterized by policy makers defending an idea of social and environmental justice at the national level, as proved by the new constitution that is currently being written, that includes many social evolutions and new environmental rights. Santiago de Chile is also a city with strong air quality preoccupations, with a structural and spatial organization that makes mobility an interesting issue to study.

The thesis is divided into four chapters to answer specific sub-questions. First, we design a tool that can be used to identify the most vulnerable households in terms of mobility in a given territory, and then use this tool to characterize the impacts of a LEZ on mobility vulnerabilities. Then, we aim to understand to what extent subjective dimensions, and more specifically perceived accessibility, play a role in car dependency in peri-urban, car-dependent contexts. Last, we explore the influence of subjective consideration of environmental risks and attributes on residential choices. To do so, we follow a multi-disciplinary approach and worked on different datasets: the French Local Household Travel Surveys (chapter 1 and 2), and two original datasets, a phone survey (chapter 3) and an online survey we conducted ourselves (chapter 4). The following is a presentation of the main results of the chapters.

The first chapter of this thesis focuses on VulMob, a composite indicator designed to evaluate mobility vulnerabilities and transport poverty at the individual level in an urban area. Applied to the Grenoble area, this indicator allowed identifying 9.6% of highly vulnerable households and 5.5% of transport poor households. Among them, five profiles of vulnerability are identified, with specific difficulties for monetary constrained households, low-accessible residential places, night workers, heavy car users and car-dependent households. This chapter therefore offers an original methodology to conduct a multidimensional and territory-specific analysis of vulnerabilities at the local level. This methodology is particularly relevant to catch the different combinations of vulnerabilities that might appear in the different sectors of a territory and therefore to identify profiles of mobility vulnerable households. This approach is interesting for policy makers in order to understand the local impacts of a transport public policy or an energy price shock on pre-existing vulnerabilities, and therefore adapt public policy, or support it as best they can, to reduce these vulnerabilities.

Then, the *ex-ante* socio-economic impacts of a LEZ implementation in the Grenoble area is assessed in chapter 2. This evaluation identifies more 28,000 households being affected by the LEZ. We also showed that previously identified highly vulnerable (HV) households are expected to be the most affected by the LEZ as they are more likely to drive a polluting car and as they travel more in the perimeter. Moreover, modal shift options are also more limited for these households that have more often constrained destinations than the rest of the population. Indeed, 45.8% of HV households affected by the LEZ have no modal shift solution and constrained destinations, *versus* 28.1% in the rest of the

population. These results highlight the necessity of implementing compensatory policies at the local level to avoid reinforcing pre-existing vulnerabilities, but also highlight the strong potential of active mobility in order to implement a fair ecological transition. To our knowledge, this thesis also provides one of the first socio-economic evaluation of the expected impacts of a LEZ.

This thesis also explores a different perspective to explain mobility and housing choices by integrating individual perceptions. In a context characterized by an important suburbanization process, residential choices are made balancing financial constraints and commuting distances to find an acceptable trade-off. Yet, mobility decisions are often the consequence of expected and perceived parameters and not necessarily objective measures of travel times or accessibility. The third chapter uses an integrated choice and latent variable model to explain mode choice in the suburban areas of Santiago de Chile. This analysis points out the existing mismatching between objective and perceived accessibility, the latter depending on factors such as the easiness to reach essential destination, the cost of moving or the pleasantness of streets. Results show that a low perceived accessibility increases the likelihood of choosing motorized modes. Moreover, residents from peripheral municipalities tend to perceive a higher accessibility than households from periurban areas, which are excluded from the public transport system. These findings show the importance of providing nearby opportunities to reduce the functional dependence to other zones of the city, but also convenient alternatives to the car in order to limit car dependency, especially in periurban areas.

Finally, given the growing importance of environmental risks and natural areas, we integrate both objective exposure to environmental risks and perceptions in residential choice models to explore to which extent they are taken into account when choosing for a new residence. The analysis is conducted across the whole French territory and included air pollution, flood risks, clay-swelling risks, and the presence of natural areas. To do so, we developed a MNL model, which gave few insights on environmental perceptions given the heterogeneity of the studied territory. Based on this observation, we used a LC model to explore the choices heterogeneity among the population. Results show that households who took into account environmental features when choosing where to live all tended to choose less polluted areas, while a small group of retired low-income households also value limited natural areas and municipalities that are less exposed to clay swelling risks.

2. Lessons for decision-making

The results of this thesis can be used to assist decision makers in the implementation of a fair ecological transition.

Firstly, after successive governments dithered over the introduction of LEZs in France, this thesis provides a better understanding of the impacts of LEZs on multi-dimensional vulnerabilities. Our results show that implementing polluting car-ban policies may strongly affect low-income and/or highly vulnerable households, and if modal shift constitutes a solution for a majority of the population, it remains a more limited solution for these specific households. In this context, this thesis provides tools and potential solutions to deal with these issues and design compensatory policies. In particular, exemptions for night workers and short-haul truck drivers are suggested in order to improve the LEZ acceptability without reducing environmental efficiency. Our work also shows that active modes (walk, bike and e-bike) constitute an important lever for modal shift in the context of a LEZ implementation in the Grenoble area. To our view, the LEZ should be seen as an opportunity to reduce car dependency, congestion and air pollution issues to encourage active mobility and the associated to positive sanitary and health effects. In this sense, personalized advice to encourage people to switch to public transport and active modes is organized in the Grenoble Metropolis. Indeed, as shown in this thesis, actual accessibility often differs from perceived accessibility and residents often misjudge their existing opportunities using other transport modes. Thus, this thesis develops a tool that aims identifying

households that remain without any adaptation solution at the local level. In the Grenoble urban area, our results show that they represent a very low share of the population (3.2%). Therefore, compensatory policies should particularly focus on providing monetary and structural solutions, depending on the specificities of these households, to ensure an equitable access to services and opportunities.

Secondly, our results on accessibility in suburban municipalities of Santiago de Chile confirm an existing mismatching between calculated and perceived accessibility. Thus, we show that a low perception of accessibility results in a higher probability of using motorized transport modes. Therefore, in order to limit car dependency and tackle the negative externalities of cars, municipalities should base their action on understanding the determinants of perceived accessibility. In Santiago, we observe that cheap transport, a pleasant environment and good quality cycling infrastructures could increase perceived accessibility. Therefore, if calculated accessibility is relevant to identify the areas that should be better connected to public transport networks, subjective evaluations also give complementary insights when planning. The replication of such types of survey that assesses satisfaction when moving around the city may allow obtaining similar but city-specific results. These insights would be particularly relevant to act on changing behaviors and encouraging the use of active modes at the local level.

Third, this thesis underlines the importance of working on perceptions of environmental risk exposure. Indeed, in a climate change context with increasing extreme events, knowing the environmental risks to which people are exposed, in particular in their residence, studying how people consider these risks is a central issue. In France, since 2022, the government has introduced a day called "Tous résilients face aux risques" ("All resilient in the face of risks"). This day is organized annually, on October 13, in line with the United Nations' International Day for Disaster Risk Reduction and aims to raise awareness, inform and acculturate all citizens to the natural risks that surround them. For instance, it is an opportunity to raise awareness of flood markers, which enable people to keep track of past events and prepare for future floods. These efforts remain insufficient, in particular when it comes to air quality or clay swelling risks that are much more complicated to visualize. Indeed, clay swelling risks are poorly documented and badly known by the general population. Therefore, more efforts should be made to communicate on the impacts (economic, environmental, and sanitary) of these environmental phenomena, mitigate the harmful effects and raise awareness in order to reduce the vulnerability and promote safe behaviors. Indeed, a growing literature on environmental health literacy suggests that communication about environmental risks should encourage individual behavior education to empower people to limit their exposure (e.g. Ramírez et al., 2019 for air pollution, or Burningham et al., 2008 for flood risks).

Lastly, for the last past years, the priorities of the political agenda were particularly centered on fighting the COVID-19 pandemic and securing the energy supply. Yet, we underline the necessity of quickly and efficiently act to tackle climate change issues without ignoring the social impacts that may emerge from the implementation of adaptation and mitigation measures. Although being confronted to high levels of air pollution in France, the fear that the most fragile households would be the most affected by LEZs had slowed the adoption of ambitious measures. Seven years earlier, the implementation of a priority action area for air quality (*Zone d'Actions Prioritaires pour l'Air*) was already cancelled because of this specific reason (Charleux, 2014). More recently, the ambition of the *Loi Climat et Résilience* (French Climate Law) have been limited once again following a Senate report published in June 2023 that recommended to withdraw the national implementation of LEZs, due to the expected adverse social consequences and the lack of support from the government. The need to improve air quality at the local level is still there and governments have to take ambitious measures in this sense.

3. Research perspectives

Specific limitations and possible research extensions have been previously discussed in each chapter. Here, we present general ideas that would allow continuing the research initiated in this thesis.

a) On vulnerabilities...

In France, as LEZs have not been standardized, each city has to define the terms and conditions of their application. Given that vulnerability issues constitute a central preoccupation, this flexibility of implementation should be used to identify the specific characteristics of each territory in terms of vulnerabilities and impacts. In this sense, a main limitation of our work is related to the exclusive study of the vulnerabilities and the LEZ impacts on the Grenoble area. Therefore, an important challenge would be to reproduce this kind of analysis on several French and/or European cities. However, the reproducibility of this method relies on the availability of trustful income data and the feasibility of connecting this data with the Household Travel Surveys. To our knowledge, access to income data might be possible in Clermont-Ferrand and Bordeaux with specific authorizations. Otherwise, to follow our methodology, future Household Travel Surveys should be designed whether by including a declarative question on income or by designing a correspondence table between the INSEE data and the Household Travel Survey when designing the survey. It would allow exploring the different socio-economic impacts on several urban structures, distinguishing monocentric, polycentric and/or composite cities, as the urban form seems to play an important role. Indeed, in France, cities follow different trajectories in terms of public transport planning. For instance, Montpellier decided to generalize free public transport for all inhabitants since 2023, while other cities such as Lyon decided to rely on the development of more than 400km of bicycle lines by 2030.

Then, to deepen the work carried out in this thesis, it would be particularly interesting to explore the combined effects of exposure vulnerabilities, environmental risks and inequalities in contribution to GHG and pollutant emissions with the impacts of public policies. This work will be initiated in the ClimAir project³¹ that partially funded this thesis, and could allow characterizing the multi-dimensional vulnerabilities that may affect households at the local level. To go a step further, it would also be relevant to study the combination of mobility and housing vulnerabilities, including heating costs. One possibility would be to extend our work to develop household profiles and city typologies according to the different identified vulnerabilities and dimensions of fuel poverty.

b) On accessibility...

This thesis also reveals the importance of accessibility issues in the different studied contexts.

On the one hand, the first chapter of this thesis underlines the transversality of the accessibility dimension, which appears to be common to almost all vulnerability profiles identified in the Grenoble area. The analysis developed in chapter 3 is also limited by a lack of existing indicators related to accessibility in periurban municipalities. This raises the challenge of trying to better characterize this lack of accessibility, whether to public transport but also to services and amenities. To do so, considering other possibilities to move, such as multimodality and carpool, that have not been taken into account in VulMob, would be particularly relevant. For now, as the public transport accessibility indicator of VulMob is calculated at the small-scale territorial level, it would be interesting to compare the use of different (and maybe more elaborated) indicators to make the assessment more powerful and realistic. In particular, being able to evaluate accessibility at the individual level is a challenge that remains. The development of a transportation model at the scale of a Metropolis that may include these different parameters could be an option to assess accessibility at such level.

³¹ The ClimAir project: Climate change and air pollution in an urbanized area: health impacts and economic costs of mitigation scenarios (2022 – 2025), coordinated by C. Staquet (atmospheric modeler, LEGI), funded by the French National Research Agency (Agence Nationale de la Recherche).

On the other hand, the exploration of mode choice determinants in the periurban and suburban areas of Santiago shows that calculated measures of accessibility are often inconsistent with perceived accessibility, as also revealed in other studies (Lättman et al., 2018; Pot et al., 2021). Therefore, working on an integrated evaluation of accessibility at the local level appears to be even more important so that individuals may have a perception of accessibility that is closer to reality. A more realistic perception of accessibility may indeed allow changing behaviors and encouraging the use of different transport modes, but this topic remains to be explored.

Focusing on the Chilean context, in 2023, the Santiago public transport network announced an extension of the subway line to the municipality of Padre Hurtado, which was not connected until now. Therefore, studying the implications of this improvement on our results would be particularly relevant, as travel time and public transport offers will be considerably modified. A future study could therefore be based on a new survey of our respondents to understand to what extent their perceptions of accessibility have changed.

c) On perceptions...

The survey of environmental perceptions is limitedly investigated in this thesis and deserves greater analysis. Our dataset includes two environmental attributes that were not integrated to the model because of missing objective data: noise and urban heat island. The integration of these two variables would be particularly relevant for our analysis but remains conditioned by the development of objective datasets that may include these variables at the municipality level. At the same time, our dataset may allow exploring other research questions. An upcoming work would be to explore residential mobility to understand if households may look for more environmental quality when leaving their previous residential place, as our data contains the previous and current addresses of respondents, and the date of their relocation. On the longer term, another research goal would be to re-interview our respondents to ask for their address, which would allow us to better characterize their actual exposure. At the time, collecting addresses was impossible due to confidentiality issues (RGPD). This future work could provide a better understanding the differences between perceptions of risk exposure and actual exposure, and thus a characterization of the gap between perception and exposure based on the respondent's socio-demographic characteristics and environmental sensitivity.

The design of the PERL survey also offers important lessons for such types of study. Based on the analysis process we conducted, a question that remains is about the relevance of working at the level of a whole country. On the one hand, it would have been particularly difficult and costly to collect representative answers at the scale of an urban area. On the other hand, working at the scale of France introduces important heterogeneity in respondents' answers, which complicates the analysis and makes the results more difficult to interpret. This point should be kept in mind for further work.

d) International context

More broadly, for the last past years, mobility habits have been shaken up by several unexpected events.

On the one hand, the COVID-19 pandemic considerably modified mobility habits as a consequence of teleworking, social distancing and limited access to activities (Wellenius et al., 2021; Baig et al., 2022). Therefore, it may have had important consequences on our datasets (the Local Household Travel Survey in Grenoble and the phone-survey in Santiago) that were collected in 2020. Moreover, if the COVID-19 pandemic disrupted mobility behaviors, in particular due to the development of teleworking (Aguilera, Pigalle, & Chevallerier, 2023), it also provided an opportunity to develop active mobility at the global level. For instance, during the pandemics, the city of Paris created more than 50 kilometers of temporary cycle lanes in order to encourage the use of bikes, among which many became permanent afterwards. This dynamic is not limited to Paris and has been observed all around the world: 24 kilometers of new bicycle lanes were also announced in Santiago de Chile in 2023.

On the other hand, the pandemics also influenced the processes of residential choices, as many households were asking for more space, less dense areas and an access to green spaces after the first lockdown (Breuillé et al., 2022; Colomb & Gallent, 2022). Indeed, if commuting times were a major criterion for residential choices before the pandemics, it became more secondary during this specific period for households who were able to work remotely. Within urban areas, the least densely populated and the furthest from the center are those where prices increased the most, which reflects the attraction for more spacious properties on the outskirts of urban centers (Chareyron, Regnier, & Sari, 2022). These recent results therefore show that a change of dynamic has taken place in the real estate market in the wake of the COVID-19 crisis. Yet, for both mobility and residential choices, the future remains uncertain and the long lasting effects of the pandemics are still to be discussed (e.g. Baig et al., 2022; Vega-Gonzalo et al., 2023).

Lastly, the Russia's war against Ukraine has raised concerns related to the security of energy supply in Europe. The war resulted in an increase in the price of oil price that reached 123\$ per barrel in June 2023, and therefore led to an important increase in motor fuel prices. This shock price also disrupted mobility habits, and the use of the car became particularly difficult especially for low-income workers. This led to a preference for public transport rather than private cars (Ladin et al., 2015) and a decrease in travel distances (Alberini, Di Cosmo, & Horvath, 2022). If the world context is necessarily influencing mobility habits and residential choices, these effects will once again not necessarily last on the long term, and the future is particularly uncertain giving the geopolitical situation. In this sense, the results of this thesis should be checked to ensure their validity after the occurrence of these events.

A. Appendices chapter 1

A.1 - Basic descriptive statistics of the 13 VulMob factors

Table A.1.1 Descriptive statistics

Dimension	Factor	Unit	Threshold	Q1	Median	Mean	Q3	Std deviation
Financial resources	Income per consumption unit	€/year	< 13,356	17,268	23,286	26,078	30,892	12,790
	Mobility expenses	%	> 18	0	7.3	11.5	19.2	31.8
Work constraints	Share of mandatory trips	%	> 75	0	25.0	35.0	66.6	37.7
	Nighttime job trips	N	> 1	0	0	0.21	0	0.50
	Commuting distance	km	> 10	0	0.82	4.64	4.28	19.40
Heavy car use	Frequency of car use			categorical				
	Share of car trips	%	≥ 100	0	50.0	48.5	100	41.4
	Maximum distance by car	km	> 40	0	0	16.87	17.96	44.11
Structural constraints	Car efficiency	Crit'Air sticker	≥ 3	1	2	1.62	2	1.19
	Accessibility	PTAL points	< 10	0.72	4.89	7.95	12.13	9.22
	Spatial mismatching	km	> 10	1.67	3.98	9.07	9.28	25.90
	Car access	N	< 0.4	0.25	0.5	0.77	1	0.69
	Household structure			categorical				

A.2 - Description of the sectors

Table A.2.1 Distribution of the population among the different sectors in the EMC² data

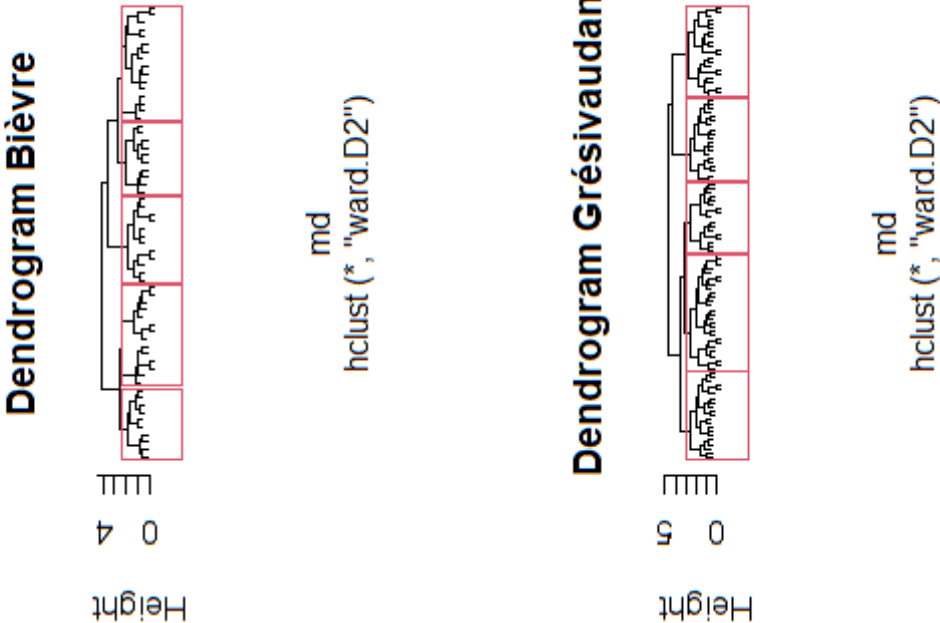
Sector	Number of households (redressed)	Share of the population (%)
Métropole	197,388	54.9
Bièvre	36,003	10.0
Grésivaudan	40,737	11.3
Voironnais	38,615	10.7
Sud Grésivaudan	18,812	5.2
Vercors	5,144	1.4
Chartreuse	4,820	1.3
Sud Isère	17,908	5.0
Total	359,427	100

Table A.2.2 Distribution of the HV households in the different sectors

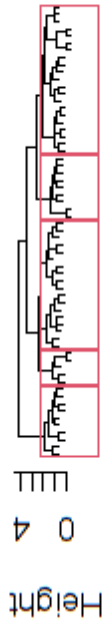
Sector	Number of HV households in this sector (redressed)	Share (%)	Share of HV households in this sector (%)
Métropole	13,973	41.0	7.1
Bièvre	3,765	11.1	10.5
Grésivaudan	4,971	14.6	12.2
Voironnais	3,625	10.6	9.4
Sud Grésivaudan	3,506	10.3	18.6
Vercors	691	13.4	13.4
Chartreuse	583	1.7	12.1
Sud Isère	3,635	10.7	20.3
Total	34,749	100	

A.3 - Hierarchical clustering (Ward's linkage method) – methodology and dendograms

We use the Ward's linkage method, which generate clusters to minimize the within variance. For each cluster, means of all variables are computed. For each household, the squared Euclidean distance (χ^2) to the cluster means is calculated and distances are summed for all the objects. The number of clusters varies according to the size of the sample but also the similitudes observed, as some sectors are more heterogeneous. The optimal number of clusters was defined according to the explained inertia associated. Each cluster accounts for a minimum of $n=10$ observations and the optimal number of cluster was determined by an optimization of the explained inertia, with a maximum threshold of 10 clusters by region.

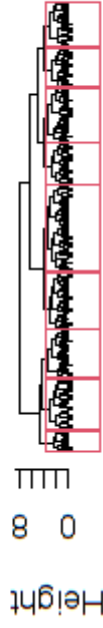


Dendrogram Sud Isère



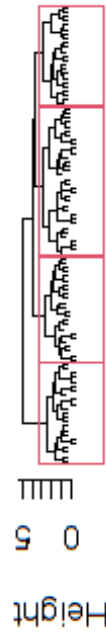
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md
hclust (*, "ward.D2")
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Dendrogram Metropole



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md
hclust (*, "ward.D2")
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Dendrogram Voironnais



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hclust (*, "ward.D2")
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Dendrogram Sud Grésivaudan



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md
hclust (*, "ward.D2")
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Figure A.3.1 Dendrograms

A.4 - Robustness analysis

Despite their great explicative power, many scholars point out the lack of robustness of CIs (Sharpe, 2004, Saisana et al., 2005, Greco et al., 2019). The construction of a CI is indeed based on several subjective or intuitive choices that need to be made at each step of the methodology. These choices refer to the theoretical framework and are justified by the objective sought through the indicator. They are thus potentially a source of sensitivity of the results. In order to verify the robustness of the VulMob indicator to draw relevant recommendations, we studied how some alternatives can modify the results obtained.

In the literature, the majority of the robustness tests applied to CIs consists in testing for different normalization, weighting and aggregation methods (Dobbie and Dail, 2013; Luzzati and Gucciardi, 2015; Greco et al., 2019). In our case, our choice for the normalization process is based on thresholds and the limits of this choice are clear: modifying the thresholds may considerably influence the results and in particular considering the identification of HV households. We carefully tried to define the most adapted thresholds for the Grenoble area and we underline that these thresholds have to be adapted if the VulMob indicator is used in another context. Yet, the choice of an equal ponderation of the individual indicators might also be criticized, as some vulnerabilities may have an higher impact than others. Indeed, the financial issues are often considered as the first vulnerability and hardest to face for the affected households.

In order to test for the global reliability of the equal weighting scheme, we used the Monte-Carlo method which relies on repeated random calculations to estimate the uncertainty associated to a statistical phenomenon, using the law of large numbers (Metropolis, 1985). We calculated n=10,000 simulations of random weights that are associated to the 13 different vulnerability factors of the indicator. Then, we identify the number HV households considering each weight distribution (see Figure A.4.1).

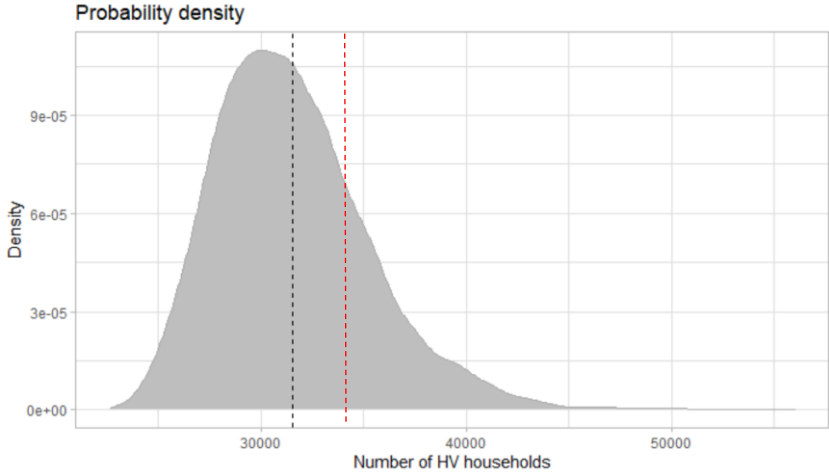


Figure A.4.1 Results of the 10000 random weights simulations to identify HV households

Note to the reader: the black line shows the observed mean and the red line the result obtained with the VulMob indicator

Results of the simulations show that on average, 31,553 households are identified as HV in the sample (8.77% of the population), while Q1 = 28,814 households (8.01%) and Q3 = 33,738 households (9.39%). In comparison, the EW method leads to a number of HV households (34,749) that is beyond Q3, which show that the indicator as proposed in the work is relatively pessimistic. One advantage of this approach is that it avoids missing households in difficult situations.

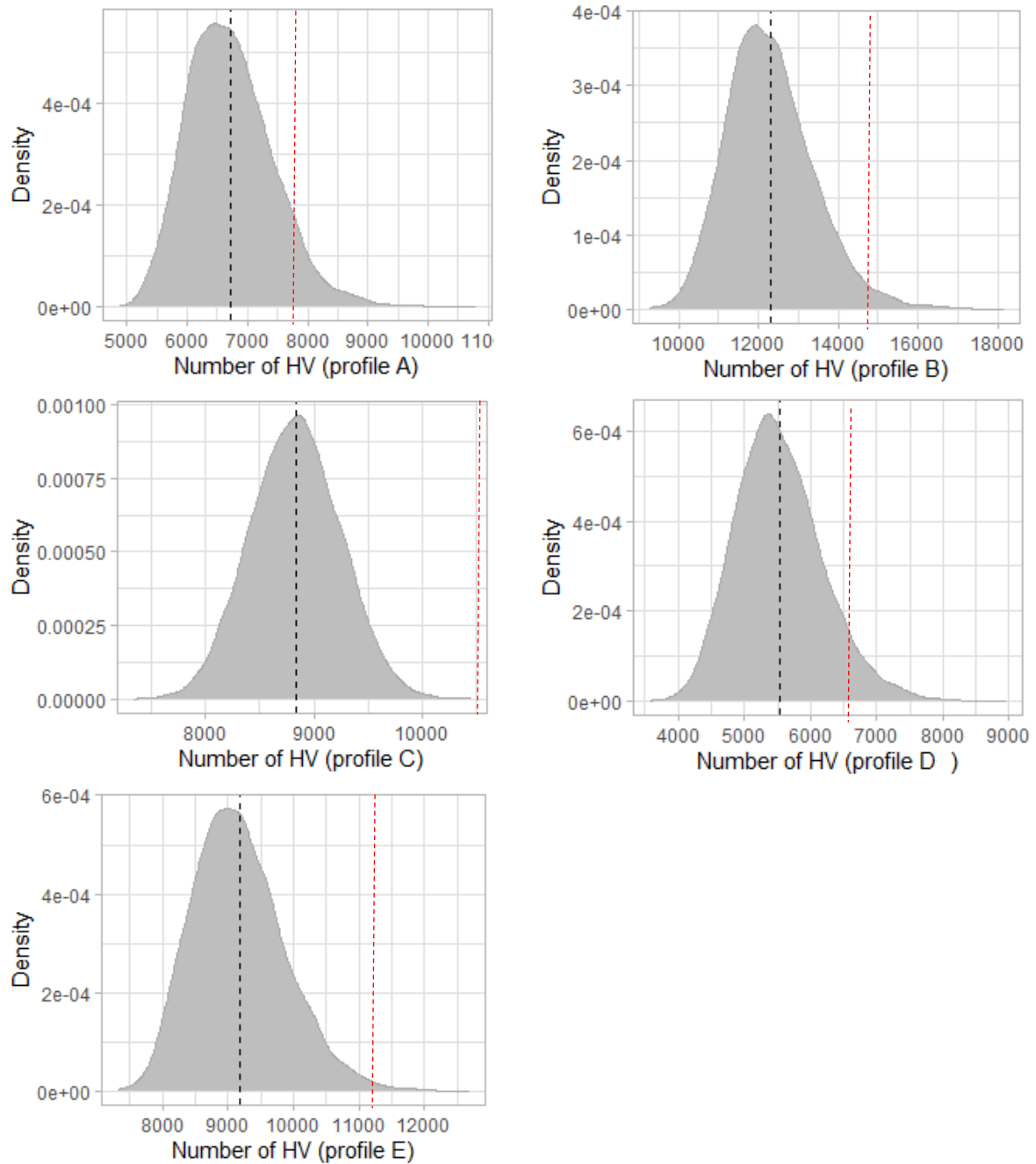


Figure A.4.2 Results of the 10000 random weights simulations for each profile of HV households

Note to the reader: the black line represent the mean value of the distribution, while the red line corresponds to the number of households obtained by the EW method

We also calculated the number of HV households with a distinction by profile (A to E). For each profile, the results show that the VulMob indicator underestimates the number of HV. The difference in the results is explained by the fact that VulMob exclusively classifies each household. Moreover, this method allows identifying all the households affected by a combination of vulnerabilities without any distinction and/or exclusion of sector or profile, which is different from the hierarchical clustering method followed in Section 1.4.

Table A.4.1 Average number of HV households associated to each profile with 10,000 random weight simulations

Profile	A monetary constrained	B without alternative	C night worker	D structural heavy car users	E costly heavy car users
\bar{N} (households)	6,730	12,241	8,843	5,534	9,221
EW method	7,872	14,494	11,291	6,617	11,254
EW method + clustering	3,452	5,705	10,702	5,000	6,024

We observe that the number of HV households identified for each profiles with equal weights remains consistent with the mean value observed with the simulations. Profile B (spatial mismatching issues and a bad public transport accessibility) appears to be the most common in the Grenoble area according to these simulations and the EW method applied to our data, while the EW method + clustering rather identified the profile C (night workers). Yet, this difference is easy to explain as households without alternative are in fact present in the majority of the territory and are often also take into account in other vulnerability profiles. This highlights one limit of the clustering method. In particular, we observe that the equal weight method + clustering does not allow catching all the households affected by a combination of vulnerabilities.

Finally, considering the importance of the monetary issues, we tested to what extent the weight associated to the variable income per consumption unit (noted w_{I1}) might influence our results. To do so, we associated different weights to the variable, selecting 11 values starting from 0 and adding 0.1 at each iteration. The other variables are associated to the same weight equal to $\frac{1-w_{I1}}{12}$. Figure A.4.3 shows that modifying the weight of this variable strongly influences the number of HV households (defined as households scoring more than 6 at the VulMob indicator). Indeed, when the income is out of our considerations ($w_{I1}=0$), we identify 24,220 HV households, while when the income has a strong weight ($w_{I1}=0.5$ to 1), the number of HV is almost multiplied by 4 and we observe more than 90,000 HV households. In particular, setting the weight at $w_{I1}=0.1$ gives us the minimum number of HVs. As we used $w_{I1} \approx 0.077$ as a common weight for all variables in our study, our hypothesis fits well with a minimization of HV households.

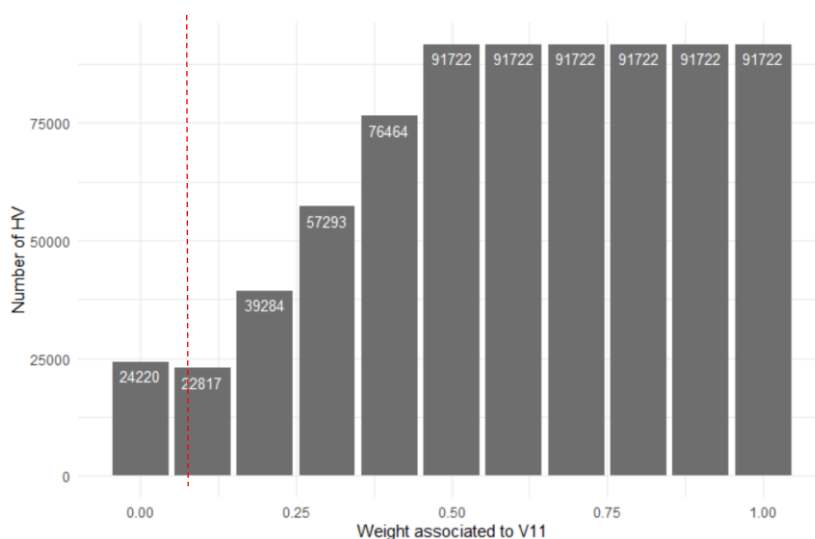


Figure A.4.3 Identification of HV households with the VulMob indicator according to the weight associated to the income variable (V11).

Note to the reader: the red line shows the threshold used in the VulMob construction (EW method).

The robustness tests show the relevance of the VulMob indicator but also its limits. To go further, it might be interesting to explore different normalization and aggregation methods. In particular, the use and definition of thresholds is an important issue to consider and might be interesting to test and discuss.

A.5 - Reproducibility: VulMob in a nutshell

VulMob is a composite indicator that might be used at the city scale in many other contexts. This appendix describes the main steps to be followed in order to reproduce the methodology described in this chapter.

1- List of the required data for the factors calculation

See the Table below

2- Adaptation of the thresholds to the local context

Thresholds were defined considering the local context of Grenoble and have to be adapted for other cities. For instance, distances were chosen considering the cities around (Lyon, Chambéry).

- Income: based on the poverty line for the country
- Heavy use of the car: modal share of the car in the area

3- Definition of geographic sectors

Sectors have to be consistent with the socio-economic dynamic of the area. We used sectors already defined in the Local household travel survey and which reflect the mobility organization of the territory (distinct transport authorities).

4- Clustering per geographical area

This step is based on a hierarchical clustering analysis (HCA) conducted in the different sectors. It was performed with the stats and ade4 packages in R.

5- Definition of main profiles according to identified similarities in the clusters across sectors

The definition of profiles should be done in order to correspond to observed realities and considering combinations that may be sources of vulnerability.

Some households may correspond to several profiles. Some clusters will not be aggregated into a main profile. Geographical sectors with few data for HV may be removed.

Data		Indicators												
		Income per consumption unit	Mobility expenses	Share of mandatory trips	Nighttime job trips	Commuting distance	Frequency of car use	Share of car trips	Maximum distance by car	Car efficiency	Accessibility	Spatial mismatching	Car access	Household structure
Source of threshold definition		French poverty line	Nicolas et al. (2012)			SDES (2019)			Mean national distances	Crit'Air Sticker	Definition of the PTAL	Berry et al. (2018)		
Source	Variable													
Fiscal data (Fideli)	Income per consumption unit (in €)	X	X											
Data on expenses and resources of households (Budget des familles)	Mobility expenses (in €)		X											
Local household travel surveys (EMC2)	Number of cars		X										X	
	Car efficiency (year of construction, fuel)									X				
	Travel distances (jobs and other services)					X			X			X		
	Number of trips			X				X						
	Number of car trips							X						
	Mobility habits							X						
	Schedule of the trips				X									
	Purposes of the trips			X										

	Members of the households (ages, relationships)												X	X
General Transit Feed Specification (GFTS)	Public transport stops, distances and schedules)										X			

B. Appendices chapter 2

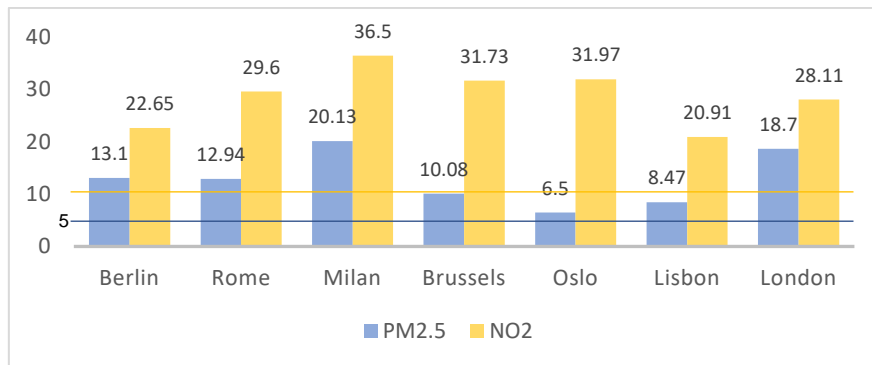
B.1 - Some LEZs information

Table B.1.1 Specificities of Milano, Roma, London and Oslo LEZs

City	Time	Area	Regulation
Roma (1989)	Monday-Friday	City core	CC, parking charge, access restriction (5 concentric zones with different rules)
Milano (2008)	7:30AM-7:30PM	71% of the city	CC, access restriction (forbidden for gasoline pre-euro, diesel pre-euro, euro I and II)
London (2008)	24/24h	Most of the city	Pay to enter or meet standard (forbidden for <Euro 6 diesel and <Euro 4 petrol)
Oslo (2017)	6:00AM-6:00PM	Most of the city	CC for all vehicles, according to Euro standard, fuel type, as well as time and distance

Figure B.1.1 Annual mean concentrations ($\mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and NO_2 in several European cities
(Source: European Environment Agency, 2019)

Note to the reader: Horizontal lines corresponds to the WHO thresholds associated to $\text{PM}_{2.5}$ (in blue) and NO_2 (in yellow)



B.2 - Mobility flows identified in and between the different sectors of the territory

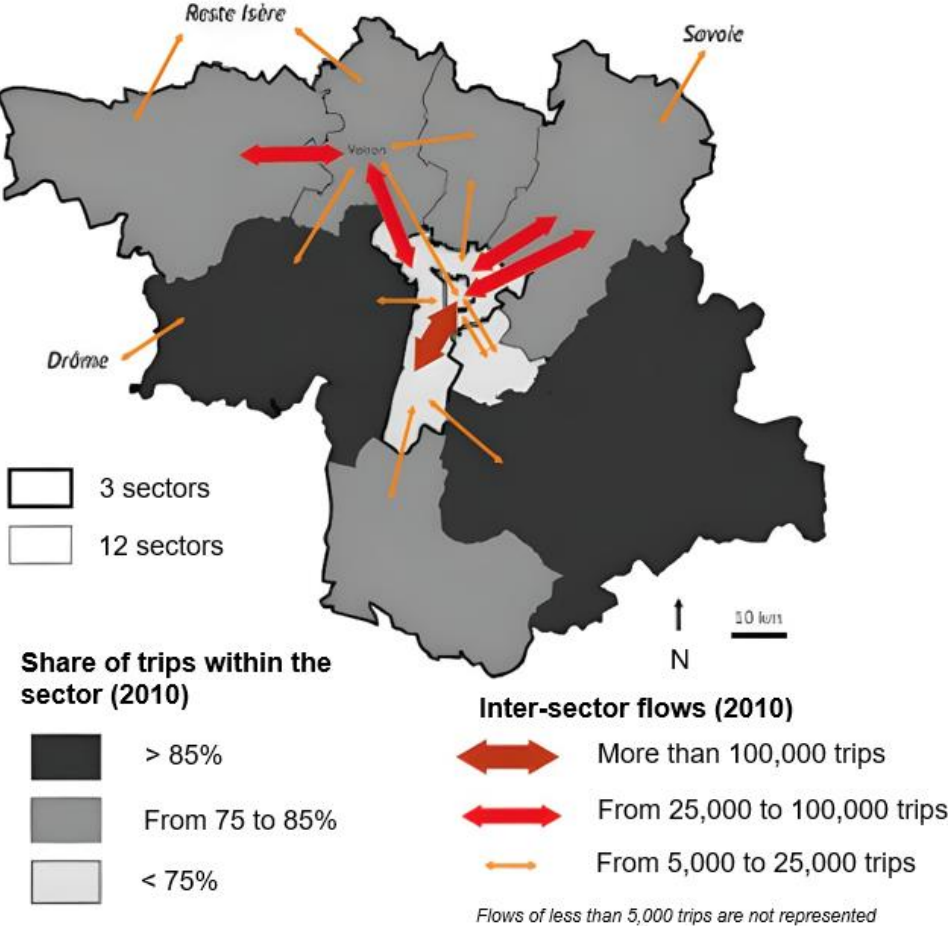


Figure B.2.1 Mobility flows in the Grenoble area
 Source: Résultats EMD 2010 SMTG Grenoble Alpes Métropole, translated to English by authors

B.3 - Evolution of the modal shares (calculated in terms of number of trips) between 2010 and 2020

Table B.3.1 Modal shares in 2010 and 2020
(Source: Authors' calculation, from 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

B.4 - Classification of the Crit'Air stickers



Figure B.4.1 Crit'Air classification (Source: Rejeb's thesis (2022, p. 134))

The Crit'Air vehicle classification sets out a list of vehicles classified according to their levels of atmospheric pollutant emissions under the Highway Code. The certificates are based on the “Euro” standards, which set pollutant emission thresholds for new vehicles sold and which are periodically made more stringent.

B.5 - Results of the different schedules studied for the LEZ implementation

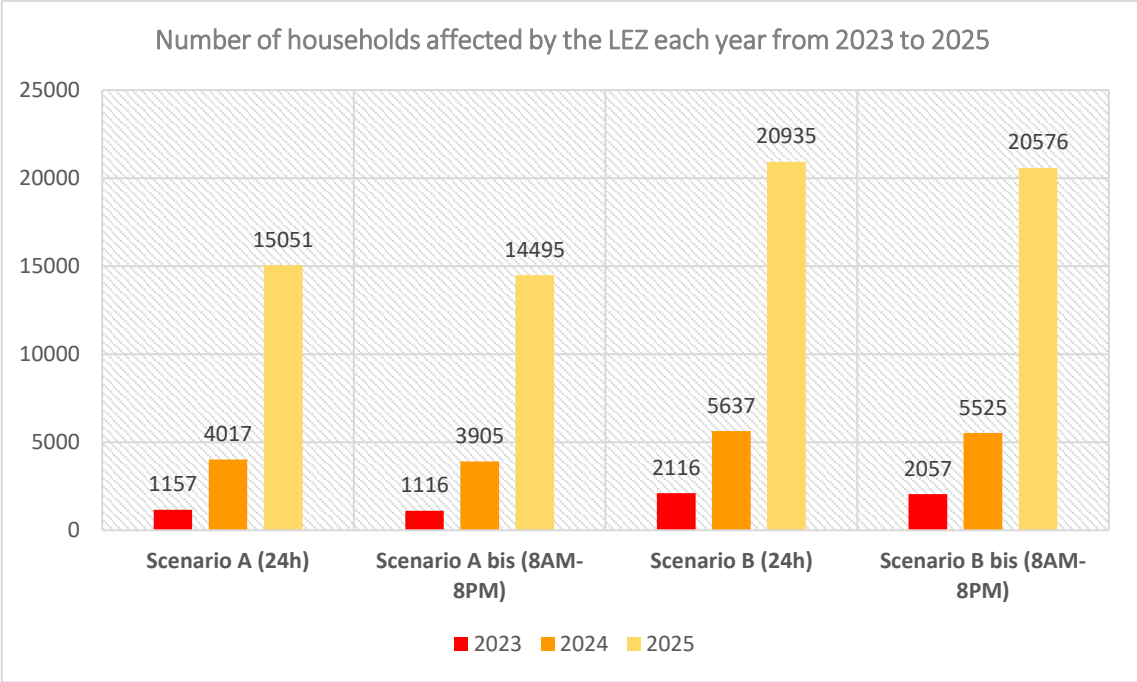


Figure B.5.1 Results of the four scenarios

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

B.6 - Crit'Air sticker associated to the households' best car according to the income by consumption unit and per year

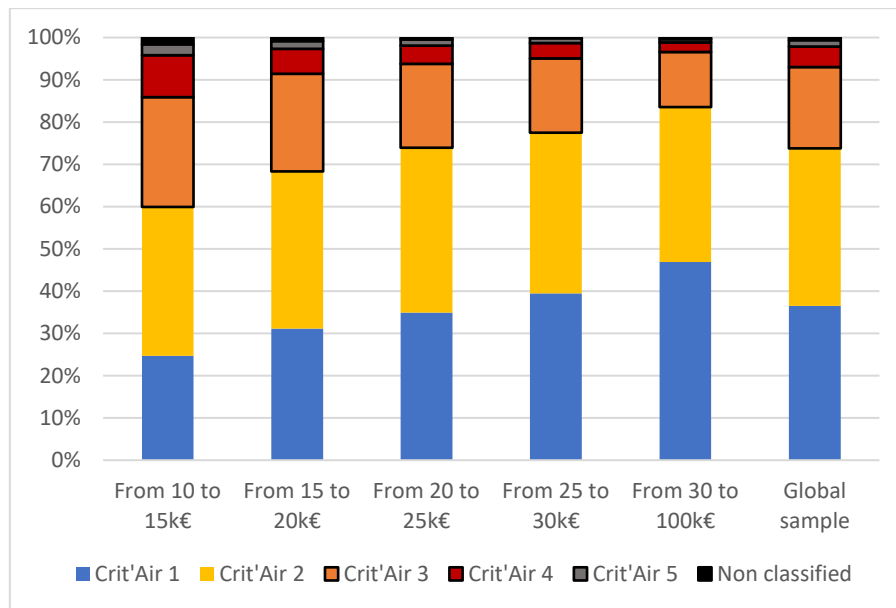


Figure B.6.1 Crit'Air sticker given the income level of the household

Source: Authors' calculation, from EMC² data

Note to the reader: Among households earning less than 15k€/year, only 24.7% have a Crit'Air 1 vehicle

B.7 – Results for scenario A

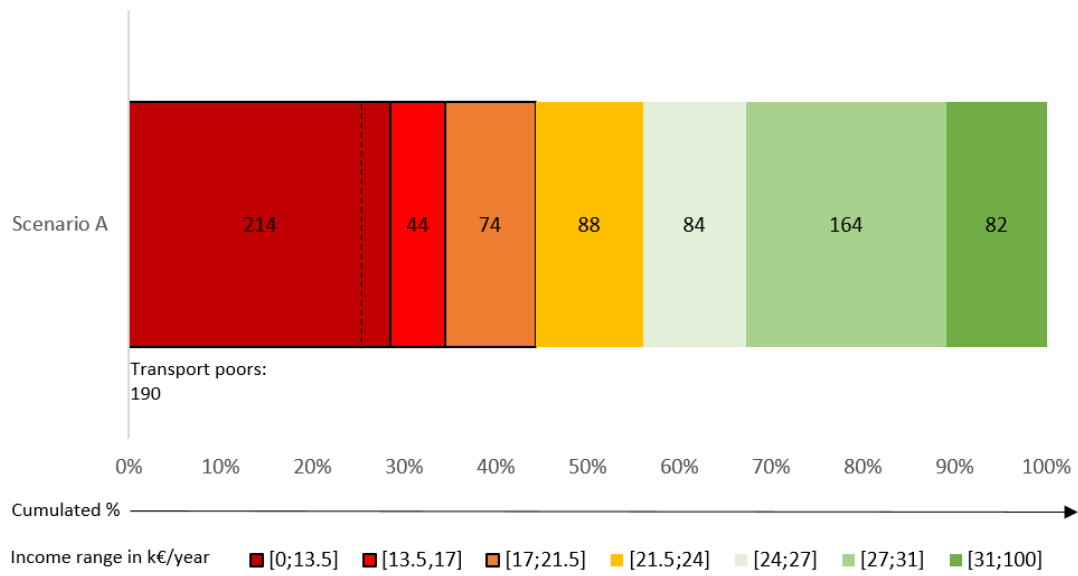
Table B.7.1 Households analysis for scenario A

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
<i>% of all households (Total - 1)</i>	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*
<i>% of all households (Total - 1)</i>	5,63%	5,03%	0,60%	0,09%	0,07%	0,11%	0,10%	0,14%
<i>% of all, non-HV and HV households (Total, non-HV, HV - 2)</i>	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*
<i>% of all households (Total - 1)</i>	1,95%	1,69%	0,26%	0,03%	0,05%	0,04%	0,02%	0,10%
<i>% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)</i>	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*
<i>% of all households (Total - 1)</i>	1,33%	1,12%	0,21%	0,02%	0,02%	0,03%	0,02%	0,10%
<i>% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)</i>	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 (transport poor)	871	678	193	92*	3	10	2	81*
<i>% of all households (Total - 1)</i>	0,24%	0,19%	0,05%	0,03%	0,01%	0,29%	0,04%	0,76%
<i>% of all, HV and non-HV affected households (Total, HV, Non-HV - 2)</i>	4,3%	3,8%	9,0%	27,7%	1,2%	2,6%	0,6%	16,5%

Table B.7.2 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
<i>% of all trips (Total - 1)</i>	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*
<i>% of all trips (Total - 1)</i>	5,9%	5,1%	0,8%	0,1%	0,1%	0,2%	0,2%	0,1%
<i>% of all, HV and non-HV trips (Total, HV, Non-HV - 2)</i>	5,9%	5,5%	10,5%					
<i>% of affected trips with a modal shift solution</i>	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*
<i>% of all trips (Total - 1)</i>	1,9%	1,6%	0,3%	0,0%	0,0%	0,1%	0,0%	0,1%
<i>% of all, HV and non-HV affected trips (Total, HV, Non-HV - 2)</i>	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*
<i>% of all households (Total - 1)</i>	1,2%	0,9%	0,2%	0,0%	0,0%	0,1%	0,0%	0,1%
<i>% of all, HV and non-HV households (Total, HV, Non-HV - 2)</i>	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 (transport poor)	2 042	1 486	556	201*	12	61	31	189*
<i>% of all households (Total - 1)</i>	0,2%	0,2%	0,1%	0,0%	0,0%	0,0%	0,0%	0,0%
<i>% of all, HV and non-HV households (Total, HV, Non-HV - 2)</i>	3,6%	3,1%	7,4%	15,3%	2,5%	4,1%	1,4%	14,8%

Figure B.7.1 Income shares associated to the households without modal shift solution and constrained by their destination



B.8 - Residential location of the different identified profiles

Figure B.8.1 Residential location of the identified profiles (Source: Blandin et al. (2023))

Note to the reader: For each profile, a cross indicates if this profile has been identified in the corresponding sector of the territory

Sectors	A monetary constrained	B without alternative	C night worker	D structural heavy car users	E costly heavy car users
Grésivaudan		x	x	x	x
Sud Grésivaudan		x	x		x
Sud Isère	x	x	x	x	
Bièvre	x	x	x	x	
Voironnais	x		x	x	x
Métropole	x	x	x	x	x

C. Appendices chapter 3

C.1 - Detailed description of the 15 psychometrics indicators

Table C.1.1 Description of the 15 psychometrics indicators

Indicator	Description
I1	Getting around the city is cheap
I2	You choose the means of transport you use most often because it is the cheapest
I3	You use your usual means of transport because it is the only one available
I4	The locations where you need to go are close to your home
I5	It is easy for you to get to the places you need to go
I6	If you were living somewhere else, it would be easier for you to get to where you need to go
I7	The environment in which you move is pleasant
I8	The environment in which you move has good quality streets and sidewalks
I9	The environment in which you move has good quality cycling infrastructure
I10	Some of your journeys involve other family members
I11	When you leave home, you usually take the opportunity to do several activities before returning home
I12	Other people depend on you to get around the city
I13	You feel insecure because of possible accidents you may suffer when moving around
I14	You have been injured while driving
I15	In general, you feel satisfied when you move

D. Appendices chapter 4

D.1. Main variables

Table D.1.1 – Description of the main variables in the survey

Category	Variable	Survey question
Dwelling characteristics	Property	You are currently [owning / renting] your main residence
	Type	This main residence is ... [a house / an apartment]
	Floors	Number of floors (for a house) / living floor (apartment)
	Buying price	How much did you pay for this dwelling?
	Buying year	When did you buy this dwelling?
	Renting price	How much do you pay to rent this dwelling?
	Home age	When this dwelling was constructed?
	Living area	What is the surface of this dwelling (in m ²)?
	Rooms	How many rooms are available?
	Heating	What types of heating system(s) are available?
Equipment		Do you have a parking, garage, garden, balcony, swimming pool or a view on a mountain/sea/forest...?
	General reasons	General reasons for choosing this residential location (accessibility, family, urban/rural environment, security...)
Environmental reasons		Environmental reasons for choosing this residential location (air quality, calm environment, sunshine, landscape...)
Environmental perceptions	Previous perceptions	Before living here, did you expect to face one of these problems? (noise, air pollution, vandalism, dirty streets, flood risks...)
	Current perceptions	Considering your experience in this dwelling, do you face one of these problems? (noise, air pollution, vandalism, dirty streets, flood risks...)
Residential location	City	Current municipality of residence
	Street	Current street of residence
	Number	Current number of residence
	Moving year	Year when moving to the current residential location
	Previous city	Previous municipality of residence
	Previous street	Previous street of residence
	Previous number	Previous number of residence
	Future	In the next 5 years, could you consider moving because of environmental phenomena to which you are exposed in your home?
Climate change impacts	On a scale of 1 to 5, are you worried about the impact of climate change on your future well-being in your home?	
Socio-demographics	Household size	How many people live in this dwelling?
	Income	What is your monthly global income?
	Household description	Relationship, gender, age, socio-professional category and occupation of each household's member
	Workplace	Municipality of the respondent's workplace
	Telework	Frequency of teleworking (respondent)
	Partner's workplace	Municipality of the partner's workplace
	Telework partner	Frequency of teleworking (partner)

	Health general Health limits General concerns	Evaluation of the global health status Have you already been limited to do [4 situations]? Which of these topics are of most concern to you? (multi-answer question)
Environmental sensitivity	ENV_A ENV_B ENV_C ENV_D ENV_E ENV_F	The balance of nature is very delicate and easily upset. The earth is like a spaceship with very limited room and resources. Plants and animals have as much right as humans to exist. Humans have the right to modify the natural environment to suit their needs. The earth has plenty of natural resources if we just learn how to use them. Humans were meant to rule over the rest of nature.

D.2. Psychometric indicators

Figure D.2.1 Definition of the 5-levels Likert scales

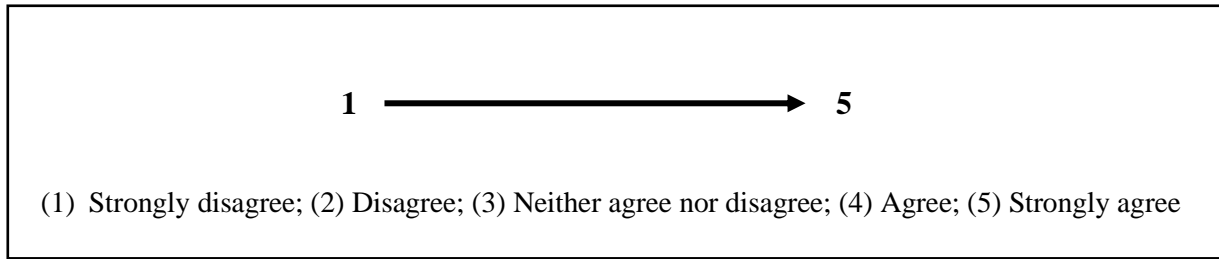


Table D.2.1 Measured perceptions associated to the four studied environmental attributes and risks.

Category	Variable	Survey affirmation
Air pollution	POL_A	When choosing for my residential place, I paid attention to the air quality in the neighborhood
	POL_B	I think I am exposed to air pollution in and around my dwelling
	POL_C	I feel concerned by air pollution issues in my neighborhood
	POL_D	I think air pollution constitutes a risk to my health
	POL_E	Since I have been living in this dwelling, I have already felt the effects of exposure to pollution on my body (pain, shortness of breath, etc.)
Natural areas	GRE_A	When choosing for my residential place, I paid attention to the proximity to green and natural areas
	GRE_B	I think the street where I live is sufficiently vegetated (trees, flowers...)
	GRE_C	I think the green spaces in my neighborhood are pleasant
	GRE_D	I feel safe in the green spaces of my neighborhood
	GRE_E	I regularly visit green spaces in my neighborhood
Floods	FLO_A	When choosing for my residential place, I paid attention to the risks of flooding in the neighborhood
	FLO_B	I think that my home is exposed to the risk of flooding in the next 30 years
	FLO_C	I feel concerned by the danger of heavy rains and floods in my neighborhood
	FLO_D	I am worried about the risk of flooding in my neighborhood
Clay swelling	CLA_A	When choosing for my residential place, I paid attention to the risks of clay swelling

- CLA_B I think that my home is exposed to the risk of clay shrinkage-swelling in the years to come
- CLA_C I feel concerned by the danger of modification of the clay soils in my neighborhood
- CLA_D I am worried about the risk of modification of the clay soils in my neighborhood

D.3. Sample composition

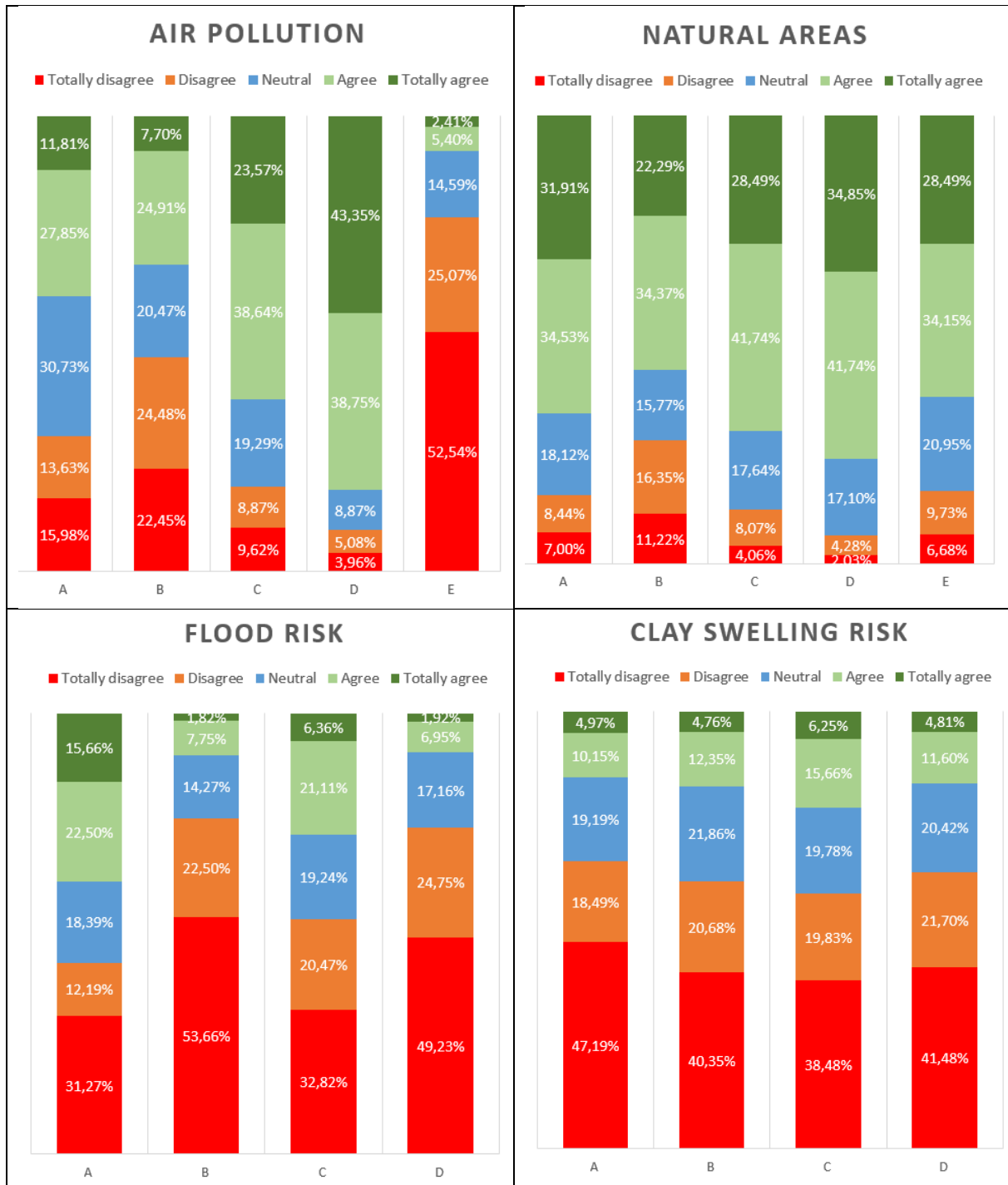
Table D.3.1 Share of respondents in the different regions

Region	Sample		General population (2023)
	N	%	%
Auvergne Rhône Alpes	244	13.0	12.5
Bourgogne Franche Comté	114	6.1	4.3
Bretagne	139	7.4	5.2
Centre Val de Loire	95	5.1	3.9
Grand Est	153	8.2	8.5
Hauts de France	124	6.6	9.1
Ile de France	297	15.9	18.9
Normandie	73	3.9	5.1
Nouvelle Aquitaine	184	9.8	9.3
Occitanie	191	10.2	9.3
Provence Alpes Côte d'Azur	142	7.6	7.9
Pays de la Loire	115	6.1	6.0
Total	1,871	100	100

D.4. Environmental risks perceptions

Figure D.1 – Descriptive statistics associated to each environmental risk

Note to the reader: see Appendix D.2 for details on the affirmations corresponding to the different environmental features.



D.5. Results of the MNL model for affirmation B

Table D.5.1 – Estimation results of the MNL model for affirmation B “I think I am exposed to [risk] in and/or around my dwelling”

Variable	Coefficient	Std. error	t-stat
log(price)	-3.424*	2.037	-1.69
log(price) * (age-18)/10	-0.141	0.094	-1.49
log(price) * log (income)	0.545***	0.274	1.99
density [1000 persons/km]	-0.017	0.021	-0.82
log(tt_{CBD})	-0.143***	0.059	-2.41
Migration cost	-0.105***	0.006	-16.25
tt_{job}	-0.156***	0.011	-13.06
socio-eco level	0.508***	0.104	4.86
housing stock	0.069*	0.037	1.86
PM2.5 _{avg}	0.089	0.284	0.32
flood _{risk}	-0.143	0.257	-0.56
natural areas	0.682***	0.271	2.52
natural areas * density	0.345***	0.108	3.18
clay _{risk}	-0.322***	0.122	-2.65
PM2.5 _{avg} * $\gamma_{pollution}$	-0.712***	0.339	-2.10
flood _{risk} * γ_{flood}	0.025	0.504	0.06
natural areas * $\gamma_{natural\ areas}$	0.598	0.527	1.14
clay _{risk} * γ_{clay}	0.402*	0.21	1.92
log(price) * $\gamma_{pollution}$	0.38	0.382	1.00
log(price) * γ_{flood}	-0.465	0.456	-1.02
log(price) * $\gamma_{natural\ areas}$	-0.253	0.459	-0.56
log(price) * γ_{clay}	-0.055	0.399	-0.14
PM2.5 _{avg} * duration/10	-0.085	0.091	-0.94
flood _{risk} * duration/10	-0.038	0.107	-0.36
natural areas * duration/10	-0.208*	0.113	-1.84
clay _{risk} * duration/10	-0.011	0.047	-0.24

* Significant at the 10% level.

** Significant at the 5% level.

*** Significant at the 1% level.

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French summary

1. Introduction générale

1.1. Contexte : la chaîne de vulnérabilités impliquée par les choix résidentiels

La dernière décennie a été caractérisée par l'émergence de divers mouvements sociaux, qui demandaient plus d'équité dans la société. En France, le mouvement des Gilets Jaunes qui a débuté à l'automne 2018 a été initialement motivé par l'annonce d'une augmentation de la taxe carbone conformément aux objectifs climatiques plus ambitieux de la France, et a ensuite été renforcé par la hausse des prix du baril des carburants, le coût élevé de la vie et les inégalités économiques. Le mouvement a souligné qu'en France, le poids de la fiscalité pesait de manière disproportionnée sur les classes populaires et moyennes, en particulier dans les zones rurales et périurbaines. Au Chili, un mouvement similaire est apparu en octobre 2019. L'Estallido Social, une série de manifestations massives et d'émeutes, a débuté à Santiago et s'est déroulée dans toutes les régions du Chili jusqu'en 2021. Les manifestations ont eu lieu en réponse à une augmentation du tarif du ticket de métro à Santiago, une hausse du coût de la vie due à la crise du marché immobilier et d'importantes inégalités socio-économiques. Ces deux exemples, tirés des deux pays couverts par cette thèse, démontrent l'interdépendance des coûts de transport et de la localisation résidentielle, ainsi que les implications sociales de cette interdépendance. En particulier, le poids des coûts de transport dans le budget des ménages est central, qu'il s'agisse de l'utilisation de la voiture ou des transports en commun.

Parallèlement, de nombreuses marches pour le climat ont été organisées dans le monde entier à la suite de la COP26 à Glasgow (2021). Plus de 200 manifestations ont été organisées dans le monde entier, notamment à Sydney, Paris, Londres, Nairobi et Mexico, afin d'exiger des gouvernements qu'ils prennent l'action climatique plus au sérieux. Ces manifestations ont démontré les préoccupations d'une jeune génération - représentée par Greta Thunberg - qui tire la sonnette d'alarme sur le besoin urgent d'agir contre le changement climatique. Outre le manque d'action forte, ils dénoncent également l'injustice de la transition écologique, illustrée par le sentiment que les riches détruisent la planète en polluant plus et en faisant peu d'efforts pour réduire leur impact, alors que les plus pauvres polluent moins mais devraient contribuer fortement à l'effort de réduction.

Il y a donc deux mouvements contradictoires dans la population, l'un axé sur les questions budgétaires, l'autre sur les questions environnementales. Ces différents mouvements mettent en effet en avant une demande de justice sociale dans la mise en œuvre de la transition écologique et plus particulièrement des politiques climatiques, qui pourraient nécessiter une forte capacité d'adaptation qui, en l'état actuel, pourrait être hors de portée d'une partie de la population. Ils soulignent notamment que la lutte contre le changement climatique ne doit pas se faire à n'importe quel prix et doit apporter des solutions alternatives et un soutien aux ménages les plus vulnérables.

En fin de compte, ces différents défis se mélangent et s'entrechoquent. Premièrement, les choix résidentiels individuels peuvent conduire à une dépendance vis-à-vis de la consommation d'énergie, créant ainsi une vulnérabilité aux prix de l'énergie. Deuxièmement, la vulnérabilité aux politiques climatiques peut conduire à une augmentation des inégalités. Ces questions soulèvent une certaine ambiguïté : d'une part, une demande de lutte contre le changement climatique et, d'autre part, un désir de préserver les vieilles habitudes en utilisant des voitures polluantes bon marché. En théorie, agir sur ces deux aspects en même temps pourrait revenir à raccourcir les distances parcourues, et donc repenser les choix de localisation résidentielle. En effet, la localisation résidentielle conditionne la mobilité, mais la mobilité est aussi un choix. Ces deux choix sont donc fortement liés et sont conditionnés par de nombreuses contraintes (financières, organisationnelles, professionnelles). Ils sont également influencés

par la façon dont les gens perçoivent leur environnement et les risques qui y sont associés. Par conséquent, pour agir sur ces secteurs spécifiques, il faut prendre en compte les vulnérabilités existantes, les impacts potentiels des politiques environnementales et le rôle des perceptions individuelles.

1.1.1. Comprendre les comportements de mobilité induits par les choix résidentiels

En France, la population a commencé à augmenter fortement dans les centres urbains dès la fin des années 1960, entraînant une hausse des prix du logement dans les villes (Dumont et al., 2022). Les centres-villes ont donc été rapidement pris d'assaut et remplis à pleine capacité. Dans un contexte de prix bas de l'énergie, et suite à la politique tout-voiture du gouvernement Pompidou (Sauvy, 1968), de nombreux ménages ont décidé de s'installer en banlieue, où ils pouvaient s'offrir une maison plus grande et avoir accès à des espaces naturels. Dans ce contexte, le processus de périurbanisation a commencé et a conduit à l'expansion des villes pour permettre aux ménages de vivre plus ou moins près des services et des emplois offerts par la ville. Premièrement, le processus de périurbanisation a entraîné une augmentation de la distance entre les lieux de résidence et les services ou emplois essentiels : dans les années 1960, le trajet quotidien moyen en France était de 3 km, contre 13,3 km en 2019 (Enquête Mobilité des Personnes, 2019). Deuxièmement, l'augmentation des prix des logements dans les centres-villes a été suivie d'une baisse des coûts des voitures particulières, et le parc automobile français est passé de 20 millions en 1980 à 41,2 millions en 2023 (Ministère de la Transition écologique, 2023).

En ce sens, le choix d'un lieu de résidence est le résultat d'un compromis entre temps de transport et prix de l'immobilier (Alonso, 1964 ; Muth, 1969 ; Mills, 1972 ; Fujita, 1989 ; Duranton et al., 2015). En particulier, le processus de périurbanisation a conduit à une distribution spatiale spécifique des prix du logement, avec peu de logements bon marché disponibles dans les quartiers centraux. Dans certaines villes, de nombreux ménages à faibles revenus ne peuvent pas choisir librement leur lieu de résidence, car ils sont limités par des questions financières (Tiznado-Aitken et al., 2022). Cette situation a progressivement conduit à une ségrégation résidentielle dans de nombreuses villes (c'est-à-dire la séparation spatiale des groupes de population entre les quartiers urbains) (Massey et Denton, 1988). En France, la question de la ségrégation se pose essentiellement en termes socio-économiques, mais elle est également liée à des préoccupations ethniques, en particulier dans les quartiers défavorisés (Pan Ké Shon, 2010). Gaschet et Le Gallo (2005) ont montré que la "distance socio-économique" entre les cadres et les travailleurs peu qualifiés entraînait une importante ségrégation socio-spatiale dans les municipalités de Paris, Lyon, Bordeaux et Dijon. En étudiant les 50 plus grandes agglomérations françaises, Madoré (2015) a confirmé ce résultat en expliquant que la hiérarchie socio-spatiale (correspondant à la classification spatiale des ménages selon leur niveau de vie) est bien marquée dans toutes les villes, avec une ségrégation plus forte dans les villes denses par rapport aux périphéries.

Au-delà des questions socio-économiques, réduire les choix résidentiels à un simple arbitrage entre les coûts de transport, la durée des trajets domicile-travail et les prix de l'immobilier masquerait l'hétérogénéité existante dans les préférences et les caractéristiques des ménages. Par exemple, les ménages avec enfants peuvent opter pour une maison avec plus de chambres, vivre loin des centres urbains au prix d'un temps de trajet plus long, tandis que les travailleurs célibataires peuvent préférer vivre près de leur lieu de travail pour profiter des commodités de la ville. Certains ménages peuvent également privilégier le fait d'avoir un jardin ou de vivre dans une zone moins polluée ou moins bruyante.

Par conséquent, ces schémas de ségrégation peuvent conduire à des inégalités socio-économiques et environnementales (Schaeffer et al., 2016). Ainsi, le choix d'un lieu de résidence conditionne notamment la qualité de l'environnement dans lequel les personnes décident de vivre, mais aussi, par conséquent, les externalités négatives auxquelles elles devront faire face. Ces choix sont particulièrement contraignants, car le loyer d'un appartement, l'achat d'une nouvelle voiture, ou l'organisation personnelle

(en termes de contraintes professionnelles par exemple) représentent des choix contraignants à long terme.

Ainsi, la localisation résidentielle apporte à la fois des contraintes et des opportunités en termes de mobilité et d'accès aux services. Les contraintes et habitudes de mobilité sont donc la conséquence des choix de localisation résidentielle. Dans nos sociétés contemporaines, la mobilité conditionne l'accès aux opportunités et aux services en permettant de se déplacer et d'aller d'un endroit à un autre. Quel que soit le lieu de résidence, chacun devrait pouvoir accéder aux activités et services essentiels. En d'autres termes, la qualité de vie augmente avec la capacité - indépendamment des handicaps physiques ou cognitifs, du sexe, de l'âge ou du statut socio-économique - de se rendre au travail, de rencontrer des gens et d'avoir accès aux soins de santé, à l'éducation, aux magasins et à la culture. Plus précisément, dans les zones périurbaines, la voiture est souvent le seul mode de transport disponible. Par conséquent, les choix résidentiels sont souvent conditionnés par la nécessité d'acheter une ou plusieurs voitures et/ou de trouver d'autres alternatives pour accéder aux services et aux emplois, qui sont principalement situés dans et autour des centres urbains. En ce sens, les choix résidentiels déterminent structurellement la mobilité, et en particulier l'utilisation des modes de transport. C'est pourquoi les questions de mobilité et de choix résidentiels devraient toujours être considérées simultanément (Coulombel, 2018).

Outre l'importance de la mobilité dans la société, les secteurs du transport et du résidentiel sont également associés à des externalités négatives et à des enjeux importants en matière de changement climatique. D'une part, le secteur des transports est le premier contributeur aux émissions de gaz à effet de serre (GES) de la France et représente 31% des émissions en 2019. Plus précisément, au sein du secteur des transports, le transport routier est de loin le plus gros émetteur, représentant plus de 70% des émissions de GES liées aux transports, 16,1% des émissions ambiantes de $PM_{2.5}$, 10,8% des émissions ambiantes de PM_{10} et 37% des émissions de NO_x à l'échelle mondiale (EEA, 2019). D'autre part, les bâtiments résidentiels (logements) représentent 17% des émissions mondiales de GES, dont 75% sont liées aux systèmes de chauffage. Le chauffage au bois peut également être à l'origine d'une importante pollution atmosphérique lorsqu'il est brûlé dans de mauvaises conditions. Si le bois est considéré comme un émetteur non lié aux GES, divers polluants sont émis lors de la combustion du bois, notamment une quantité importante de particules fines (PM_{10} et $PM_{2.5}$), qui sont particulièrement nocives pour la santé humaine. En ce sens, les transports et le logement ont des effets négatifs importants sur l'environnement et la santé humaine, tels que la pollution de l'air, le bruit et les îlots de chaleur urbains. En particulier, la pollution de l'air a des effets majeurs et avérés sur la mortalité et la morbidité, principalement en ce qui concerne la santé cardiovasculaire et respiratoire. En 2019, dans le monde, neuf personnes sur dix vivant en zone urbaine ont été exposées à des niveaux de particules fines ($PM_{2.5}$) provenant de la pollution de l'air extérieur supérieurs à la valeur guide de l'Organisation mondiale de la santé (OMS) de 2005 (concentration annuelle moyenne de $PM_{2.5}$ de $10 \mu g/m^3$), et plus encore à la valeur guide actuelle de $5 \mu g/m^3$. Elle représente un problème majeur de santé publique : l'exposition aux $PM_{2.5}$ ambiantes provoque chaque année environ 4,2 millions de décès dans le monde, 417 000 en Europe, et environ 40 000 en France (OMS, 2022).

1.1.2. Évaluer les vulnérabilités multidimensionnelles liées aux choix de résidence et de mobilité

1.1.2.1. Vulnérabilité ou vulnérabilités ?

Nous avons déjà mentionné les questions de vulnérabilité découlant de la localisation résidentielle et des choix de mobilité. Dans cette thèse, nous explorons le concept de vulnérabilité dans différents contextes : par exemple, la vulnérabilité aux risques naturels tels que les inondations, ou la vulnérabilité à l'augmentation du prix des carburants. En ce sens, la vulnérabilité peut être définie, mesurée, interprétée et appliquée de différentes manières, et il n'existe pas de théorie ou de définition universelle

de la vulnérabilité. En particulier, chaque discipline étudiée tend à considérer la vulnérabilité d'une manière légèrement différente. En ce sens, Alwang et al. (2001) ont proposé une définition multidisciplinaire attrayante de la vulnérabilité, basée sur cinq principes identifiés :

- a) La vulnérabilité est un concept prospectif, défini comme la probabilité de subir une perte dans le futur par rapport à un niveau de référence ;
- b) Un ménage peut être vulnérable à une perte future de bien-être, et cette vulnérabilité est due à des événements incertains ;
- c) Le degré de vulnérabilité dépend des caractéristiques du risque et de la capacité du ménage à y faire face et/ou à s'y adapter ;
- d) La vulnérabilité dépend de l'horizon temporel. Un ménage peut être vulnérable aux risques sur une période d'un mois, d'un an ou plus courte ;
- e) Les ménages pauvres ou quasi-pauvres ont tendance à être vulnérables en raison de leur accès limité aux ressources (au sens le plus large) et de leur capacité limitée à faire face aux risques.

Selon Adger (2006), *"la vulnérabilité est le plus souvent conceptualisée comme étant constituée de composantes qui incluent l'exposition et la sensibilité aux perturbations ou aux stress externes, et la capacité d'adaptation"*, ce qui signifie que la vulnérabilité globale dépend de trois facteurs : l'exposition, la sensibilité et l'adaptation. Pour être vulnérable, un ménage doit être menacé par un risque, un changement ou, plus généralement, une modification de ses conditions de vie actuelles susceptible d'avoir un impact sur son bien-être (exposition). Il doit également être sensible à ce risque : par exemple, un ménage sans voiture ne sera pas sensible à une augmentation des prix du carburant. La vulnérabilité est également influencée par le potentiel d'adaptation, qui est souvent lié à l'aspect financier, mais pas uniquement. Par exemple, une mesure politique compensatoire peut contribuer à augmenter les capacités d'adaptation.

Sur la base de ces définitions, nous pouvons donc supposer que le fait de vivre dans un lieu de résidence spécifique peut être à l'origine de différentes vulnérabilités. En effet, la ségrégation socio-spatiale existante, les caractéristiques environnementales, les risques et les problèmes de mobilité associés à ce lieu de résidence sont des caractéristiques importantes qui peuvent affecter le bien-être. En ce sens, les vulnérabilités peuvent prendre plusieurs formes : vulnérabilité socio-économique, vulnérabilité environnementale (aux risques environnementaux (Cutter et al., 2003), au changement climatique (Otto et al., 2017), aux politiques climatiques (Kortetmäki et Järvelä, 2021)) ou, plus spécifiquement, vulnérabilité en matière de carburant/mobilité, qui peut même conduire à la pauvreté en carburant/transport (Mayer et al., 2014). Dans les sous-sections suivantes, nous nous concentrons sur les vulnérabilités liées à l'environnement et à la mobilité, qui sont au cœur de cette thèse.

1.1.2.2. Vulnérabilités environnementales

Le choix du lieu de résidence conditionne d'abord l'environnement dans lequel un ménage va vivre, mais aussi plusieurs paramètres spécifiques tels que la qualité de l'air, les risques environnementaux et l'accès à des espaces verts ou à des zones de loisirs. Ce choix peut donc impliquer d'être affecté par des vulnérabilités environnementales ou nécessiter de pouvoir s'adapter pour faire face aux risques environnementaux.

Tout d'abord, en ce qui concerne la qualité de l'air, de nombreuses études concluent que les groupes les plus précaires ont tendance à être plus exposés aux polluants atmosphériques et aux substances toxiques et soulignent la répartition inégale de la charge environnementale entre les groupes sociaux (Finkelstein et al., 2005 ; Chaix et al., 2006 ; Marshall, 2008 ; Laurian et Funderburg, 2014 ; Verbeek, 2019). Une méta-analyse réalisée pour les années 2010-2017 en Europe a confirmé que les indices de privation plus élevés et les niveaux économiques faibles sont généralement liés à des niveaux plus élevés de polluants,

sans distinction (Fairburn et al., 2019). La littérature prouve donc que les ménages les plus précaires sont généralement exposés à des niveaux de polluants plus élevés en Écosse (Fairburn et al., 2005), en Suède (Chaix et al., 2006), aux Pays-Bas (Kruize et Bouwman, 2004) et en France (Havard et al., 2009 ; Lanier et al., 2019). En particulier, une étude récente réalisée en France a montré que 60% des quartiers où vivent les 10% de la population aux plus faibles revenus sont exposés à des niveaux de PM_{2.5} qui dépassent la norme de l'OMS, alors que 80% des quartiers des 10% aux revenus les plus élevés respectent au contraire cette norme (Champalaune, 2021). Le même phénomène est observé à l'échelle des villes de Londres (Goodman et al., 2011) et de Grenoble (Morelli et al., 2019). Toutefois, cette dernière étude souligne également que la forme de la ville conditionne ces conclusions ; par exemple, à Lyon, les classes moyennes semblent être les plus touchées. D'autres études portant sur des services spécifiques ont également montré des inégalités d'exposition similaires. Ainsi, Carrier et al. (2014) ont constaté que les concentrations de NO₂ à proximité des écoles sont positivement associées aux niveaux de privation plus élevés et que les écoles ayant un indice de privation plus élevé ont tendance à être situées dans les zones les plus polluées de Montréal.

Deuxièmement, tant au niveau des pays que des individus, les plus démunis sont aussi les plus vulnérables aux impacts du changement climatique (Guivarch et Taconet, 2020), mais aussi plus généralement aux risques multirisques tels que les tornades, les ouragans ou les inondations (Räsänen et al., 2016 ; Forzieri et al., 2016). En effet, dans ce cas, les vulnérabilités sont souvent associées à la mauvaise qualité des habitations (bidonvilles *versus* bâtiments en dur), mais aussi à l'accès à l'eau potable et à l'assainissement. L'ampleur des impacts du réchauffement climatique est donc corrélée aux vulnérabilités et limite les capacités d'adaptation (Hallegatte, 2016). Les vulnérabilités sont ainsi exacerbées par des inégalités préexistantes de différentes natures, qui interagissent entre elles et se renforcent.

Pour limiter ces vulnérabilités environnementales, l'accès aux parcs et aux espaces verts constitue un potentiel d'adaptation important. En effet, les espaces verts dans les quartiers sont des éléments essentiels de l'environnement bâti et sont souvent répartis de manière inéquitable dans l'espace public. En particulier, dans le contexte nord-américain, de nombreuses études ont montré que la majeure partie de la couverture arborée était fortement liée à une situation socio-économique élevée (Shanahan et al., 2014 ; Landry et Chakraborty, 2009 ; Pham et al., 2012 ; Schwarz et al., 2015).

1.1.2.3. Vulnérabilités liées à la mobilité

Outre les vulnérabilités environnementales, le choix d'un lieu de résidence peut être à l'origine de vulnérabilités en matière de mobilité. En raison de différents facteurs, tels que des coûts de mobilité élevés, de grandes distances à parcourir, le prix des carburants, des contraintes liées à l'emploi ou à la famille, certains ménages peuvent être confrontés à des difficultés, que l'on pourrait qualifier de vulnérabilités en matière de mobilité. En effet, la vulnérabilité ne peut être réduite à l'aspect financier et dépend d'une combinaison de facteurs qui renvoient à différentes dimensions : dimension économique, spécificité des distances et des déplacements, structure familiale, capacité à se reporter sur d'autres modes de transport, etc.

Les vulnérabilités en matière de mobilité peuvent provenir de différentes sources. Tout d'abord, les vulnérabilités peuvent être la conséquence de politiques environnementales visant à faire face aux externalités des contributions des transports au réchauffement climatique et aux émissions qui y sont liées. Compte tenu de l'importance des émissions liées au transport routier, les politiques de transport visent souvent à s'attaquer aux problématiques liées aux voitures, en mettant l'accent sur les effets de la pollution de l'air. Ces politiques et interventions publiques peuvent prendre différentes formes, telles que de nouvelles infrastructures (par exemple, l'extension des réseaux de transports publics existants ou la construction de pistes cyclables) ou des stratégies de tarification (par exemple, la taxation des voitures

les plus polluantes ou la gratuité des transports publics). Ces mesures peuvent également s'appuyer sur des réglementations (par exemple, limiter la production de véhicules à carburant dans le secteur industriel) ou sur des campagnes d'information et de sensibilisation. Cependant, ces politiques peuvent avoir des impacts hétérogènes parmi les groupes sociaux, à la fois en termes de bénéfices pour la santé et d'impacts économiques (Sanchez, 2018). De nombreuses études empiriques ont été réalisées dans le monde entier, à Rio (Pereira et al., 2019), San Francisco (Bills et Walker, 2017) ou Seattle (Franklin, 2006), et confirment que les politiques de transport peuvent exacerber les inégalités socio-spatiales au lieu de les réduire, et soulignent donc la nécessité de mesures de redistribution, en particulier pour les ménages à faible revenu.

Parmi ces mesures, les zones à faibles émissions (ZFE) sont désormais très communes en Europe. Les ZFE ont été créées dans le but d'améliorer la qualité de l'air et protéger la santé des habitants des grandes agglomérations où la pollution atmosphérique est très élevée. Les ZFE sont basées sur un périmètre où seuls les véhicules les moins polluants sont autorisés à circuler. En France, la Loi Climat et Résilience (2021) a introduit l'obligation de mettre en place une ZFE, d'ici décembre 2024, dans toutes les agglomérations de plus de 150 000 habitants. Cela aurait représenté une quarantaine d'agglomérations mais le gouvernement français a finalement reculé sur cette obligation en juillet 2023 notamment par crainte que ces zones ne soient pas acceptées par une partie de la population. Les ZFE ne seront obligatoires que dans les cinq agglomérations où les seuils réglementaires de NO₂ sont régulièrement dépassés : Lyon, Paris, Rouen, Marseille et Strasbourg.

Si une telle politique est censée bénéficier aux personnes vivant à l'intérieur et à l'extérieur du périmètre de restriction, comme cela a été démontré à Paris (Poulhès et Proulhac, 2021), d'autres études soulignent que la mise en œuvre d'une ZFE pourrait en fait avoir l'effet inverse et accroître les inégalités de santé préexistantes en améliorant davantage la santé des plus riches que celle des plus pauvres. Plusieurs études menées à Rome (Cesaroni et al., 2012) ou à Paris (Host et al., 2020) ont conclu qu'une ZFE était efficace pour réduire la pollution atmosphérique liée au trafic et les effets sur la santé (tels que les décès prématurés ou l'asthme), mais que la plupart de ces gains de santé étaient déviés vers les résidents les plus riches.

D'un point de vue social, les restrictions de mobilité imposées par les ZFE n'affectent pas seulement les ménages vivant dans le périmètre délimité et augmentent donc le risque d'exclusion sociale, qui correspond à un manque de ressources, de droits, de biens et de services, et à l'incapacité de participer aux relations et aux activités normales (Levitas et al., 2007 ; Lucas, 2012). En effet, comme on l'a vu par exemple à Anvers, certaines personnes vivant dans la ZFE se sentent coupables lorsque des amis extérieurs à la zone leur rendent visite, ce qui les oblige à respecter les restrictions imposées par la ZFE. (De Vrij et Vanoutrive, 2022). La situation peut donc être compliquée du point de vue des relations sociales pour ceux qui n'ont pas les moyens d'acheter un véhicule plus propre mais plus cher.

Outre les politiques environnementales, de nouvelles vulnérabilités en matière de mobilité peuvent également résulter de changements dans les conditions de voyage. Ces changements peuvent survenir à la suite de différents événements. Par exemple, le contexte géopolitique actuel et l'invasion de l'Ukraine par la Russie ont entraîné une augmentation du prix des carburants, ce qui conduit à une situation particulièrement difficile pour les usagers de la voiture et particulièrement les ménages dépendants à la voiture. Dans le même temps, la pandémie de COVID-19, qui a réduit les déplacements au strict minimum et conduit à l'adoption du télétravail, a également modifié les habitudes de mobilité, même si les effets à long terme restent incertains pour l'instant. Cependant, les transports publics ont été fortement évités et les déplacements en voiture individuelle ont été privilégiés, ce qui a encouragé l'achat d'une voiture à un moment donné (Kim et al., 2023 ; Vega-Gonzalo et al., 2023). Par conséquent, selon la capacité d'adaptation à ces chocs soudains et à ces épidémies, des vulnérabilités en matière de mobilité peuvent apparaître ou non.

1.1.2.4. Vulnérabilité *versus* pauvreté

Lorsque l'on évoque la vulnérabilité, on pense souvent en premier lieu aux ménages les plus modestes. Les pauvres et les quasi-pauvres ont tendance à être vulnérables en raison de leur accès limité aux ressources (au sens large) et de leur capacité limitée à faire face aux risques (Alwang et al., 2001). Dans le secteur des transports, le concept de "pauvreté transport" (*Transport Poverty*) résulte de la transposition du concept de "pauvreté énergétique" au secteur des transports afin de désigner les ménages qui ne sont pas en mesure de satisfaire tous leurs besoins basiques de mobilité. Cependant, ce concept est récent et n'a pas encore de définition établie dans la littérature académique ou politique. Il est actuellement utilisé pour décrire les situations dans lesquelles les personnes n'ont pas accès aux services essentiels ou au travail en raison d'un manque d'options de mobilité. Parmi les éléments conduisant à la pauvreté en matière de transport suggérés, on trouve dans la littérature l'absence de disponibilité des transports, une mauvaise accessibilité des transports, un coût élevé des transports, des temps de trajet importants ou des conditions de transport inadéquates (Lucas et al., 2016).

Si l'étude de la pauvreté transport met en lumière les personnes actuellement pauvres, de nombreuses vulnérabilités liées à la mobilité peuvent également conduire à une situation de pauvreté à l'avenir, si les ménages ne sont pas en mesure de s'adapter et de faire face à la situation. Cependant, la vulnérabilité est différente des questions de pauvreté. En effet, la vulnérabilité ne peut être réduite à l'aspect financier et dépend d'une combinaison de facteurs, qui peuvent être économiques, mais aussi organisationnels, structurels ou liés à l'emploi, par exemple. Si l'on prend l'exemple d'un gros rouleur qui pourrait être affecté par une interdiction de circulation (type ZFE) ou une augmentation des prix du carburant, il ne sera pas nécessairement vulnérable s'il peut se reporter à d'autres modes de transport, tels que les modes actifs ou les transports publics. Par conséquent, en fonction de la capacité d'adaptation pour réduire la dépendance à la voiture, les vulnérabilités observées ne seront pas les mêmes et pourront concerner différents groupes de population, qui ne sont pas nécessairement pauvres.

1.1.2.5. Une accumulation de vulnérabilités révélant une problématique de justice sociale

Des vulnérabilités de différentes natures peuvent se cumuler et affecter certains groupes de population, en particulier les plus vulnérables et les plus pauvres. En effet, malgré l'ambition de l'Accord de Paris, de nombreuses études ont montré que les pays qui ont le plus contribué au changement climatique seront aussi les moins impactés par ses effets (Islam et Winkel, 2017 ; Guivarch et Taconet, 2020 ; Chancel et al., 2022). En effet, les pays les moins avancés sont responsables de moins de 4% des émissions mondiales de CO₂, mais ont subi 69% des décès causés par les catastrophes climatiques depuis 1972 (CNUCED, 2022). Au sein des pays, les ménages les plus démunis contribuent généralement moins aux émissions, mais sont les plus susceptibles d'être exposés aux effets négatifs du changement climatique. En France, les émissions de GES ont tendance à augmenter avec le niveau de vie (Pottier et al., 2020), de même que les émissions de particules fines (Fosse et al., 2022).

Enfin, les politiques climatiques tendent à générer des coûts de transition qui pourraient peser plus lourdement sur les personnes les plus vulnérables aux effets du réchauffement climatique (Reghezza-Zitt, 2023). En particulier, de nombreuses études montrent que le risque de résultats sociaux et distributifs négatifs des politiques d'atténuation du climat augmente "dans des contextes caractérisés par des niveaux élevés de pauvreté, de corruption et d'inégalités économiques et sociales" (Markkanen et Anger-Kraavi, 2019, p.837) (voir par exemple Hunsberger et al., 2014 ; Larson et al., 2015 ; Westholm, 2016). D'emblée, les politiques climatiques peuvent être source d'inégalités lorsque leurs coûts pèsent plus lourdement sur les personnes à faible revenu ou lorsque certaines catégories sociales sont exclues de leurs bénéficiaires.

Si l'on se concentre plus particulièrement sur le secteur des transports, les émissions sont également très hétérogènes en fonction du niveau de vie. En France, les ménages les plus riches se déplacent presque trois fois plus que les plus pauvres. Cette variabilité des émissions liées au transport peut être décomposée en examinant les différences de distances parcourues et les modes de transport. En particulier, la disponibilité des équipements de transport joue un rôle important : la part des ménages sans voiture privée diminue régulièrement avec le niveau de vie. À Paris, Leroutier (2020) a constaté que les émissions de CO₂ liées aux déplacements des individus ont tendance à augmenter sans équivoque avec le revenu. Simultanément, les choix résidentiels ont une forte influence sur les émissions car ils affectent à la fois la mobilité et les modes de transport disponibles. Par exemple, les ruraux ont tendance à parcourir de plus grandes distances que les citadins et utilisent souvent des modes de transport plus polluants. Pour un jour de semaine représentatif, Leroutier et Quirion (2022) ont constaté que les 20% les plus émetteurs contribuent à 85% des émissions de NO_x, 78% des émissions de CO₂ et 78% des émissions de PM_{2,5} dans le secteur des transports.

Par conséquent, le fait que les ménages les plus démunis soient également les plus susceptibles d'être affectés par les effets du changement climatique et les politiques climatiques, mais aussi ceux qui contribuent le moins aux émissions et aux dommages, soulève une importante question de justice sociale. En effet, la justice sociale vise à garantir un traitement équitable des individus et des groupes et à faire en sorte que chaque groupe socio-économique reçoive une part équitable des avantages sociaux et économiques, ainsi que des avantages environnementaux.

D'une part, alors que la justice sociale et la dégradation de l'environnement étaient perçues comme deux questions opposées, les mouvements sociaux de justice environnementale nous invitent à examiner leurs interactions (Mohai et al., 2009). Par exemple, les récentes "marches pour le climat" qui ont eu lieu dans le monde entier illustrent le fait que la crise écologique et les problèmes sociaux qui y sont liés constituent désormais une préoccupation transnationale partagée par des personnes de différents pays (Schlosberg et Collins, 2014). Ces manifestations font pression sur les décideurs pour qu'ils prennent des mesures justes et adaptées aux conséquences du réchauffement climatique auxquelles les individus sont actuellement confrontés, en adoptant une approche favorable aux pauvres. En particulier, la demande d'un environnement sain pour tous et d'une distribution équitable des bénéfices environnementaux (tels que les espaces verts) et des dommages (tels que la pollution ou les risques d'inondation) est centrale. En effet, en observant la corrélation entre les externalités environnementales et les territoires les plus précaires, les populations affectées soulignent les impacts cumulés des inégalités sociales, environnementales et politiques dont elles souffrent (Drique et Lejeune, 2017).

D'autre part, l'exigence de justice et d'équité dans la distribution des biens et des services, l'accessibilité pour les personnes, le caractère abordable de tous les types de services (y compris les biens immobiliers), font écho au concept de justice dans les transports (*Transport Justice*) (Litman, 2002 ; Bullard et al., 2004). En effet, la justice dans les transports souligne que l'accessibilité est une condition essentielle à la réalisation de la justice sociale, grâce à sa contribution à la réduction de l'exclusion sociale (Hine, 2008). La justice dans les transports soutient donc que les gouvernements doivent fournir à chaque personne un transport adéquat et ainsi atténuer les disparités sociales qui ont été créées dans le passé, avec une préoccupation particulière pour les personnes défavorisées (Martens, 2016). En ce sens, les défis de la justice sociale, qu'ils soient liés aux vulnérabilités et aux inégalités en matière d'environnement ou de mobilité, sont fortement interconnectés et interdépendants.

Afin de réduire les vulnérabilités induites par les choix résidentiels, deux leviers principaux peuvent être utilisés. Premièrement, les vulnérabilités environnementales, qui sont directement liées aux risques environnementaux perçus, doivent être soigneusement évaluées lors du choix d'un lieu de résidence. Deuxièmement, modifier les comportements de mobilité en encourageant le report modal vers des

alternatives à la voiture peut également permettre de limiter les vulnérabilités de mobilité associées au choix d'un mode de transport.

1.1.3. Améliorer la perception des risques pour limiter les problèmes de vulnérabilité environnementale

En général, un risque correspond à "une situation, un événement ou une activité qui peut conduire à des résultats négatifs incertains affectant quelque chose qui nous tient à cœur" (Böhm et Tanner, 2018, p.16). Les deux composantes essentielles du risque sont la gravité et l'incertitude de l'issue défavorable (ou perte), qui sont particulièrement difficiles à évaluer. En outre, si les risques sont étudiés et quantifiés de manière objective, différents facteurs externes jouent également un rôle sur la manière dont les personnes feront face à ces risques.

En particulier, les approches du risque sont fondamentalement déterminées par les attitudes et les perceptions du risque (c'est-à-dire l'inclination de l'individu à prendre des risques qui émerge de sa personnalité) (Vasvári, 2015). Ces perceptions créent un biais dans l'évaluation subjective des risques au niveau individuel. La perception des risques est le jugement que les gens portent sur les caractéristiques et la gravité d'un risque), cognitifs (gravité des événements, couverture médiatique, mesures d'atténuation des risques, etc.), contextuels (cadre des informations sur les risques, disponibilité d'autres sources d'information, etc).

Différentes approches techniques, économiques, psychologiques, sociologiques et anthropologiques de la perception des risques ont été développées (Renn, 1992). Une approche bien établie pour étudier la perception des risques est le paradigme psychométrique (Slovic, 1987), qui vise à identifier la "carte cognitive" de divers événements, activités ou technologies à risque et ses dimensions psychologiques sous-jacentes qui amènent les individus à percevoir quelque chose comme plus ou moins risqué. Ensuite, la conceptualisation du cadre de l'amplification sociale du risque - une approche interdisciplinaire - a tenté d'expliquer le processus par lequel les risques sont amplifiés lorsqu'ils reçoivent l'attention du public (amplification sociale), ou atténués lorsqu'ils reçoivent moins d'attention (atténuation sociale) (Kasperson et al., 1988).

Ces différentes approches ont permis d'identifier les principaux facteurs influençant la perception des risques, qui sont énumérés et décrits dans le Tableau S.1.

Tableau S.1 Principaux facteurs expliquant la perception des risques

Facteur	Description	References
Evenements extraordinaires	À première vue, il semblerait logique que les événements plus fréquents soient plus facilement récupérés dans la mémoire, mais les événements "choquants" majeurs ont tendance à rester dans les esprits et sont donc perçus comme étant plus fréquents.	Kahneman and Tversky (2012)
Fréquence	Les personnes ont tendance à surestimer les petites fréquences et à sous-estimer les grandes lorsqu'ils évaluent la fréquence de divers dangers.	Lichtenstein et al. (1978)
Actualisation temporelle	Les perceptions sont davantage influencées par les événements récents ou actuels que par ceux qui se sont produits des années auparavant.	Böhm and Pfister (2005)
Familiarité	Les perceptions sont biaisées par la familiarité et l'affect avec la source de risque, ce qui réduit la perception sensorielle du danger et/ou fait juger le risque comme faible et le bénéfice comme élevé.	Finucane et al. (2000)
Optimisme	Un optimisme irréaliste peut être observé lorsque les personnes pensent que les événements négatifs ont tendance à arriver aux autres plutôt qu'à elles-mêmes.	Weinstein (1980)
Valeurs protégées	Demander aux gens de "mettre un prix" sur des choses qu'ils considèrent comme protégées - en rapport avec leurs valeurs, leur éthique et leur morale - peut induire de fortes réactions affectives négatives.	Baron and Spranca, (1997); Hanselmann and Tanner, (2008)
Fiabilité et clarté des sources d'information	Des descriptions différentes des risques peuvent créer des effets de cadrage susceptibles d'altérer les décisions des personnes.	Tversky and Kahneman (1981)
Confiance	La confiance dans les programmes de contrôle et de gestion des risques gérés par l'État encourage des choix plus risqués.	Colquitt et al. (2007); Earle (2010)

Le réchauffement climatique et la trajectoire actuelle des émissions à l'échelle mondiale ont considérablement augmenté la probabilité d'être affecté par des changements environnementaux irréversibles (GIEC, 2023). Par conséquent, les catastrophes naturelles associées - telles que les inondations, les tempêtes, les cyclones, les tremblements de terre, les incendies de forêt, les glissements de terrain ou les vagues de chaleur - sont une source de risques qu'il convient de prendre sérieusement en considération.

Les risques environnementaux diffèrent des autres risques à plusieurs égards. Premièrement, les risques environnementaux se caractérisent par un degré élevé de complexité et d'incertitude, impliquant des relations de cause à effet complexes et des conséquences multiples. Deuxièmement, les risques environnementaux résultent souvent de l'accumulation des comportements de nombreux individus (par exemple, l'utilisation généralisée des combustibles fossiles) plutôt que d'une activité unique, ce qui rend l'atténuation de ces risques particulièrement difficile. Enfin, les conséquences des risques environnementaux sont souvent décalées dans le temps et géographiquement éloignées. Ainsi, les

personnes qui contribuent à un risque (par exemple en émettant des GES) ne sont pas nécessairement celles qui en subiront les conséquences (générations futures).

Les risques environnementaux existants sont bien documentés à l'échelle locale. Cependant, ces risques environnementaux objectifs pourraient être sous ou sur perçus, car la perception des risques constitue un aspect important des comportements individuels. Il est donc essentiel d'examiner la manière dont les gens perçoivent les risques environnementaux pour comprendre leurs décisions et leurs comportements face à l'exposition à ces risques (Böhm et Tanner, 2018). En effet, les perceptions des risques environnementaux ne sont souvent pas cohérentes avec les mesures objectives de l'exposition, ce qui signifie qu'une fois de plus, les ménages se relocalisent dans un lieu en fonction de leurs propres perceptions de l'environnement local plutôt que de se concentrer sur des caractéristiques objectives. La difficulté de percevoir le niveau réel de sa propre vulnérabilité est en partie due au fait que l'on ne perçoit pas à quel point les individus et les sociétés sont responsables des catastrophes (Wachinger et al., 2013). En effet, percevoir la vulnérabilité implique d'accepter le fait que les risques sont aussi le résultat de facteurs internes aux sociétés et ne sont pas seulement des conséquences des aléas. Par conséquent, ce faible niveau de perception entraîne souvent une sous-estimation des risques (Nezlek et Zebrowski, 2001 ; Kim et al., 2018).

En effet, les ménages évaluent souvent à tort leur exposition à la qualité de l'air et/ou à la pollution sonore. À Madrid, Chasco et Le Gallo (2013) ont montré que les prix des logements s'expliquent mieux par des facteurs d'évaluation subjectifs que par des mesures objectives de la pollution atmosphérique et sonore, ce qui est cohérent avec les résultats d'Adamowicz en Alberta, au Canada (1997). En effet, ils ont montré que les résidents des quartiers riches ne perçoivent pas leur environnement comme étant très pollué car ils sont influencés par leur conviction que la qualité de l'air dans d'autres quartiers de la ville est bien pire.

Le même phénomène est observé pour les risques d'inondation, qui ont été largement étudiés dans la littérature. Lechowska (2018) a réalisé une étude systématique sur la perception des risques d'inondation et a identifié plusieurs facteurs susceptibles d'influencer les perceptions. Tout d'abord, l'inquiétude ou l'expérience antérieure directe d'un risque naturel est très significative. Ensuite, le fait d'être préparé à l'événement (facteur comportemental) et d'être informé (sensibilisation) semble être particulièrement important. En conclusion, les risques d'inondation ont été particulièrement bien étudiés d'un point de vue subjectif dans la littérature. Des analyses similaires ont été menées sur les perceptions des tremblements de terre (Palm, 1998 ; Armaş, 2006) ou des tornades aux États-Unis (Ellis et al., 2018 ; Jauernic et Van Den Broeke, 2016). Ils ont tous conclu à l'importance des facteurs subjectifs et en particulier des expériences antérieures. En fait, lorsque l'on considère les multirisques, les ménages ont tendance à se déplacer en fonction de leurs attentes concernant la proximité des dangers, l'expérience antérieure des dangers et la perception du risque personnel (Lindell et Hwang, 2008).

Par conséquent, la mise en œuvre de mesures d'adaptation aux différents impacts climatiques et aux risques associés devrait être basée sur des évaluations comprenant à la fois des variables objectives et des perceptions subjectives des risques afin de mieux correspondre aux comportements réels. En effet, si les perceptions ne correspondent pas aux variables objectives, les mesures d'adaptation ne seront pas efficaces pour résoudre les problèmes de vulnérabilité. Dans le même temps, les perceptions peuvent également conduire les individus à adopter des stratégies d'adaptation qui ne sont pas forcément les plus bénéfiques. Par exemple, plusieurs études analysant la manière dont les perceptions des agriculteurs peuvent expliquer les contraintes liées à l'adaptation au changement climatique ont été menées dans les pays en développement. Elles ont montré que la perception d'un manque d'information était un facteur important expliquant la réticence à adopter des mesures d'adaptation (voir par exemple Datta et al., 2022 ; Pickson et He, 2021). En ce sens, les perceptions sont un facteur central à prendre en compte pour l'élaboration des politiques et, en particulier, pour l'adoption de stratégies d'adaptation.

1.1.4. Modifier les comportements en matière de mobilité pour réduire les impacts et les vulnérabilités induites par les choix de mode de transport

Outre la gestion des vulnérabilités environnementales, le deuxième grand défi consiste également à réduire les vulnérabilités en matière de mobilité. Pour ce faire, le principal levier consiste à modifier les comportements de mobilité en faveur de modes de transport moins polluants, moins chronophages et/ou moins coûteux. Il est donc essentiel de comprendre les déterminants du choix des modes de transport afin d'encourager les ménages à se tourner vers les transports publics ou les modes actifs plutôt que d'utiliser leur voiture.

1.1.4.1. Déterminants du choix du mode de transport

Les déterminants de la mobilité et du changement de mode de transport sont nombreux et multidimensionnels. Pour les identifier, De Witte et al. (2013) ont adopté une approche multidisciplinaire, définissant le choix modal comme "le processus de décision pour choisir entre différentes alternatives de transport, qui est déterminé par une combinaison de facteurs sociodémographiques individuels et de caractéristiques spatiales, et influencé par des facteurs socio-psychologiques". L'examen de 76 papiers sur le choix modal a permis de définir trois catégories de facteurs objectifs : 1) les indicateurs sociodémographiques (tels que l'âge, le sexe, l'éducation, le revenu, la disponibilité d'une voiture ou la structure du ménage), 2) les indicateurs des caractéristiques du trajet (but du trajet, durée du trajet, distance, enchaînement des trajets ou conditions météorologiques) et 3) les indicateurs spatiaux (stationnement ou proximité des infrastructures et des services). Les facteurs socio-psychologiques sont constitués des expériences antérieures, du mode de vie, des habitudes et des perceptions. Plus récemment, Javaid et al. (2020) ont réalisé une méta-analyse de 75 articles traitant des déterminants de l'adoption des modes actifs (modes à faible émission de carbone). L'analyse de la littérature permet de classer les déterminants du report modal en trois catégories principales : 1) les facteurs individuels tels que les attitudes, les croyances ou les habitudes ; 2) les facteurs sociaux (influence sociale, normes sociales) ; et 3) les facteurs liés à l'infrastructure (aménagement du territoire, qualité et coûts du système de transport).

Les deux études soulignent que si le choix du mode de transport est particulièrement bien expliqué par les caractéristiques du trajet et/ou les facteurs liés aux infrastructures, les facteurs subjectifs tels que les perceptions sont rarement étudiés et moins significatifs que d'autres facteurs. Par exemple, ces perceptions peuvent inclure les temps de trajet et les coûts des différents modes de transport, car la variation des modes de paiement peut entraîner une différence dans la perception des prix et la façon dont le temps est vécu (confort, retard) peut influencer le choix.

L'approche socio-psychologique vise à expliquer le choix modal par l'étude des attitudes des individus à l'égard des moyens de transport disponibles. Les concepts d'intentions et d'habitudes sont des éléments importants de cette approche. Dès 1965, Lovelock a souligné l'importance des variables psychologiques dans la compréhension du choix modal. Par la suite, de nombreux chercheurs ont convenu que le choix modal ne devait pas seulement être étudié sur la base de mesures objectives, mais qu'il devait également prendre en compte les caractéristiques subjectives (voir par exemple Hine et Scott, 2000 ; Van Acker et al., 2010 ; Lang et al., 2011 ; Bamberg, 2012). L'étude de Javaid a en effet confirmé que les perceptions relatives au comportement commun en matière de déplacements (normes sociales descriptives), en particulier si elles sont soutenues par les croyances normatives perçues des autres (normes injonctives), influencent fortement le changement de mode de transport. Par conséquent, le choix modal ne devrait pas être étudié uniquement en tenant compte des aspects économiques, mais aussi des facteurs liés à la géographie des transports et à la psychologie sociale.

1.1.4.2. L'influence des perceptions sur le choix du mode de transport

Les perceptions sont à la base des habitudes et des choix de mobilité, car elles sont censées conditionner les comportements. En effet, comme ces perceptions influencent les comportements de mobilité des individus, elles peuvent également être la source de vulnérabilités en matière de mobilité ou, pire encore, de pauvreté transport. Un exemple typique est la sous-estimation des coûts de mobilité (temps et argent) associés à leur lieu de résidence (Tiznado-Aitken et al., 2022). C'est pourquoi la prise en compte des perceptions dans l'étude des comportements de mobilité est particulièrement importante pour l'élaboration des politiques.

Plusieurs études empiriques ont pris en compte les facteurs attitudinaux et les perceptions pour expliquer le choix du mode de transport. Aux États-Unis, une étude sur le choix du mode de transport a montré que les variables démographiques et les variables attitudinales sont extrêmement importantes pour expliquer le choix du mode de transport. Les résultats soulignent notamment que la contribution des facteurs attitudinaux est plus importante que celle des variables démographiques (Kuppam et al., 1999). Une étude portant plus particulièrement sur les autobus a également montré que les perceptions de la fiabilité et du confort des services d'autobus ont un impact plus important sur les préférences des passagers que les perceptions de la disponibilité et de la sécurité en Chine. En France, une étude menée dans la région Rhône-Alpes a également montré que la perception d'un niveau de confort élevé était un facteur déterminant dans le choix des transports publics (Bouscasse et de Lapparent, 2019). Par ailleurs, lorsqu'on compare le train à l'avion, les préférences des voyageurs aériens sont principalement motivées par la minimisation de leur temps de trajet perçu alors que les usagers du train valorisent la productivité du temps de trajet (Dällenbach, 2020), ce qui est confirmé par une autre étude menée en Rhône Alpes sur les retards dans les transports (Bouscasse et de Lapparent, 2020).

Parmi toutes les perceptions et attitudes étudiées dans la littérature, la perception de l'accessibilité constitue un autre facteur important, qui est également déterminant pour les choix résidentiels (Blijie, 2005). Si l'accessibilité est traditionnellement mesurée en fonction du temps de trajet et de la distance vers un certain nombre de destinations prédéterminées, le concept d'accessibilité perçue a suscité de l'intérêt au cours de la dernière décennie afin de saisir la perspective individuelle de l'accessibilité en utilisant un certain mode de déplacement (Lättman et al., 2016) et/ou en se rendant dans des lieux spécifiques. L'introduction de ce concept dans de nouvelles études a montré que les études sur l'accessibilité qui tendent à comprendre les comportements individuels ne peuvent pas se limiter à l'accessibilité calculée (Pot et al., 2021).

En particulier, les études sur l'accessibilité perçue indiquent que les évaluations auto déclarées de l'accessibilité correspondent souvent mal aux mesures d'accessibilité calculées, ce qui signifie que l'accessibilité objective n'était pas nécessairement la raison pour laquelle les gens décident de choisir un mode de transport spécifique ((Lotfi et Koohsari (2009) ; Dewulf et al. (2012) ; Curl et al. (2015) ; Curl (2018) ; Van der Vlugt et al. (2019). Cette inadéquation a été étudiée dans différents contextes et pour différents groupes de population. Par exemple, en Australie, Ryan et al. (2016) ont montré que les personnes âgées connaissent l'accessibilité la plus faible, tandis que les personnes d'âge moyen perçoivent l'accessibilité la plus élevée. En Suède, Lättman et al. (2018) ont montré que les niveaux d'accessibilité calculée ne permettent pas de prédire l'accessibilité perçue dans une zone résidentielle donnée, mais ont également souligné que les niveaux d'accessibilité perçue diffèrent entre les principaux modes de transport. Par conséquent, les perceptions incorrectes de l'accessibilité peuvent également être à l'origine des vulnérabilités en matière de mobilité, et devraient donc être prises en compte dans les évaluations de l'impact des politiques.

1.1.5. Résumé et manques de la littérature

Les politiques climatiques et environnementales sont souvent axées sur les secteurs du transport et du logement en raison de leurs contributions importantes aux émissions. Pourtant, la littérature a montré que ces politiques peuvent créer ou exacerber des inégalités préexistantes.

Si les questions de précarité énergétique et de vulnérabilité ont considérablement intéressé les chercheurs, notamment lorsqu'ils se sont concentrés sur le secteur du logement, l'ensemble des vulnérabilités induites par les choix résidentiels reste à explorer. En effet, l'identification des vulnérabilités liées au transport et, en particulier, la possibilité de mener une évaluation multidimensionnelle de ces vulnérabilités est particulièrement limitée. Si certains indicateurs existent pour mesurer les vulnérabilités liées à l'utilisation de la voiture, aux dépenses de carburant, aux faibles revenus ou aux temps de trajet, l'intégration de ces dimensions complémentaires reste un défi important. De plus, à notre connaissance, il n'existe pas de méthodologie permettant de définir des profils de ménages vulnérables spécifiques à un territoire. Pourtant, cela constituerait un outil particulièrement utile pour la prise de décision, en particulier lorsqu'il est reproductible à l'échelle des villes.

Dans le même temps, l'action climatique incite et les décideurs mettent en œuvre de nouvelles politiques aux niveaux national et local sans nécessairement avoir le recul nécessaire pour comprendre les impacts sociaux attendus. Si les ZFE sont très répandues en Europe, leur mise en place en France a débuté récemment et a été brutalement stoppée en juillet 2023 suite à une recommandation du Sénat. A notre connaissance, la plupart des études portant sur les ZFE se concentrent sur l'efficacité environnementale et sanitaire, mais peu explorent les impacts socio-économiques ou de mobilité attendus, en particulier avant la mise en œuvre. Dans ce contexte, les tentatives d'amélioration de la qualité de l'air dans les villes pourraient conduire à une aggravation de la situation des ménages vulnérables, ce qui représente un défi majeur en termes de justice sociale (De Vrij et Vanoutrive, 2022). Or, cette évaluation est essentielle pour assurer l'acceptabilité de la politique par le public mais aussi pour adapter la ZFE au contexte local et définir des mesures d'accompagnement afin de minimiser leur impact sur les personnes les plus vulnérables. En effet, les récents revirements en France montrent que plus les ZFE sont adaptées et spécifiques au contexte local, plus elles ont de chances d'être acceptées, mises en œuvre et donc efficaces. D'où l'importance d'une étude *ex ante*.

L'étude de la pauvreté transport soulève également la question importante de la dépendance à la voiture, qui est particulièrement fréquente dans les zones périurbaines. En effet, l'évolution des habitudes de mobilité vers des modes plus propres implique une augmentation de l'accessibilité pour ceux qui dépendent actuellement de la voiture. Or, dans les zones urbaines, les transports publics ne sont pas toujours une option réaliste. En outre, l'accessibilité telle qu'elle est traditionnellement mesurée par les temps de parcours ou les indicateurs basés sur les distances n'est pas suffisante pour évaluer véritablement les comportements et les préférences des ménages. En fait, l'accessibilité perçue semble mieux expliquer le choix d'un mode de déplacement, ce qui montre l'importance d'inclure et d'analyser les perceptions des automobilistes lors de la conception de systèmes de transport accessibles et durables (Lättman et al., 2020). Les chercheurs ont donc récemment commencé à intégrer l'accessibilité perçue dans leurs études, mais ces travaux restent principalement limités au contexte du nord et aux centres urbains, tandis que les zones périurbaines ont reçu moins d'attention.

Enfin, comme le choix d'un lieu de résidence conditionne les habitudes de mobilité, mais détermine également la qualité de l'environnement (qualité de l'air, accès aux espaces verts, risques de danger), il est essentiel de comprendre dans quelle mesure les risques environnementaux sont pris en compte dans les choix de localisation résidentielle afin de pouvoir limiter les vulnérabilités. En effet, aujourd'hui, dans le contexte du changement climatique, on peut penser que les gens ont tendance à accorder plus d'importance aux caractéristiques environnementales, tout en équilibrant les contraintes budgétaires et les distances à parcourir. Si certains attributs environnementaux ont été intégrés dans des modèles de choix résidentiels, ils ont surtout été étudiés individuellement. En outre, le rôle des perceptions est une

fois de plus central et a été moins étudié dans la littérature. Il serait donc intéressant d'étudier si les perceptions qu'ont les individus de plusieurs facteurs environnementaux peuvent avoir un impact significatif sur les choix résidentiels et dans quelle mesure ces perceptions peuvent augmenter ou réduire l'exposition aux risques environnementaux.

1.2. Contributions de cette thèse

1.2.1. *Questions de recherche*

Si les mesures d'atténuation sont souvent perçues comme opposées aux intérêts économiques des ménages, il est pourtant essentiel de construire une transition écologique juste afin de renforcer la cohésion sociale, de réduire les inégalités et d'offrir des alternatives désirables et durables pour l'avenir. Pour ce faire, la transition écologique nécessite de prendre en compte les différentes dimensions des vulnérabilités et des inégalités : vulnérabilités socio-économiques, d'exposition, de contribution et cumulatives au niveau individuel. Cela pose également la question de la faisabilité politique de cette transition. En particulier, les récents mouvements sociaux montrent qu'il est important de prendre en compte ces dimensions sociales avec soin. Ainsi, comprendre les choix de mobilité et de logement à travers le prisme des différentes dimensions des vulnérabilités, des politiques publiques et des perceptions est crucial pour mettre en place une transition écologique juste et équitable.

Cette thèse vise à mettre en lumière les questions de vulnérabilité des ménages dans ce contexte de transition énergétique. Ceci est particulièrement pertinent pour définir des politiques environnementales ambitieuses sans oublier les questions de justice sociale qui y sont associées. La **question centrale de cette thèse** est donc la suivante : *Comment les politiques publiques et les perceptions individuelles influencent-elles les décisions de mobilité et de logement, et les vulnérabilités qui en découlent ?*

Nous répondons à cette question de recherche principale en définissant quatre sous-questions.

Tout d'abord, il est important de pouvoir identifier les ménages les plus vulnérables, qui sont souvent les plus touchés par les chocs énergétiques ou les politiques publiques. En particulier, sur un territoire spécifique, différents profils de vulnérabilité peuvent émerger en fonction des spécificités des lieux de résidence des ménages. Dans la littérature, de nombreux indicateurs existent pour mesurer les phénomènes liés à la pauvreté transport, tels que les difficultés financières, la dépendance à la voiture, le manque d'accessibilité, mais il est nécessaire de créer un indicateur qui permettrait d'explorer toutes ces vulnérabilités cumulées à la fois et d'identifier des profils types. Notre **première question de recherche** est donc la suivante : *quel outil peut être utilisé pour identifier les ménages les plus vulnérables en termes de mobilité sur un territoire donné ?* Pour répondre à cette question, nous avons conçu VulMob, un indicateur composite permettant d'évaluer les vulnérabilités et la pauvreté à l'échelle locale, et l'avons appliqué à la région grenobloise.

En particulier, la stratégie française visant à limiter les émissions de GES et de polluants du secteur des transports prévoyait initialement la mise en place de ZFE dans une quarantaine de zones urbaines. Même si ce projet était soudainement stoppé en juillet 2023, il reste important d'évaluer les impacts potentiels des ZFE afin de définir des modalités qui pourraient améliorer l'acceptabilité et aider à définir des politiques compensatoires pour fournir un soutien aux ménages vulnérables dont le potentiel d'adaptation est limité. Pourtant, la plupart des publications évitent d'explorer les impacts socio-économiques *ex ante* de la mise en œuvre d'une ZFE, ou le font *a posteriori*. Notre **deuxième question de recherche** est donc la suivante : *quels sont les impacts d'une ZFE sur les vulnérabilités en matière de mobilité ?* En particulier, nous nous attachons à distinguer les impacts sur les ménages pauvres et vulnérables et sur le reste de la population en analysant les comportements de mobilité sur la base des enquêtes locales sur les déplacements des ménages.

Néanmoins, les politiques publiques visant à limiter la dépendance à la voiture doivent tenir compte de la manière dont les gens perçoivent leur potentiel de mobilité. Pour ce faire, il est également important de comprendre les déterminants subjectifs du choix du mode de transport dans les environnements dépendants de la voiture. Dans les zones périurbaines, qui sont souvent déconnectées des réseaux de transport public et donc fortement dépendantes de la voiture, le potentiel de report modal est souvent limité. Par conséquent, l'étude des perceptions, et plus particulièrement de l'accessibilité perçue, peut être éclairante pour trouver des solutions afin d'améliorer la mobilité. Pourtant, dans la littérature, ces questions sont le plus souvent étudiées d'un point de vue objectif, et se concentrent plus spécifiquement sur le cœur urbain dans le contexte des pays du Nord. Notre **troisième question de recherche** est la suivante : *dans quelle mesure les dimensions subjectives, et plus particulièrement l'accessibilité perçue, jouent-elles un rôle dans la dépendance à la voiture dans les contextes périurbains ?* Nous avons répondu à cette question en développant un modèle intégré de choix avec variables latentes qui a été appliqué à quatre municipalités périurbaines situées autour de Santiago du Chili.

Enfin, les choix résidentiels et les habitudes de mobilité étant étroitement liés, si les gens s'installent en dehors des centres urbains, par exemple pour vivre dans une maison plus grande avec un jardin, c'est souvent au détriment de l'accessibilité. Il est donc essentiel de trouver un équilibre entre une bonne qualité environnementale et le potentiel de mobilité. En effet, dans le contexte actuel de réchauffement de la planète, les risques multiples associés au changement climatique vont considérablement augmenter et de devenir de plus en plus dévastateurs (GIEC, 2023). Par conséquent, notre **dernière question de recherche** vise à comprendre *dans quelle mesure les risques environnementaux et les espaces naturels sont-ils pris en compte lors des choix résidentiels ?* Nous répondons à cette question en utilisant deux modèles de choix discrets conçus pour expliquer le choix résidentiel à l'échelle de la municipalité en France.

1.2.2. Cas d'étude

Les différents chapitres se concentrent sur trois zones d'étude : les chapitres 1 et 2 prennent Grenoble (France) comme cas d'étude, puis le chapitre 3 se concentre sur Santiago (Chili), tandis que le chapitre 4 est basé sur l'ensemble de la France métropolitaine. Ce dernier cas d'étude ne sera pas détaillé.

1.2.2.1. Grenoble, France

Nous avons choisi Grenoble comme première étude de cas pour cette thèse. Le laboratoire d'Economie Appliquée (GAEL) étant situé à Grenoble, notre équipe de recherche a développé au fil des années des relations solides avec les décideurs politiques et les institutions locales, ce qui constitue un grand avantage en termes de connaissance des spécificités du territoire et d'accès aux données utiles. De plus, dans le cadre de la Loi Climat et Résilience (2021), la mise en place d'une ZFE pour les véhicules personnels concernait l'agglomération grenobloise, même si cette exigence a finalement été levée en juillet 2023. Grenoble a également été l'une des premières agglomérations à mettre en place une ZFE pour les véhicules de livraison en 2019, ainsi qu'une "zone 30", limitant la vitesse à 30km/h dans le centre urbain.

La métropole Grenoble-Alpes est située dans les Alpes françaises, dans le sud-est de la France. Elle comprend la ville de Grenoble (158 240 habitants) et 48 communes voisines, accueillant au total une population d'environ 450 000 habitants sur une superficie d'environ 550 km². La région grenobloise est communément décrite selon un schéma en sept secteurs, définis à partir des massifs montagneux existants : la Bièvre, le Voironnais, le Grésivaudan, le Sud-Grésivaudan, le Sud-Isère, la Chartreuse et le Vercors entourent la métropole.

Grenoble est entourée de trois chaînes de montagnes, mais c'est l'une des villes les plus plates de France. Cette situation a des conséquences importantes sur la qualité de l'air, car les montagnes ont tendance à

restreindre les flux d'air et donc à concentrer les particules fines et ainsi augmenter la pollution atmosphérique locale. Cette situation topographique particulière a également des conséquences en termes d'organisation du territoire de l'agglomération avec une altitude qui augmente très rapidement au fur et à mesure que l'on s'éloigne du centre et que l'on se rapproche de l'un des trois massifs montagneux. De ce fait, il est plus difficile de mettre en place des réseaux de transports en commun à l'extérieur de Grenoble que dans la plupart des autres villes françaises.

Un maire écologiste dirige Grenoble depuis 2014. La ville est souvent considérée comme pionnière en France en matière d'écologie et d'environnement, et a été élue "Capitale verte de l'Europe" en 2022. Une politique volontariste en matière de transports en commun et de vélo a notamment été développée ces dernières années.

La ville est attractive pour les étudiants et les travailleurs hautement qualifiés, grâce à son université et à son marché du travail dynamique (avec un taux d'accès à l'emploi de 38%, contre 34% en moyenne en France). Le taux de chômage est faible (5,8% dans la région grenobloise contre 7,0% en France en 2023 (Data Emploi, T4 2022)) et les opportunités d'emploi dans le secteur industriel sont importantes. Les ménages sont donc en moyenne plus aisés et plus diplômés que dans la plupart des aires urbaines françaises de taille comparable. En effet, près d'un quart des actifs occupés de la zone sont des cadres, contre un cinquième dans la zone de référence. De plus, le revenu moyen par habitant dans la métropole grenobloise est plus élevé que dans le reste de la France (respectivement 25 801 €/an et 22 040 €/an (INSEE, 2022)).

Cependant, cette situation favorable cache de fortes inégalités de revenus et des dynamiques de ségrégation résidentielle. La ville de Grenoble accueille à la fois des ménages aisés et des ménages défavorisés. En effet, la municipalité se caractérise par d'importantes inégalités de revenus : les 10% de ménages les plus riches gagnent près de 4 fois plus que les 10% les plus pauvres, ce qui constitue l'écart le plus important de l'agglomération. Malgré un niveau de vie élevé, 27 000 personnes vivent sous le seuil de pauvreté, soit un taux de pauvreté de près de 20% (contre moins de 15% pour l'ensemble de l'agglomération). A Grenoble, les familles avec enfants et les retraités isolés sont surreprésentés dans les situations de pauvreté monétaire. Le diagnostic social de l'agglomération grenobloise révèle que 23 000 ménages seraient en situation de précarité énergétique (c'est-à-dire qu'ils n'auraient pas les moyens de chauffer leur logement à un coût raisonnable, compte tenu de leurs revenus) en 2020 (ADES, 2023). Grenoble est également connue pour ses quartiers urbains défavorisés, avec une forte concentration de pauvres, de chômeurs, de personnes peu qualifiées et d'immigrés. En effet, contrairement à d'autres villes de France, les personnes précaires ont tendance à vivre dans le centre urbain (la moitié des bénéficiaires de l'aide sociale de la région vivent à Grenoble) (INSEE, 2015), où elles peuvent avoir accès aux transports publics et aux services, mais où elles sont aussi plus touchées par les problèmes de qualité de l'air.

1.2.2.2. Santiago, Chili

Santiago du Chili constitue le deuxième cas d'étude. Cette région est particulièrement intéressante pour l'objet de cette thèse étant donné les mouvements de justice sociale qui s'y sont déroulés récemment. Mon parcours scolaire antérieur m'a déjà conduit à plusieurs reprises en Amérique Latine, et cette nouvelle expérience a été possible grâce à l'aimable invitation du Professeur Giovanni Vecchio. Cette partie de ma thèse a été réalisée à l'Instituto de Estudios Urbanos y Territoriales (IEUT), à l'Université Catholique de Santiago (*Pontificia Universidad Católica de Chile*), un institut de recherche qui se concentre sur les études urbaines et les questions de mobilité et qui regroupe principalement des chercheurs en géographie, planification urbaine, économie et ingénierie des transports.

En 2012, en Amérique latine, près de 80% de la population vivait dans des villes, ce qui en fait la région la plus urbanisée du monde (ONU, 2012). En particulier, les zones urbaines sont essentielles dans l'organisation spatiale du Chili, puisque près de 90% de la population vit en ville. En effet, les trois principales régions métropolitaines (RM) du pays génèrent plus de 63% du PIB et 60% de la population vit dans la région métropolitaine centrale de Santiago.

Le Chili, situé à l'ouest de l'Amérique latine, est le pays le plus méridional du monde et le plus proche de l'Antarctique. Il s'étend sur une étroite bande de terre entre la cordillère des Andes et l'océan Pacifique. Le pays compte plus de 17 millions d'habitants. Le Chili s'étend sur plus de 4 300 km du nord au sud, mais seulement 350 km à son point le plus large, d'est en ouest. Cela englobe une remarquable variété de climats et de paysages, avec le désert le plus aride au nord et des glaciers au sud. La cordillère des Andes est également la raison pour laquelle de nombreuses villes chiliennes sont confrontées à d'importants problèmes de qualité de l'air, comme c'est le cas à Santiago.

Santiago, la capitale et principale ville du Chili, est située dans la zone centrale du pays, entourée de montagnes, et compte plus de 6 millions d'habitants répartis dans de nombreuses municipalités. Ces municipalités étaient d'anciennes villes rurales qui ont été progressivement intégrées au "Gran Santiago". Cependant, dans la région métropolitaine, chaque municipalité fonctionne de manière autonome, sans autorité métropolitaine supérieure. En ce sens, l'organisation fonctionnelle de la RM de Santiago peut être décrite en considérant 48 municipalités, 14 autres municipalités ayant également des liens étroits avec le noyau urbain (Fuentes et al., 2018).

Le Chili est considéré comme une économie à haut revenu et est l'une des nations les plus stables d'Amérique du Sud, en tête de l'Amérique Latine en termes de compétitivité, de revenu par habitant, de mondialisation, de paix et de liberté économique. La dictature de Pinochet (1973-1990) a eu des conséquences importantes sur le développement du Chili. Sur le plan économique, son régime a été marqué par la libéralisation de l'économie, la liberté du commerce et l'ouverture du pays à la concurrence internationale, des réformes inspirées par les "Chicago boys", en rupture avec les politiques économiques interventionnistes antérieures. Les partisans de ces réformes ont loué la situation de "stabilité économique" atteinte par le Chili sous le régime de Pinochet, mais l'étendue, voire la réalité, de ce succès économique a fait l'objet de nombreux débats.

En particulier, le développement historique de Santiago a été fortement influencé par la dictature et la mise en œuvre de politiques néolibérales fortes. En particulier, les processus d'éradication menés dans le cadre de la politique nationale de développement urbain (1979-1985) ont entraîné le déplacement de milliers de ménages à faibles revenus du cadre nord-est de la métropole vers ses marges occidentales et méridionales. Ce phénomène exacerbe les inégalités socio-spatiales et la ségrégation existante à la fois dans la métropole et entre les municipalités (Garreton, 2017). En particulier, les résidents les plus riches vivent actuellement dans la partie orientale de Santiago, où se trouvent la plupart des activités, tandis que les ménages les plus vulnérables sont plus susceptibles de vivre à l'ouest, loin des opportunités d'emploi. Il en résulte une localisation inégale des emplois mais aussi des richesses dans la région métropolitaine de Santiago. Suazo-Vecino et al. (2020) montrent que cette évolution de la ville a été préjudiciable aux familles vulnérables, en augmentant de manière significative le temps de trajet moyen vers le centre de la ville et l'inégalité entre les différents groupes socio-économiques. En particulier, les ménages à faible revenu semblent être les plus touchés et les résultats suggèrent qu'ils bénéficieraient de politiques orientant l'évolution du centre d'activités vers eux.

En raison de la répartition inégale des activités et de l'importante ségrégation spatiale observée dans la région métropolitaine, la mobilité est donc un élément clé à Santiago.

À Santiago, l'utilisation de la voiture a augmenté, en particulier depuis les pandémies, augmentant ainsi les temps de trajet associés aux "coûts de congestion". À Buenos Aires, Blanco et Apaolaza (2018) ont trouvé une corrélation significative entre la possession d'une voiture et le niveau de revenu. En effet, à Santiago, un revenu élevé implique souvent des temps de trajet plus courts et une utilisation plus importante de la voiture. De plus, les ménages ayant les revenus les plus élevés se déplacent plus, plus rapidement et ont un meilleur accès à la voiture en moyenne (Iglesias et al., 2019). Pourtant, si l'extension urbaine semble être corrélée à des temps de parcours plus élevés, cela dépend de la préférence des ménages pour la voiture ou les transports en commun. La préférence pour le véhicule privé est souvent justifiée par le confort et le caractère bon marché des véhicules, les voitures ayant un prix final plus bas au Chili que dans le reste des pays de la région. Cependant, tout le monde ne peut pas se permettre de l'acheter et de l'utiliser, et les ménages à faible revenus sont captifs des transports publics. Pour ceux qui peuvent se le permettre, les résultats montrent une très forte inélasticité par rapport au coût direct de son utilisation : malgré l'augmentation du prix du carburant, il n'y a pas de réduction du trafic à court ou moyen terme (Cortés Salinas et al., 2016).

En particulier, dans les zones périurbaines, les seules infrastructures de transport public existantes sont des services de bus qui ne sont pas inclus dans le système de transport public intégré TranSantiago. Pourtant, certaines zones périphériques se caractérisent par des temps de trajet égaux, voire supérieurs, à ceux des zones périurbaines, pourtant spatialement plus éloignées du centre économique (Vecchio et Tiznado-Aitken, 2022). Cela montre que certaines zones spécifiques ne sont pas facilement accessibles sans voiture. Par exemple, à Guadalajara, passer de la zone périurbaine au centre urbain peut prendre d'une à plus de deux heures (González Pérez, 2018). Cependant, le temps de trajet n'est pas le seul problème auquel il faut faire face : dans les zones périurbaines, l'arrêt de bus peut être éloigné du lieu d'habitation et le trajet peut également être dangereux, par exemple s'il faut marcher la nuit ou à proximité d'une autoroute pour rentrer chez soi. En se concentrant en particulier sur l'accès aux services tels que l'éducation, une étude montre que la plupart des opportunités d'écoles publiques gratuites et de meilleure qualité sont concentrées dans les zones centrales et péri-centrales (Tiznado-Aitken et al., 2021). Par conséquent, les zones périphériques et périurbaines, où réside une grande partie de la demande d'écoles publiques, ont besoin d'opportunités plus proches pour améliorer leur accès à ce service essentiel.

1.2.3. Structure de la thèse

Nous répondons à la question principale de la recherche en définissant quatre sous-questions, chacune d'entre elles constituant un chapitre distinct de la thèse. Cette section présente les principales analyses et les résultats de chaque chapitre.

1.2.3.1. Chapitre 1 : Identification et typologie des ménages hautement vulnérables sur le plan de la mobilité à l'aide de VulMob, un nouvel indicateur composite

Dans les sociétés actuelles, l'accès de tous à des systèmes de transport sûrs, abordables, accessibles et durables permet d'accéder aux emplois et aux services, mais doit également répondre à l'impératif d'inclusion sociale (Cass et al., 2005 ; Preston et Rajé, 2007 ; Stanley et al., 2011).

Or, dans un contexte où la mobilité est largement assurée par le transport individuel motorisé (Mattioli, 2021), certains ménages à faibles revenus ont des coûts de carburant et de mobilité élevés, ce qui les soumet à une pression économique sévère qui peut être définie comme la "pauvreté transport". Par ailleurs, il existe un large éventail de vulnérabilités en matière de mobilité. Ces vulnérabilités découlent de changements dans les conditions de la mobilité individuelle : par exemple, la hausse des prix des carburants ou l'introduction de politiques visant à réduire les externalités négatives de la voiture privée,

telles que la ZFE. Cependant, selon la capacité d'adaptation des ménages, les vulnérabilités ne seront pas les mêmes. Ainsi, être vulnérable ou non dépend d'une combinaison de facteurs qui renvoient à différentes dimensions : dimension économique, spécificité des distances et des déplacements, structure familiale, capacité à se reporter vers d'autres modes, horaires de travail, etc.

Il est donc important de pouvoir identifier à la fois les ménages vulnérables et les ménages pauvres en transport, ainsi que les différentes combinaisons de vulnérabilités en matière de mobilité, afin d'élaborer des politiques qui doivent être géographiquement spécifiques en fonction des caractéristiques du territoire, mais aussi en termes de population ciblée. Ces questions sont essentielles pour mettre en œuvre des politiques justes et équitables visant à réduire les externalités des voitures. En effet, les politiques dans le secteur des transports sont souvent pointées du doigt comme augmentant la pauvreté ou les vulnérabilités en matière de transport. Si les questions de justice sociale ne sont pas prises en compte, la mise en œuvre de ces mesures pourrait être bloquée (Fandio et al., 2020). Dans ce chapitre, nous tentons de répondre à la question suivante : *Quel outil peut-on utiliser pour identifier les ménages les plus vulnérables en termes de mobilité sur un territoire donné ?*

Pour répondre à cette question, nous avons mis au point un indicateur composite permettant d'évaluer, sur un territoire (tel qu'une zone urbaine), le nombre de ménages se trouvant dans les différentes situations de vulnérabilité en matière de mobilité et/ou dans une situation de "pauvreté transport" à la suite de changements dans les conditions de mobilité (augmentation du prix des carburants, politiques, nouvelles infrastructures). Nous avons élaboré l'indicateur VulMob en suivant les lignes directrices de l'OCDE (Nardo et al., 2005, Nardo et al., 2008). Il se compose de treize facteurs individuels organisés en quatre dimensions : ressources financières, contraintes professionnelles, dépendance à la voiture et contraintes structurelles.

Nous avons appliqué cet indicateur à la région de Grenoble en utilisant les données EMC² qui décrivent précisément les habitudes de mobilité de plus de 7 500 ménages vivant dans la région (à la fois à l'intérieur et à l'extérieur de la métropole). Les résultats de cette analyse ont permis d'identifier 9,6% de la population globale comme "hautement vulnérable" (c'est-à-dire cumulant au moins six facteurs de vulnérabilité) et 5,5% comme pauvre en transport (cumulant deux facteurs de problèmes financiers). 1,3% des ménages ont été identifiés comme étant à la fois pauvres en transport et hautement vulnérables et devraient donc faire l'objet d'une attention particulière de la part des pouvoirs publics. Une analyse de regroupement hiérarchique a permis d'identifier cinq profils de ménages hautement vulnérables : certains sont soumis à des contraintes monétaires ; d'autres sont de gros rouleurs, travaillent de nuit ou sont confrontés à des problèmes d'accessibilité territoriale. Ces résultats montrent l'importance de prendre en compte les spécificités des secteurs pour mettre en œuvre les réponses les plus adaptées afin de limiter les vulnérabilités.

1.2.3.2. Chapitre 2 : Évaluation des impacts *ex ante* de la mise en œuvre d'une ZFE dans la région de Grenoble

Le secteur des transports est l'un des plus importants en termes d'émissions de gaz à effet de serre et de polluants atmosphériques et constitue donc un enjeu environnemental majeur. Dans ce contexte, des ZFE ont été mises en place dans toute l'Europe. Elles visent à limiter la circulation des véhicules les plus polluants dans les zones urbaines afin d'améliorer la qualité de l'air. Les impacts positifs des ZFE sur la qualité de l'air ont été prouvés dans de nombreuses villes européennes (Cesaroni, 2012 ; Ferreira et al., 2015 ; Lebrusán et Toutouh, 2021). Cependant, les impacts socio-économiques restent moins étudiés et font l'objet de ce deuxième chapitre.

En France, la crainte que les ménages les plus fragiles soient les plus touchés par les ZFE a ralenti leur adoption. Par exemple, en 2012, la mise en place d'une Zone d'Actions Prioritaires pour l'Air a finalement été annulée par crainte de la faible acceptabilité de ces zones (Charleux, 2014). En 2021, la Loi Climat et Résilience a généralisé la mise en œuvre des ZFE dans toutes les zones urbaines françaises dépassant les valeurs limites. Pourtant, le projet a de nouveau été brutalement arrêté en juillet 2023 suite à une recommandation du Sénat qui mettait notamment en garde contre les impacts sociaux négatifs attendus. Grenoble était l'une des villes qui auraient dû mettre en place une telle ZFE ciblant la mobilité individuelle. La ville a mis en place un comité d'experts pour définir les modalités de mise en œuvre. Malgré la décision du gouvernement de stopper le processus, Grenoble a maintenu le cap et mis en place la ZFE au début de l'été 2023... Il a donc été nécessaire d'identifier les ménages susceptibles d'être concernés par la ZFE et la nature de leurs vulnérabilités préexistantes afin d'en améliorer l'acceptabilité et de définir des politiques compensatoires adaptées.

Nous contribuons à cette littérature en utilisant la région de Grenoble comme étude de cas pour évaluer les impacts *ex ante* de la mise en place d'une ZFE. En particulier, nous essayons de répondre à la question suivante : *quels sont les impacts d'une ZFE sur les vulnérabilités en matière de mobilité ?* Cette évaluation est particulièrement importante pour mettre en œuvre une politique ambitieuse et efficace mais aussi pour définir des mesures compensatoires afin de faciliter l'acceptabilité de la ZFE. L'objectif de ce chapitre est donc de proposer dans un premier temps une évaluation *ex ante* des impacts de la ZFE au niveau individuel, à la fois sur les populations vulnérables et non vulnérables de la région grenobloise, mais aussi d'explorer le potentiel d'adaptation des ménages. En tant que membres du comité scientifique pour la mise en œuvre de la ZFE, nous avons présenté les résultats de ce chapitre aux décideurs locaux de la métropole grenobloise.

Pour répondre à cette question de recherche, nous nous sommes à nouveau appuyés sur les données de l'EMC². Nous avons conçu quatre scénarios pour la mise en œuvre de la ZFE (deux périmètres et deux plages horaires) et évalué les déplacements qui seraient affectés. Ensuite, pour les ménages et les trajets concernés, nous avons exploré trois étapes potentielles d'adaptation. Tout d'abord, nous avons examiné le potentiel de report modal (en tenant compte des distances, des boucles et de l'altitude), puis le potentiel de modification des déplacements (en tenant compte des destinations) et enfin la possibilité d'acheter une nouvelle voiture (en tenant compte du niveau de revenu).

Les résultats montrent que le périmètre le plus large affecterait donc 28 688 ménages (8,0% de la population globale), soit une augmentation de 41,8% par rapport au périmètre le plus petit. Toutefois, une ZFE temporaire ne réduit pas considérablement le nombre de ménages touchés, mais pourrait accroître l'acceptabilité. En outre, les effets de la ZFE ne sont pas répartis uniformément au sein de la population, les ménages identifiés comme hautement vulnérables au chapitre 1 étant particulièrement touchés. Le report modal offre une solution à 57% des ménages concernés et concerne 68% des déplacements. Les déplacements des ménages vulnérables ne sont que légèrement plus dépendants de la voiture (63,2 % sont transférables à d'autres modes, contre 68,1% pour les ménages non vulnérables), mais les ménages vulnérables sont plus susceptibles d'avoir au moins un déplacement qui n'est pas transférable à d'autres modes (58,8% contre 43,5%).

Les modes actifs (marche, vélo) constituent une grande opportunité de report modal et une solution également accessible aux deux types de ménages (vulnérables et non vulnérables). Cependant, les transports publics semblent moins accessibles aux ménages vulnérables. En particulier, en explorant les profils de vulnérabilité, certains profils spécifiques (tels que les gros rouleurs) sont particulièrement menacés par l'absence de solution d'adaptation.

1.2.3.3. Chapitre 3 : Dépendance à la voiture dans les zones péri-urbaines : l'influence de l'accessibilité perçue sur le choix du mode de transport

Dans un contexte caractérisé par la nécessité de réduire la dépendance à la voiture, ce troisième chapitre prend du recul et se concentre sur l'influence des perceptions pour expliquer les choix de mobilité. En effet, l'efficacité des politiques de transport et le potentiel réel d'adaptation à ces politiques dépendent de la compréhension de la manière dont les gens choisissent leur mode de transport. L'étude de l'influence des perceptions sur le choix du mode de transport peut offrir de nouveaux leviers qui pourraient être activés pour promouvoir d'autres modes de transport. En particulier, la dépendance à la voiture induit une pauvreté en matière de transport et des vulnérabilités en matière de mobilité. Dans un contexte de dépendance à la voiture, les personnes sont obligées d'utiliser une voiture pour se déplacer et accéder aux activités et aux opportunités qui sont essentielles pour satisfaire leurs besoins, en raison de l'absence de modes de transport alternatifs et de l'absence de telles opportunités à proximité de leur résidence (Mattioli, 2016).

La plupart des études se concentrent sur les caractéristiques objectives, alors que les dimensions subjectives pourraient également expliquer les formes de vulnérabilité en matière d'accessibilité rencontrées dans les environnements dépendants de la voiture. Comme l'explique le concept d'accessibilité perçue, la manière dont les individus évaluent leur environnement et leur capacité subjective à atteindre une destination et à accéder à des opportunités ne reflète pas nécessairement les résultats des évaluations objectives de l'accessibilité (Lättman et al., 2016 ; 2018). Pourtant, les dimensions subjectives telles que l'accessibilité perçue ont reçu moins d'attention, alors qu'elles pourraient confirmer - voire remettre en question - les résultats des évaluations objectives.

Dans ce troisième chapitre, nous visons à examiner dans quelle mesure l'accessibilité perçue influence les choix modaux dans un contexte de dépendance à la voiture. Nous répondons donc à la question suivante : *Dans quelle mesure les dimensions subjectives, et plus particulièrement l'accessibilité perçue, jouent-elles un rôle dans la dépendance à la voiture dans les contextes périurbains ?* Nous nous concentrons sur Santiago du Chili, un contexte latino-américain dans lequel les questions de pauvreté en matière de transport ont été largement examinées, mais seulement en partie en tenant compte de leurs dimensions subjectives. En particulier, nous avons l'intention de comparer les environnements périphériques et périurbains, qui partagent une dépendance fonctionnelle vis-à-vis des zones de la ville dans lesquelles se concentrent la plupart des opportunités (emplois, santé, etc.), mais dont les conditions socio-économiques et l'accès aux transports publics sont différents (Tiznado-Aitken et al., 2023).

Pour répondre à cette question, nous avons examiné les données d'une enquête téléphonique menée en 2020 dans le cadre du projet Centro de los Objetivos de Desarrollo Sostenible para América Latina y el Caribe (CODS), impliquant 300 ménages dans quatre municipalités périphériques et périurbaines de la région métropolitaine de Santiago. Nous avons développé un modèle intégré de choix avec variables latentes qui inclut les attributs des ménages, les attributs du voyage et les indicateurs psychométriques. Une analyse factorielle menée sur ces indicateurs psychométriques a permis d'identifier la variable latente de l'accessibilité perçue qui est intégrée dans le modèle.

Les résultats ont montré que l'accessibilité perçue a un impact net négatif sur les utilités des modes motorisés, ce qui signifie qu'une faible accessibilité perçue augmente la probabilité de choisir la voiture, et encore plus les transports publics. En outre, les habitants des municipalités périphériques ont tendance à percevoir une plus grande accessibilité que les ménages des zones périurbaines, qui sont exclues du système de transport public. Ces résultats montrent qu'il est important d'offrir des possibilités de proximité et des alternatives pratiques à la voiture afin de limiter la dépendance à la voiture, en particulier dans les zones périurbaines.

1.2.3.4. Chapitre 4 : Avez-vous tenu compte des risques et attributs environnementaux lors du choix de votre lieu de résidence ? Une analyse des choix discrets en France

Dans le contexte actuel du changement climatique, le risque d'exposition à des risques environnementaux extrêmes et multiples augmente. En France, les inondations, la pollution de l'air ou encore les vagues de chaleur constituent des enjeux environnementaux et sanitaires majeurs. Les solutions d'adaptation peuvent également s'appuyer sur la présence d'attributs environnementaux, tels que les espaces naturels. Il est donc particulièrement intéressant d'explorer les déterminants des choix résidentiels afin de comprendre si ces risques et attributs environnementaux influencent les choix résidentiels.

Dans ce dernier chapitre, nous cherchons à comprendre dans quelle mesure les caractéristiques environnementales sont prises en compte lors du choix d'un lieu de résidence, en considérant à la fois les indicateurs d'exposition objectifs et les perceptions. Nous considérons trois risques environnementaux différents : la pollution de l'air, les inondations et le retrait-gonflement des argiles, ainsi qu'un attribut : l'accès aux espaces naturels, en tant qu'indicateur de l'atténuation des îlots de chaleur urbains. Nous cherchons à comprendre *dans quelle mesure les risques environnementaux et les espaces naturels sont-ils pris en compte lors des choix résidentiels ?* Un objectif majeur de ce travail est donc de montrer l'effet de la prise en compte déclarée de ces attributs sur les choix résidentiels au niveau de la municipalité.

Pour ce faire, notre étude s'appuie sur un ensemble de données originales collectées en 2023 au moyen d'une enquête en ligne à laquelle ont participé 1 871 personnes. Nous avons développé deux modèles de choix discrets. Le premier est basé sur un modèle logit multinomial (MNL) qui inclut les prix du logement, le revenu, la densité, le nombre d'emplois, la distance au travail et les attributs environnementaux objectifs et subjectifs. Ensuite, nous avons développé un modèle à classes latentes (LC) composé de deux classes définies par le revenu, les enfants et l'occupation.

Notre modèle MNL montre l'influence des attributs et des risques environnementaux dans les choix résidentiels. Les risques environnementaux tels que les risques d'inondation et de retrait-gonflement des argiles ont un effet négatif et significatif sur les préférences tandis que les espaces naturels sont évalués positivement. Cependant, ce modèle ne donne que peu d'indications sur l'importance des perceptions environnementales. Ceci nous a conduit à l'hypothèse que la prise en compte de ces risques et attributs environnementaux est hétérogène au sein de la population. Nous avons donc développé un modèle LC afin d'évaluer ces préoccupations différenciées.

Le modèle LC s'ajuste mieux à notre question de recherche et met en évidence les différences existantes entre les groupes de population, même si des variables omises sont également révélées. Les résultats mettent en évidence que les ménages qui ont pris en compte les risques et attributs environnementaux lors du choix de leur lieu de résidence ont tous tendance à choisir des zones moins polluées, tandis qu'un petit groupe de ménages retraités à faible revenu valorise également les espaces naturels limités et les municipalités moins exposées aux risques de retrait-gonflement des argiles. Ainsi, l'étude conjointe des effets objectifs et subjectifs des risques environnementaux semble particulièrement pertinente pour bien comprendre les choix résidentiels.

2. Conclusion générale

2.1. Principaux résultats

Cette thèse contribue à une meilleure compréhension des choix résidentiels et de mobilité au prisme des vulnérabilités existantes en considérant les impacts des perceptions individuelles et des politiques environnementales. Ces résultats sont particulièrement importants dans le contexte actuel de transition écologique, compte tenu des enjeux sociaux soulevés par les politiques environnementales, rendues essentielles par les effets négatifs des modes de transport motorisés sur la santé et l'allongement des distances. En particulier, cette thèse répond à la question suivante : *Comment les politiques publiques et les perceptions individuelles influencent-elles les décisions de mobilité et de logement, et les vulnérabilités qui en découlent ?*

Nous répondons à cette question à l'aide de deux études de cas : La France, et plus particulièrement Grenoble, et le Chili avec un focus sur Santiago du Chili, deux villes entourées de chaînes de montagnes. D'une part, Grenoble constitue une zone d'étude pertinente car la ville est affectée par un niveau élevé de pollution malgré une forte volonté de développer la mobilité active et d'assurer l'équité environnementale et sociale au niveau de la ville. D'autre part, le Chili est en pleine mutation, caractérisé par des décideurs politiques qui défendent une idée de justice sociale et environnementale au niveau national, comme le prouve la nouvelle constitution en cours de rédaction, qui comprend de nombreuses évolutions sociales et de nouveaux droits environnementaux. Santiago du Chili est également une ville très préoccupée par la qualité de l'air, avec une organisation structurelle et spatiale qui fait de la mobilité une question intéressante à étudier.

La thèse est divisée en quatre chapitres pour répondre à des sous-questions spécifiques. Tout d'abord, nous concevons un outil qui peut être utilisé pour identifier les ménages les plus vulnérables en termes de mobilité dans un territoire donné, puis nous utilisons cet outil pour caractériser les impacts d'une ZFE sur les vulnérabilités en matière de mobilité. Ensuite, nous cherchons à comprendre dans quelle mesure les dimensions subjectives, et plus particulièrement l'accessibilité perçue, jouent un rôle dans la dépendance à la voiture dans les contextes périurbains dépendants de la voiture. Enfin, nous explorons l'influence de la prise en compte subjective des risques et attributs environnementaux sur les choix résidentiels. Pour ce faire, nous avons suivi une approche pluridisciplinaire et travaillé sur différents jeux de données : les enquêtes locales de déplacements des ménages français (chapitres 1 et 2), et deux jeux de données originaux, une enquête téléphonique (chapitre 3) et une enquête en ligne que nous avons réalisée nous-mêmes (chapitre 4). Les principaux résultats de ces chapitres sont présentés ci-dessous.

Le premier chapitre de cette thèse porte sur VulMob, un indicateur composite conçu pour évaluer les vulnérabilités en matière de mobilité et la pauvreté en transport au niveau individuel dans une zone urbaine. Appliqué à l'agglomération grenobloise, cet indicateur a permis d'identifier 9,6% de ménages hautement vulnérables et 5,5% de ménages pauvres en transport. Parmi eux, cinq profils de vulnérabilité sont identifiés, avec des difficultés spécifiques pour les ménages soumis à des contraintes monétaires, les lieux d'habitation peu accessibles, les travailleurs de nuit, les gros utilisateurs de voiture et les ménages dépendants de la voiture. Ce chapitre propose donc une méthodologie originale pour mener une analyse multidimensionnelle et spécifique au territoire des vulnérabilités au niveau local. Cette méthodologie est particulièrement pertinente pour appréhender les différentes combinaisons de vulnérabilités qui peuvent apparaître dans les différents secteurs d'un territoire et donc pour identifier les profils des ménages vulnérables à la mobilité. Cette approche est intéressante pour les décideurs politiques afin de comprendre les impacts locaux d'une politique publique de transport ou d'un choc sur les prix de l'énergie sur des vulnérabilités préexistantes, et donc d'adapter les politiques publiques, ou de les soutenir au mieux, afin de réduire ces vulnérabilités.

Le chapitre 2 évalue ensuite les impacts socio-économiques *ex ante* de la mise en œuvre d'une ZFE dans la région de Grenoble. Cette évaluation identifie plus de 28 000 ménages affectés par la ZFE. Nous

avons également montré que les ménages hautement vulnérables (HV) précédemment identifiés devraient être les plus affectés par la ZFE car ils sont plus susceptibles de conduire une voiture polluante et qu'ils se déplacent davantage dans le périmètre. En outre, les possibilités de report modal sont également plus limitées pour ces ménages dont les destinations sont plus souvent limitées que pour le reste de la population. En effet, 45,8% des ménages HV affectés par la ZFE n'ont pas de solution de report modal et ont des destinations contraintes, contre 28,1% dans le reste de la population. Ces résultats soulignent la nécessité de mettre en place des politiques compensatoires au niveau local pour éviter de renforcer les vulnérabilités préexistantes, mais aussi le fort potentiel des mobilités actives pour mettre en place une transition écologique équitable. A notre connaissance, cette thèse fournit également l'une des premières évaluations socio-économiques des impacts attendus d'une ZFE.

Cette thèse explore également une perspective différente pour expliquer la mobilité et les choix de logement en intégrant les perceptions individuelles. Dans un contexte caractérisé par un important processus de périurbanisation, les choix résidentiels sont réalisés en tenant compte des contraintes financières et des distances à parcourir pour trouver un compromis acceptable. Or, les décisions en matière de mobilité sont souvent la conséquence de paramètres attendus et perçus et pas nécessairement de mesures objectives des temps de trajet ou de l'accessibilité. Le troisième chapitre utilise un modèle intégré de choix avec variables latentes pour expliquer le choix du mode de transport dans les zones périurbaines de Santiago du Chili. Cette analyse met en évidence le décalage existant entre l'accessibilité calculée et l'accessibilité perçue, cette dernière dépendant de facteurs tels que la facilité à atteindre la destination essentielle, le coût du déplacement ou l'agrément des rues. Les résultats montrent qu'une faible accessibilité perçue augmente la probabilité de choisir des modes motorisés. En outre, les habitants des municipalités périphériques ont tendance à percevoir une plus grande accessibilité que les ménages des zones périurbaines, qui sont exclues du système de transport public. Ces résultats montrent l'importance d'offrir des possibilités de proximité pour réduire la dépendance fonctionnelle à d'autres zones de la ville, mais aussi des alternatives pratiques à la voiture afin de limiter la dépendance à la voiture, en particulier dans les zones périurbaines.

Enfin, étant donné l'importance croissante des risques environnementaux et des espaces naturels, nous intégrons à la fois l'exposition objective aux risques environnementaux et les perceptions dans les modèles de choix résidentiels afin d'explorer dans quelle mesure ils sont pris en compte lors du choix d'une nouvelle résidence. L'analyse est menée sur l'ensemble du territoire français et inclut la pollution de l'air, les risques d'inondation, les risques de retrait-gonflement des argiles et la présence d'espaces naturels. Pour ce faire, nous avons développé un modèle MNL, qui révèle que les risques d'inondation et de retrait-gonflement des argiles affectent négativement les préférences, tandis que les espaces naturels les augmentent. Cependant, ce modèle donne peu d'indications sur les perceptions compte tenu de l'hétérogénéité du territoire étudié. Sur la base de cette observation, nous avons développé un modèle LC pour explorer l'hétérogénéité des choix au sein de la population. Les résultats montrent que les ménages qui ont pris en compte les caractéristiques environnementales dans le choix de leur lieu de résidence ont tous tendance à choisir des zones moins polluées, tandis qu'un petit groupe de ménages retraités à faible revenu valorise également les espaces naturels limités et les municipalités moins exposées aux risques de retrait-gonflement des argiles.

2.2. Enseignements pour la prise de décision

Les résultats de cette thèse peuvent être utilisés pour aider les décideurs à mettre en œuvre une transition écologique équitable.

Tout d'abord, après que les gouvernements successifs aient longtemps délibéré sur l'introduction des ZFE en France, cette thèse permet de mieux comprendre les impacts des ZFE sur les vulnérabilités multidimensionnelles. Nos résultats montrent que la mise en place de politiques d'interdiction des

voitures polluantes peut fortement affecter les ménages à faibles revenus et/ou hautement vulnérables, et que si le report modal constitue une solution pour une majorité de la population, il reste une solution plus limitée pour ces ménages spécifiques. Dans ce contexte, cette thèse fournit des outils et des solutions potentielles pour traiter ces questions et concevoir des politiques compensatoires. En particulier, des exemptions pour les travailleurs de nuit et les petits rouleurs sont suggérées afin d'améliorer l'acceptabilité de la ZFE sans réduire l'efficacité environnementale. Notre travail montre également que les modes actifs (marche, vélo et vélo électrique) constituent un levier important pour le report modal dans le contexte de la mise en œuvre d'une ZFE dans la région de Grenoble. Selon nous, la ZFE doit être vue comme une opportunité de réduire la dépendance à la voiture, les problèmes de congestion et de pollution de l'air afin d'encourager la mobilité active et les effets positifs sur la santé qui y sont associés. Dans ce sens, des conseils personnalisés pour encourager les gens à se tourner vers les transports publics et les modes actifs sont organisés dans la Métropole Grenobloise. En effet, comme le montre cette thèse, l'accessibilité réelle diffère souvent de l'accessibilité perçue et les résidents évaluent souvent mal les opportunités existantes en utilisant d'autres modes de transport. Ainsi, cette thèse développe un outil qui vise à identifier les ménages qui restent sans solution d'adaptation au niveau local. Dans l'agglomération grenobloise, nos résultats montrent qu'ils représentent une très faible part de la population (3,2%). Par conséquent, les politiques compensatoires devraient particulièrement se concentrer sur l'implémentation de solutions basées sur les spécificités de ces ménages, afin d'assurer un accès équitable aux services et aux opportunités.

Deuxièmement, nos résultats sur l'accessibilité dans les municipalités periurbaines de Santiago du Chili confirment l'existence d'un décalage entre l'accessibilité calculée et l'accessibilité perçue. Ainsi, nous montrons qu'une faible perception de l'accessibilité se traduit par une probabilité plus élevée d'utiliser des modes de transport motorisés. Par conséquent, afin de limiter la dépendance à la voiture et de s'attaquer aux externalités négatives des voitures, les municipalités devraient fonder leur action sur la compréhension des déterminants de l'accessibilité perçue. A Santiago, nous observons que des transports bon marché, un environnement agréable et des infrastructures cyclables de bonne qualité pourraient augmenter l'accessibilité perçue. Ainsi, si l'accessibilité calculée est pertinente pour identifier les zones qui devraient être mieux connectées aux réseaux de transports publics, les évaluations subjectives fournissent également des informations complémentaires lors de la planification. La reproduction de ce type d'enquête, qui évalue la satisfaction lors des déplacements dans la ville, pourrait permettre d'obtenir des résultats similaires mais spécifiques à la ville. Ces informations seraient particulièrement utiles pour modifier les comportements et encourager l'utilisation des modes actifs au niveau local.

Troisièmement, cette thèse souligne l'importance de travailler sur les perceptions de l'exposition aux risques environnementaux. En effet, dans un contexte de changement climatique où les événements extrêmes se multiplient, connaître les risques environnementaux auxquels les personnes sont exposées, notamment dans leur résidence, étudier la manière dont les personnes considèrent ces risques est un enjeu central. En France, depuis 2022, le gouvernement a instauré une journée intitulée "Tous résilients face aux risques". Cette journée est organisée chaque année, le 13 octobre, en lien avec la Journée internationale de la réduction des risques de catastrophes des Nations Unies et vise à sensibiliser, informer et acculturer tous les citoyens aux risques naturels qui les entourent. C'est par exemple l'occasion de faire connaître les repères de crues, qui permettent de garder une trace des événements passés et de se préparer aux inondations futures. Ces efforts restent insuffisants, notamment en ce qui concerne les risques liés à la qualité de l'air ou au gonflement des argiles, beaucoup plus complexes à visualiser. En effet, les risques de retrait-gonflement des argiles sont peu documentés et mal connus de la population. Par conséquent, des efforts supplémentaires devraient être faits pour communiquer sur les impacts (économiques, environnementaux et sanitaires) de ces phénomènes environnementaux, atténuer les effets nocifs et sensibiliser la population afin de réduire la vulnérabilité et de promouvoir des comportements sûrs. En effet, une littérature croissante sur l'éducation à la santé environnementale

suggère que la communication sur les risques environnementaux devrait encourager l'éducation au comportement individuel pour permettre aux gens de limiter leur exposition (par exemple, Ramírez et al., 2019 pour la pollution de l'air, ou Burningham et al., 2008 pour les risques d'inondation).

Enfin, au cours des dernières années, les priorités de l'agenda politique ont été particulièrement centrées sur la lutte contre la pandémie de COVID-19 et la sécurisation de l'approvisionnement en énergie. Pourtant, nous soulignons la nécessité d'agir rapidement et efficacement pour résoudre les problèmes liés au changement climatique sans ignorer les impacts sociaux qui peuvent émerger de la mise en œuvre des mesures d'adaptation et d'atténuation. Bien que confrontés à des niveaux élevés de pollution atmosphérique, la crainte que les ménages les plus fragiles soient les plus touchés par les ZFE a ralenti l'adoption de mesures ambitieuses en France. Sept ans plus tôt, la mise en œuvre d'une zone d'actions prioritaires pour l'air avait déjà été annulée pour cette raison précise (Charleux, 2014). Plus récemment, l'ambition de la Loi Climat et Résilience a été à nouveau limitée suite à un rapport du Sénat publié en juin 2023 qui recommandait de retirer la mise en œuvre nationale des ZFE, en raison des conséquences sociales négatives attendues et du manque de soutien de la part du gouvernement. La nécessité d'améliorer la qualité de l'air au niveau local est donc toujours présente et les gouvernements doivent prendre des mesures ambitieuses en ce sens.

2.3. Perspectives de recherche

Les limites spécifiques et les extensions possibles de la recherche ont été discutées précédemment dans chaque chapitre. Nous présentons ici des idées générales qui permettraient de poursuivre la recherche initiée dans cette thèse.

a) *Sur les vulnérabilités...*

En France, les ZFE n'étant pas standardisées, il appartient à chaque ville de définir les modalités de leur application. Etant donné que les questions de vulnérabilité constituent une préoccupation centrale, cette flexibilité de mise en œuvre devrait être utilisée pour identifier les caractéristiques spécifiques de chaque territoire en termes de vulnérabilités et d'impacts. En ce sens, une des principales limites de notre travail est liée à l'étude exclusive des vulnérabilités et des impacts des ZFE sur la région grenobloise. Par conséquent, un défi important serait de reproduire ce type d'analyse sur plusieurs villes françaises et/ou européennes. Cependant, la reproductibilité de cette méthode dépend de la disponibilité de données fiables sur les revenus et de la faisabilité de la connexion de ces données avec les enquêtes sur les déplacements des ménages. A notre connaissance, l'accès aux données sur les revenus pourrait être possible à Clermont-Ferrand et à Bordeaux avec des autorisations spécifiques. Autrement, pour suivre notre méthodologie, les futures Enquêtes Ménages Déplacements devraient être conçues soit en incluant une question déclarative sur les revenus, soit en concevant une table de correspondance entre les données INSEE et l'Enquête Ménages Déplacements lors de la conception de l'enquête. Cela permettrait d'explorer les différents impacts socio-économiques sur plusieurs structures urbaines, en distinguant les villes monocentriques, polycentriques et/ou composites, car la forme urbaine semble jouer un rôle important. En effet, en France, les villes suivent des trajectoires différentes en termes de planification des transports publics. Par exemple, Montpellier a décidé de généraliser la gratuité des transports en commun pour tous les habitants à partir de 2023, tandis que d'autres villes comme Lyon ont décidé de s'appuyer sur le développement de plus de 400 km de pistes cyclables d'ici 2030.

Ensuite, pour approfondir les travaux menés dans cette thèse, il serait particulièrement intéressant d'explorer les effets combinés des vulnérabilités d'exposition, des risques environnementaux et des inégalités de contribution aux émissions de GES et de polluants avec les impacts des politiques publiques. Ce travail sera initié dans le cadre du projet ClimAir qui a partiellement financé cette thèse, et pourrait permettre de caractériser les vulnérabilités multidimensionnelles qui peuvent affecter les

ménages au niveau local. Pour aller plus loin, il serait également pertinent d'étudier la combinaison des vulnérabilités liées à la mobilité et au logement, y compris les coûts liés au chauffage. Une possibilité serait d'étendre notre travail pour développer des profils de ménages et des typologies de villes en fonction des différentes vulnérabilités identifiées et des différentes dimensions de la précarité énergétique.

b) Sur l'accessibilité...

Cette thèse révèle également l'importance des questions d'accessibilité dans les différents contextes étudiés.

D'une part, le premier chapitre de cette thèse souligne la transversalité de la dimension de l'accessibilité, qui semble être commune à presque tous les profils de vulnérabilité identifiés dans la région de Grenoble. L'analyse développée dans le chapitre 3 est également limitée par le manque d'indicateurs existants relatifs à l'accessibilité dans les municipalités périurbaines. Cela soulève le défi d'essayer de mieux caractériser ce manque d'accessibilité, qu'il s'agisse des transports publics ou des services et équipements. Pour ce faire, la prise en compte d'autres possibilités de déplacement, telles que la multimodalité et le covoiturage, qui n'ont pas été prises en compte dans VulMob, serait particulièrement pertinente. Pour l'instant, l'indicateur d'accessibilité aux transports publics de VulMob étant calculé au niveau territorial à l'échelle fine, il serait intéressant de comparer l'utilisation d'indicateurs différents (et peut-être plus élaborés) pour rendre l'évaluation plus puissante et plus réaliste. En particulier, la possibilité d'évaluer l'accessibilité au niveau individuel reste un défi à relever. Le développement d'un modèle de transport à l'échelle d'une métropole qui pourrait inclure ces différents paramètres pourrait être une option pour évaluer l'accessibilité à ce niveau.

D'autre part, l'exploration des déterminants du choix du mode de transport dans les zones périphériques et périurbaines de Santiago montre que les mesures calculées de l'accessibilité sont souvent incohérentes avec l'accessibilité perçue, comme le révèlent également d'autres études (Lättman et al., 2018 ; Pot et al., 2021). Par conséquent, travailler sur une évaluation intégrée de l'accessibilité au niveau local semble encore plus important pour que les individus puissent avoir une perception de l'accessibilité plus proche de la réalité. Une perception plus réaliste de l'accessibilité peut en effet permettre de changer les comportements et d'encourager l'utilisation de différents modes de transport, mais ce sujet reste à explorer.

Dans le contexte chilien, le réseau de transport public de Santiago a annoncé en 2023 l'extension de la ligne de métro jusqu'à la municipalité de Padre Hurtado, qui n'était pas connectée jusqu'à présent. Il serait donc particulièrement pertinent d'étudier les implications de cette amélioration sur nos résultats, puisque le temps de trajet et l'offre de transport public seront considérablement modifiés. Une future étude pourrait donc se baser sur une nouvelle enquête auprès de nos répondants afin de comprendre dans quelle mesure leur perception de l'accessibilité a changé.

c) Sur les perceptions...

L'enquête des données de l'enquête PERL reste limitée dans cette thèse et mériterait une analyse plus approfondie. Notre jeu de données comprend deux attributs environnementaux qui n'ont pas été intégrés au modèle en raison de données objectives manquantes : le bruit et les îlots de chaleur urbain. L'intégration de ces deux variables serait particulièrement pertinente pour notre analyse, mais reste conditionnée par le développement d'ensembles de données objectives pouvant inclure ces variables au niveau de la municipalité. En même temps, notre ensemble de données peut permettre d'explorer d'autres questions de recherche. Un travail à venir consisterait à étudier la mobilité résidentielle pour comprendre si les ménages peuvent rechercher une meilleure qualité environnementale lorsqu'ils quittent leur lieu de résidence précédent, étant donné que nos données contiennent les adresses précédentes et actuelles

des personnes interrogées, ainsi que la date de leur déménagement. À plus long terme, un autre objectif de recherche serait de réinterroger nos répondants pour leur demander leur adresse, ce qui nous permettrait de mieux caractériser leur exposition réelle. À l'heure actuelle, la collecte des adresses est impossible pour des raisons de confidentialité (RGPD). Ce travail futur pourrait permettre de mieux comprendre les différences entre les perceptions de l'exposition au risque et l'exposition réelle, et donc de caractériser l'écart entre la perception et l'exposition en fonction des caractéristiques sociodémographiques et de la sensibilité environnementale du répondant.

La conception de l'enquête PERL offre également des enseignements importants pour ce type d'études. Sur la base du processus d'analyse que nous avons mené, une question demeure quant à la pertinence de travailler au niveau d'un pays entier. D'une part, il aurait été particulièrement difficile et coûteux de collecter des réponses représentatives à l'échelle d'une zone urbaine. D'autre part, travailler à l'échelle de la France introduit une hétérogénéité importante dans les réponses des enquêtés, ce qui complique l'analyse et rend les résultats plus difficiles à interpréter. Cet élément doit donc être gardé à l'esprit pour la suite des travaux.

d) Contexte international

Plus largement, au cours des dernières années, les habitudes de mobilité ont été bouleversées par plusieurs événements inattendus.

D'une part, la pandémie de COVID-19 ont considérablement modifié les habitudes de mobilité en raison du télétravail, de l'éloignement social et de l'accès limité aux activités (Wellenius et al., 2021 ; Baig et al., 2022). Par conséquent, elle peut avoir eu des conséquences importantes sur nos ensembles de données (l'enquête locale sur les déplacements des ménages à Grenoble et l'enquête téléphonique à Santiago) qui ont été collectées en 2020. Par ailleurs, si la pandémie de la COVID-19 a perturbé les comportements de mobilité, notamment en raison du développement du télétravail (Aguilera et al., 2023), elles ont aussi été l'occasion de développer les mobilités actives au niveau mondial. Ainsi, pendant la pandémie, la ville de Paris a créé plus de 50 kilomètres de pistes cyclables temporaires afin d'encourager l'usage du vélo, dont beaucoup sont devenues permanentes par la suite. Cette dynamique ne se limite pas à Paris et a été observée partout dans le monde : 24 kilomètres de nouvelles pistes cyclables ont également été annoncés à Santiago du Chili en 2023.

D'autre part, la pandémie a également influencé les processus de choix résidentiels, puisque de nombreux ménages ont demandé plus d'espace, des zones moins denses et un accès aux espaces verts après le premier confinement (Breuillé et al., 2022; Colomb & Gallent, 2022). En effet, si la durée des trajets domicile-travail était un critère majeur des choix résidentiels avant la pandémie, elle est devenue plus secondaire durant cette période spécifique pour les ménages qui ont pu travailler à distance. Au sein des aires urbaines, les zones les moins denses et les plus éloignées du centre sont celles où les prix ont le plus augmenté, ce qui traduit l'attrait pour des biens plus spacieux en périphérie des centres urbains (Chareyron et al., 2022). Ces résultats récents montrent donc qu'un changement de dynamique s'est opéré sur le marché immobilier à la suite de la crise COVID-19. Cependant, tant pour la mobilité que pour les choix résidentiels, l'avenir reste incertain et les effets à long terme de la pandémie sont encore à discuter (e.g. Baig et al., 2022 ; Vega-Gonzalo et al., 2023).

Enfin, l'attaque de l'Ukraine par la Russie a suscité des inquiétudes quant à la sécurité de l'approvisionnement énergétique en Europe. La guerre a entraîné une augmentation du prix du pétrole qui a atteint 123\$ le baril en juin 2023, et a donc conduit à une augmentation importante des prix des carburants. Ce choc des prix a également bouleversé les habitudes de mobilité, et l'utilisation de la voiture est devenue particulièrement difficile, surtout pour les travailleurs à faible revenu. Cela a conduit à une préférence pour les transports publics plutôt que pour les voitures particulières (Ladin et al., 2015)

et à une diminution des distances de déplacement (Alberini et al., 2022). Si le contexte mondial influence nécessairement les habitudes de mobilité et les choix résidentiels, ces effets ne perdureront pas nécessairement sur le long terme, et l'avenir est particulièrement incertain compte tenu de la situation géopolitique. En ce sens, les résultats de cette thèse devraient être vérifiés afin de s'assurer de leur validité après la survenue de ces événements.