École polytechnique de Louvain

Robust evaluation of energy transition policies

A new system modeling approach based on the integration of social acceptance studies

Author: **Nicolas Ghuys**
Supervisors: **Francesco Contino, Panaïotis Varelas**
Readers: **Francesco Contino, Panaïotis Varelas, Hervé Jeanmart**
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Abstract

The influence of Greenhouse Gas (GHG) emissions due to human activity on climate change are unequivocal. As energy consumption is mainly responsible (not solely) for these emissions, changing our energy system (production, consumption, and management) is necessary. However, it is sometimes difficult to predict the social impact and the social acceptance of this transition.

In this work, we describe a socio-technical methodology aiming to estimate the potential future of the End-Use Demand (EUD), responsible for energy consumption, based on planned behavior theory and social practice theory. The new EUD is obtained by a statistical analysis of the social acceptance of practice changes obtained from a survey on a specific behavior/practice. This methodology provides a robust estimation of the emissions cut resulting from a defined transition scenario based on social acceptance rather than "what if" assumptions.

The cross-sectional approach, as general as possible, is used to evaluate the potential GHG emissions cut from commuting to work by inhabitants of Walloon Brabant which is massively dominated by cars responsible for more than 90% of these trips' emissions. It has been found that most workers are in favor of using an alternative mode to the car. The lack of flexibility, accessibility, and infrastructure for these alternatives are the main reasons for the automobile's dominance. This is highlighted by the strong correlation between car use and the level of accessibility of the place of residence and/or work. A structured public transport network combined with soft modes of transport emerges as the most popular solution. The deployment of such a network should lead to an effective reduction of emissions from commuting between 14.5% and 24% with an estimated cost per ton of carbon dioxide equivalent ($CO2_{eq}$) avoided between 125€ and 300€, which is about 6 times cheaper than a scenario of switching to electric cars. The gap between opinion and action is a key factor in the transition regarding changing the population's behavior. It requires monitoring of measures throughout their implementation to maximize their impact.

Acknowledgments

If I have the opportunity to propose this thesis today, it is because people have trusted me, listened to me, advised me, and supported me. To all these people I would like to say thank you.

I would like to thank Professor Francesco Contino for trusting me and giving me the opportunity to explore a field, at first sight, not intended for engineers. *"Life is trying things to see if they work."* (R. Bradbury)

I also thank the Ph.D. student Panagiotis Varelas for the time he devoted to me, for all the discussions we had on the subject, and for their enriching digressions. Thanks to the Ph.D. student Line Vanparys for her precious help in the construction of the sociological survey and to Gauthier Limpens for having awakened me to the subject but also advised and supported me in my approach.

I would also like to thank my family for having awakened me to the world of the very small and the very large, the technical and the human, the rigorous and the intuitive. Thanks to my best friend for feeding our reflections, from the most naive to the most marvelous, since always and forever.

Thank you to meu sol, for your light when it was cloudy, for your heat when it was cold, for your rainbows when it rained. Today, the sky is blue.

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Introduction

General context

Climate change is a growing concern in the international scientific community. Indeed, by emitting GreenHouse Gases (GHG), humanity has caused rapid and widespread changes in the atmosphere, cryosphere (land and sea ice), biosphere (living things) and oceans [14]. To limit these changes and their impact as much as possible, Belgium, a member of the United Nations Framework Convention on Climate Change, agreed on targets and a roadmap to achieve carbon neutrality by 2050 [35]. As energy consumption is mainly responsible for these emissions, changing our energy system (production, consumption, and management) is necessary. However, the difficulty in predicting the social impact and social acceptance of these changes sometimes leads to significant gaps between the emission reduction expected at the time of planning and the one achieved during implementation [9]. How can we integrate social acceptance in transition planning?

Current energy system models allow us to obtain different *"what if"* scenarios of transition based on forecasts of future energy demand from the EU commission [19]. However, this does not allow us to robustly determine the scenario that has the best chance of being accepted by the population and succeeding.

In the same way that society will evolve, our practices and consumption habits will change. It is therefore essential to anticipate the population's reaction to such changes and explore all the transition paths allowing us to reduce our emissions. Therefore, the analysis and consideration of the practices underlying the End-Use Demand[1] (EUD) and the social acceptance of their modification are essential.

[1] the end-use demand concerns requirements in energy services (e.g. the mobility needs) [19]

Objectives and outlines of the thesis

This thesis aims to bridge the gap between transition planning and implementation by developing a novel socio-technical methodology to robustly estimate the future of the EUD, responsible for energy consumption, based on the theory of planned behavior, social practice, and social acceptance.

The case study focuses on the commuting behavior of the residents of Walloon Brabant and has as its primary objective the development and validation of the methodology on a small scale. The choice to focus on commuting to work to validate the methodology developed seems to be a relevant choice due to the large share of national emissions represented by private mobility (12.65%) and the share of trips made for this reason (20%) [25].

The first chapter of this thesis aims to review existing frameworks; First, the current representation of the demand in engineering and sociology is reviewed. Their respective limits, as well as their complementarity, are highlighted. Then a review of existing socio-technical frameworks is conducted and discussed.

The second chapter presents the new transversal methodology developed; First, the condition needed for a representative database are presented. Second, the analysis process used for practice and individual characterization is described. Then, the robust methodology developed to assess the social acceptance of practice changes is presented. Finally, the simplified model used to evaluate the GHG emissions reduction resulting from these practice changes is described.

In chapter three, the case study on commuting to work for inhabitants of Walloon Brabant is performed; First, an overview of the case study is proposed and the current GHGs emissions due to commute are analyzed. Second, the methodology developed in chapter 2 is applied to the case study. The general results are presented and discussed. Then, the measures are selected according to existing scenarios and the needs of the population. Finally, the results specific to social groups and measures as well as their costs and emissions cut potential are presented.

To conclude, a general discussion on the work's limitations and potential future work is held.

Chapter 1

Representation of energy demand in engineering and sociology

The representation of demand in energy system models in terms of Final Energy Consumption (FEC) prevents the consideration of the social dynamics underlying this demand such as social acceptance of transition scenarios or rebound effect. While sociology can explain and model these dynamics, only a few models attempt to bridge the gap between these two complementary disciplines. This section aims to determine the complementarity of the disciplines by reviewing their respective representations of demand.

1.1 Representation of the demand in a typical energy system model

An overview of the long-term Energy System Optimisation Model (ESOM) EnergyScope Typical Days (ESTD) is provided. The main parameters of the model and, more specifically, the way demand is currently represented and taken into account are defined while its limitations are discussed.

1.1.1 Overview of the energy system model ESTD

ESTD is an open-source model that aims at providing an energy system able to meet yearly demand by optimizing both Capital Expenditure (CAPEX) and Operating Expenditure (OPEX)[18]. The system is separated into three parts: resources, energy conversion, and demand. Constraints can be added to the optimization problem such as the limit on the $CO2_{eq}$ emissions of the system or the share of renewables in the energy mix. The working principle of the model is illustrated in

Figure 1.1 with energy flows usually from primary energy resources on the left to the End-Use Demand (EUD) on the right.

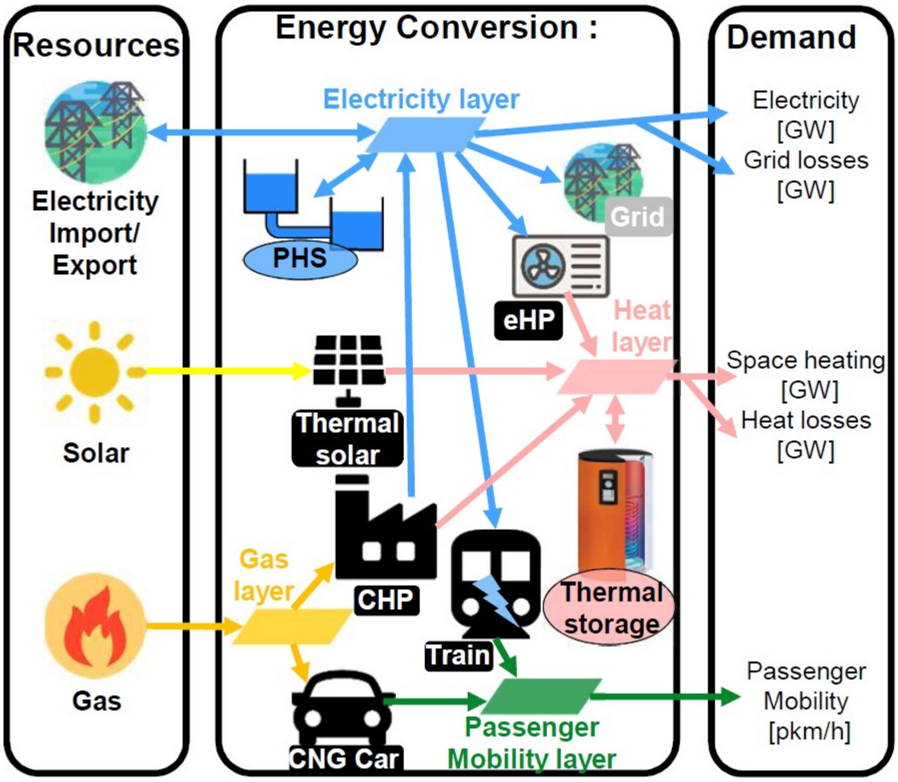

Figure 1.1: Representation of an energy system. 4 layers are represented here (Electricity, Heat, Passenger Mobility and Gas) and 7 technologies allow conversion of quantities between layers.[19]

As mentioned above, ESTD is open source so that anyone with sufficient skills and knowledge can modify it to explore new approaches and implement new features. Compared to other existing energy models, which are proprietary, and focused on the electricity sector [18], EnergyScope TD optimizes both the investment and operating strategy of an entire energy system [19]. Additionally, its concise mathematical formulation and computational efficiency are appropriate for uncertainty applications.

1.1.2 Representation of the demand in ESTD

The primary objective of ESTD is to satisfy the energy balance, meaning that the demand is known and the supply has to meet the demand [19]. This demand is expressed in terms of FEC and is the amount of input energy needed to satisfy the EUD. The European Commission defines the FEC as *"the energy which reaches the final consumer's door"*[10]. The input EUD is represented as the sum of three components: heating, electricity, and mobility. The yearly EUD for all sectors is calculated from the forecast carried out by the European Commission for Belgium. We note that a difference is made between the demand for passenger mobility and freight mobility [18] and that the demand for both mobilities is assumed to grow in proportion to the population.

1.1.3 Limitations of demand representation in ESTD

One of the limitations of the current demand representation is that while Europe explores future energy needs and tries to identify ways in which these might be met in a suitable low-carbon manner, they struggle to take the dynamics of demand into account[32], and determine the conditions necessary to make the energy transition and the transition to a low-carbon economy socially acceptable [11]. Consequently, current projection and thus, the scenario of transitions fail to engage in the complex social practices that constitute daily life [32]. The common strategy is to take current practices for granted [7], to treat the perpetuation of current "norms" as part of the equation, and focus on how effectively the resulting demand can be met [19].

This limited representation of daily life changes hides the potential social reluctance towards the proposed measures. While the government targets to increase the share of renewable energy and accelerate the energy transition, it is increasingly recognized that social acceptance is a constraining factor in achieving this target [38]. There is currently no such model that considers the expected social acceptance in the choice of transition measures and the design of transition scenarios.

1.2 Representation of the demand in social practice and social acceptance

The social concepts that are useful in connecting energy demand, as defined in energy system models, to the behaviors that drive that demand are presented. This section provides an understanding of the sociological concepts necessary to understand and develop a socio-technical approach.

1.2.1 The theory of social practice

In the research context, the social practice aims to integrate the individual with their surrounding environment while assessing how context and culture relate to the individual's current actions and practices. Just as a social practice is an activity in and of itself, research focuses on how social activity takes place and identifies its primary causes and outcomes [20].

The use of social practices to define energy demand is based on the assumption that energy is not used for its own sake but as part of accomplishing social practices. For example, if we drive a certain amount of kilometers per year, it is mainly because we have to go to work every day or because we have to do shopping rather than because we like to drive. Shove sees conventional approaches as having the unintended consequence of reproducing contemporary forms of “normal” practices [32]. As a result, the politics and economics of supply are typically discussed aside from an understanding of the underlying dynamics of demand as the representation influences the comprehension and cope the action.

1.2.2 The concept of social acceptance

Acceptance is a concept that involves a reaction to something which is proposed externally, acceptance being "the act of accepting" and thus "giving a positive response to" something. Social acceptance is generally defined, as a positive attitude towards new technology or measure, which leads to supporting behavior if needed or requested [15]. For example, the social acceptance of wind turbines because of the NIMBY syndrome [1] is considered a key factor in their deployment [38].

[1]Nimby: Not in My Back Yard: is a characterization of a person who does not want something unpleasant to be built or done near where they live [1]. It carries the connotation that such residents are only opposing the development because it is close to them and that they would tolerate or support it if it were built farther away.

The purpose of taking social acceptance into account when planning the future of demand and the energy transition is to anticipate the positive or negative reaction of the population to the various measures that make up the transition. For example, if we could determine the average financial compensation expected by the population concerned by the implementation of wind turbines near their homes, a new economic equilibrium could be obtained for a transition scenario with greater chances of success. Since the success of climate-friendly technologies and measures depend largely on their social acceptance, it is important to have a clear insight into what influences public attitudes [15].

1.3 Representation of the demand in a socio-technical system

A study was previously conducted to review existing Socio-Technical Energy Transition (STET) models capable of capturing and exploring the dynamics of socio-technical energy transitions [17]. This study suggests three key requirements for STET models that derive from the paradigms of energy modeling and socio-technical transitions theory:

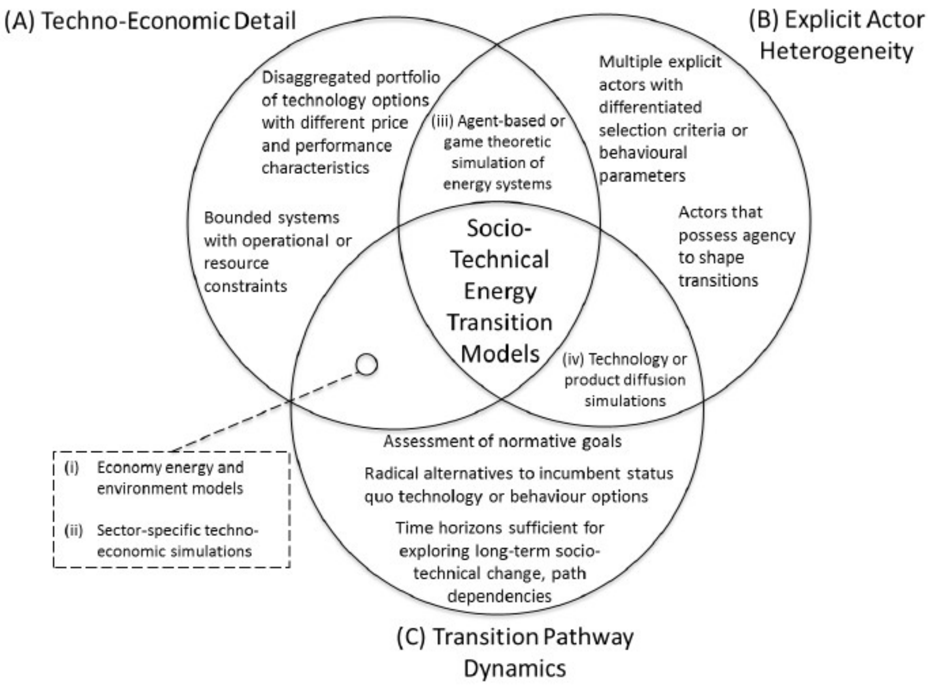

Figure 1.2: Key requirements for Socio-Technical Energy Transition modelling [17]

To date, only a few attempts have been made to integrate lifestyle choices and socio-cultural factors into models of future energy demand by adopting a Socio-Technical Systems Design that considers human, social, and organizational factors, as well as technical factors in the design of organizational systems [2].

One of them is mixing the United Kingdom Transport Carbon Model (UKTCM) [3] with the Scottish Transport Energy and Air pollution Model (STEAM) [4]. The methodology used in this model combines the strength of an energy environment system modeling framework with the UKTCM and a bottom-up modeling framework, built around a set of exogenous scenarios of socio-economic, socio-technical, and political developments with the STEAM.

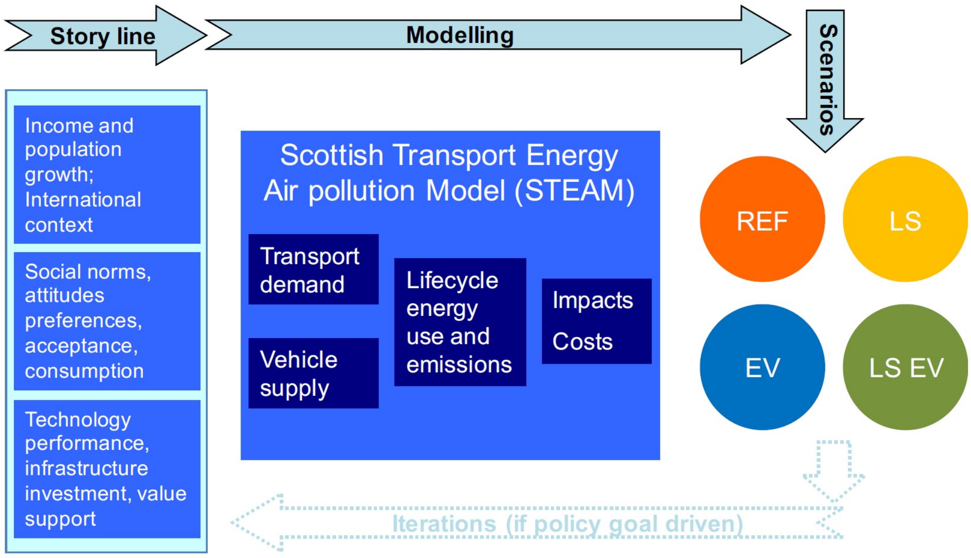

Figure 1.3: Representation of the Scottish Transport Energy and Air Pollution Model (STEAM) [5]

The interest of such an approach is that by decomposing current travel choices by trip purpose, duration, and mode, the potential impact of long-term structural changes in society and on the composition of travel can be assessed [6]. It fills the gap between research and practice by using an integrated transport-energy-environment systems model to explore transport-related lifestyle changes and socio-cultural factors that influence mobility transition. However, this model is based on *"what if"* scenarios more or less ambitious to challenge policymakers to consider how to formulate policies to meet ambitious climate change objectives [5]. In the following, we will use this approach combined with results from social acceptance studies to determine which scenarios are most likely to succeed and have the greatest impact on GHG emissions reduction.

Chapter 2

Methodology

The general methodology developed in this section makes it possible to assess the GHG emissions reduction potential of a given social practice limited by the social acceptance of the proposed transition measures related to it. As the methodology presented here is intended to be as general as possible, an informed application of this methodology to the sector and practice under consideration is necessary for it to work properly. Figure 2.1 provides an overview of the methodology.

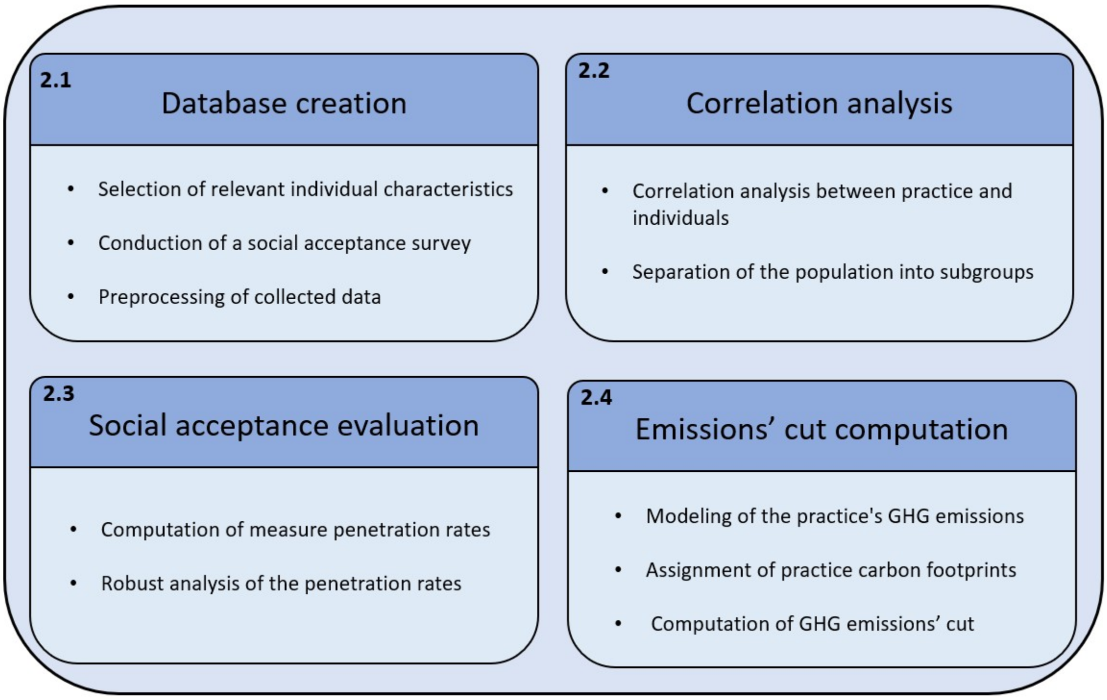

Figure 2.1: General methodology overview

2.1 Creation of a representative database

A survey is conducted to characterize the individuals concerned by the practice and to assess the social acceptance of the change in practice within the target population.

Characteristics selection

The choice of relevant individual characteristics is essential to assess the potential correlation between practice and social groups. It differs across cases depending on the studied practice. A previous study on practice characterization identified 4 categories of factors to characterize an individual [33]. Three of them are common to all characterizations of individuals and the fourth varies according to the practice considered:

- Sociodemographic factors (age, gender, education, etc.)
- Socio-psychological factors (familiarity, parenthood, lifestyle, etc.)
- Practices characteristic indicators (for mobility: trip's purpose, distance, time, cost, etc.)
- Spatial indicators (level of urbanization, level of accessibility, etc.)

The recent climate survey conducted by the Federal Public Service (SPF) [30] uses the same 3 categories of characteristics, i.e. socio-demographic (age, gender, education, etc.), socio-psychological (employment status, home ownership, etc.) and spatial (region, urbanization levels). Since this survey did not explicitly target practices, the last category was not explicitly included. However, various sector and practice characteristics were still assessed through specific questions on types of heating, home ownership, car ownership, etc.

This characterization ensures the second key requirement suggested for STET modeling presented earlier in Figure 1.3, namely explicit heterogeneity of actors with differentiated selection criteria or behavioral parameters [17].

Conduction of the survey

The questionnaire constructed for the case study analyzed in this thesis is available in Appendix F. To ensure the validity of the survey, the methodology used for the 2021 climate survey conducted by the SPF [30] is used and must respect the following steps :

- Sample size : The equation 2.1 is used to obtain the minimum sample size needed for a given population size *N*, a given margin of error e and a given conversion rate p depending on the desired confidence interval with a z-score z corresponding to a 95% confidence level [21].

$$\text{Sample size } = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1+\left(\frac{z^2 \times p(1-p)}{e^2 N}\right)} \tag{2.1}$$

- Data cleaning: Sorting between valid and non-valid surveys varies on a case-by-case basis. However, a good practice is to keep only the surveys with a minimum of 90% response to questions.

- Statistical weighting: The weighting is based on 3 variables simultaneously: gender (2 categories) x education (3 categories) x age (4 categories); this corresponds to a total of 24 cells. These weighted data give a good overview of the target population.

2.2 Correlation analysis between practice and individuals

The population emissions due to the practice under consideration result from individual emissions specific to that practice and may vary between individuals. To assess the impact that population behavior changes would have on GHG emissions, it is first necessary to evaluate the social dynamics between individual characteristics, behavior, and practice.

Impacting characteristics selection

The correlation between an individual's characteristics and a practice is obtained with the formula 2.2 by calculating the weighted variance [37] of the practice in each of the subgroups with these characteristics in common. For example, a value x_{ij} of a characteristic j in a group i could be the proportion of vegetarians among women. In this case, $\overline{x_j}$ would be the proportion of vegetarians in the population, m would be equal to one because we evaluate only one characteristic (being vegetarian), n would be equal to two because there are only two groups (men and women), and $\frac{n_i}{N}$ would be around 50% because there is more or less the same number of women and men in the population.

$$\mathbf{Corr}_{ij} = \sum_i^n \frac{n_i \cdot \sqrt{\frac{\sum_j^m |x_{ij} - \overline{x_j}|^2}{m}}}{N} \tag{2.2}$$

with :

- $\overline{x_j}$ = mean value of characteristic j in the population
- x_{ij} = value of the parameter j in the group i
- n_i = sample size of group i in the population
- N = population size

Separation of the population into subgroups

Because the response of the population to different transition measures may vary across individuals, the population is separated into different social groups based on the characteristics that most influence the practice. A trade-off must be made between a sufficiently large number of groups that best represent the diversity of the population and a sufficient number of respondents in the groups to ensure statistical representativeness. Indeed, an insufficient number of individuals per group would lead to a too large margin of error (CF. section 2.5). Moreover, a limited number of groups ensures that each of them is responsible for a significant part of the emissions and therefore that a change in their behavior will have a significant impact on the reduction of GHG emissions. For n characteristics x that have a significant impact on the practice of individuals and can take m values, the number of social groups is obtained as follows:

$$\text{Groups} = \sum_i^n \sum_j^m \mathrm{x}_{ij} \tag{2.3}$$

2.3 Evaluation of the social acceptance of practice changes

Once the individual characteristics that have the greatest impact on the practice under consideration have been identified and individuals sharing common attributes have been grouped together, the social acceptability of transition measures to reduce GHG emissions from that practice is assessed within these different groups.

Penetration rate of practice changes

The social acceptance of transition measures is assessed through the survey. As the database is representative of the population (CF. section 3.1.1) we can evaluate the potential of practice changes within the different social group's constituting the population.

The effective penetration of a new practice/behavior k alternative to the current one in a group of individuals i can be estimated by evaluating the social acceptance rate of this new practice through the application of the measure j meeting the conditions n that are specific to it. The penetration rate of a measure j, encouraging the use of a different mode alternative to the car to go to work in our case study, in a group of individuals i can thus be obtained through the following formula:

$$\%_{Penetration_{ij}} = \%_{Change_i} \cdot \%_{Alternative_k} \cdot \%_{Conditions_n} \cdot \%_{Gap} \tag{2.4}$$

with :

- $\%_{Penetration_{ij}}$: penetration rate of measure j in group i.
- $\%_{Change_i}$: share of a group i in favor of any practice change.
- $\%_{Alternative_k}$: share of the subgroup $\%_{Change_i}$ in favor of switching from current behavior to an alternative practice k.
- $\%_{Conditions_n}$: share of the $\%_{Change_i}$ subgroup in favor of alternative k under the n conditions, relative to the factors currently blocking its use and potentially favoring it.
- $\%_{Gap}$: share of practices actually replaced by the alternative k. This factor is intended to reduce the gap between the individual's opinion and the actual change in practices. It can be refined by a preliminary test to minimize uncertainty.

Note that each rate is calculated within the subgroup obtained by the calculation of the rate which precedes it. For example, the rate "$\%_{Alternative_k}$" is calculated within the subgroup concerned by the rate "$\%_{Change_i}$".

Robust analysis of penetration rate

The calculation of the penetration rates within the different groups as well as the different intermediate rates are based on a small sample of individuals. Although this sample is intended to be as representative as possible of the population of interest, the limited number of respondents creates uncertainty [21]. By calculating the margins of error [34] for defined population size and different sample sizes specific to the number of respondents for each intermediate rate, we can determine how confident we can be that we would get the same results if the entire population was surveyed. The margin of error for each intermediate rate i is calculated as follows:

$$\text{Margin of Error}_i = Z \cdot \sqrt{\frac{P \cdot (1-P)}{N}} \quad (2.5)$$

With:

- Z : z-score corresponding to a 95% confidence level equal to 1.96
- P : sample size compared to the size of the population concerned
- N: size of the population concerned

With a few conditions to ensure a minimum representation of the population:

- $N \cdot P$: must equal 10 or more
- $N \cdot (1-P)$: must equal 10 or more

As mentioned above, we see that the margin of error increases as the sample size N decreases. Once we have obtained the margins of error for the different intermediate rates, we can combine them to obtain the global margin of error for the penetration rate of the measure j:

$$\text{Global Margin of Error}_j = \mu_j \cdot \sum_{i=1}^{n} \frac{ME_i}{\mu_i} \quad (2.6)$$

With:

- μ_i : average value of the intermediate rate i
- μ_j : average incidence rate of the measure j
- ME_i : margins of error of the intermediate rate i

2.4 Calculation of the GHG emission reduction

Since the main objective is to reduce the GHG emissions resulting from the social practice under consideration, the final step is to quantify the expected emission reduction resulting from a behavior change. In a typical energy system model, such as the ESTD, demand is represented in terms of EUD. A link between EUD and practice change is therefore necessary. To do so, we use the penetration rates computed at section 2.4 to evaluate the practice shift and obtain the new EUD. Next, we use a simplified model similar to ESTD but specific to the practice sector to estimate the potential emissions reduction for the new EUD.

The GHG emissions resulting from a practice done by an individual i using a technology j is defined as follows :

$$\mathrm{GHG}_{ijk} = \sum^{i}\sum^{j}\sum^{k} \mathrm{EUD}_{ij} \cdot \mathrm{Footprint}_{k} \tag{2.7}$$

with :

- EUD_{ij}: The final end-use demand of a group i using technology j and resulting from the practice considered.
- $\mathrm{Footprint}_{k}$: The GHG emissions of technology j using an energy source k.

The carbon footprints are expressed in grams of CO_2 equivalent. The robust assignment of carbon footprints depends on the practice under consideration and the technologies involved. This is done in appendix A.1 for the case study.

Chapter 3

Case study: Commuting in Walloon Brabant

Context

Environmental challenges require ambitious and coherent actions to reorganize society, including the transport sector, which is responsible for a significant portion of GHG emissions. In 2019, the emissions of the road transport sector accounted for **24%** of the global GHG emissions in Wallonia[29], 99% of which are due to road vehicles alone[28]. Of these emissions, **55%** result from passenger transport [13].

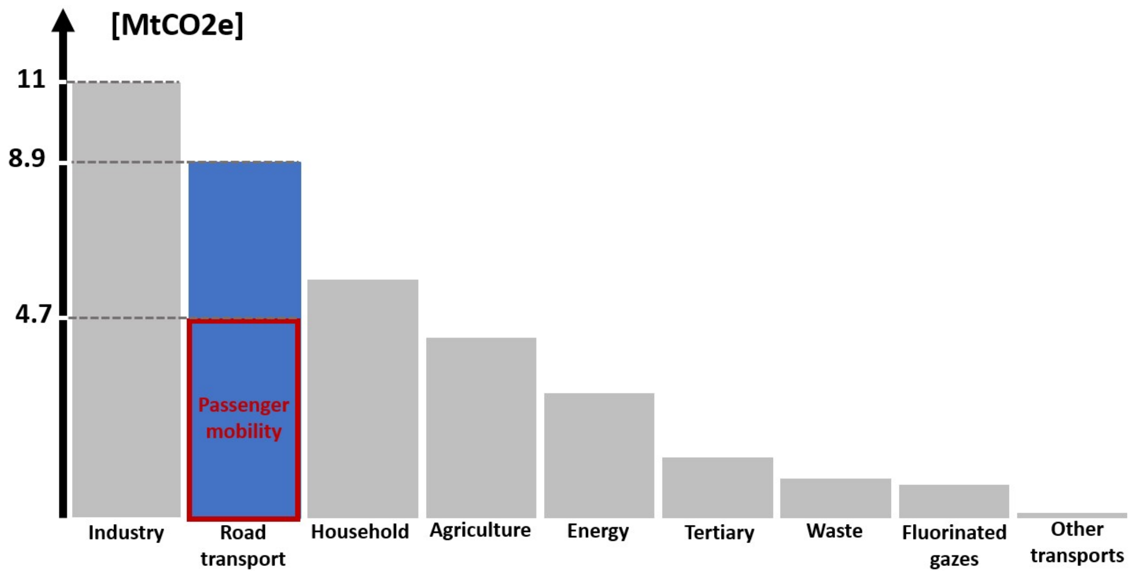

Figure 3.1: GHG emissions by sector in Wallonia in 2019

In its strategic vision for mobility by 2030, the Walloon Region has set itself the ambition of decreasing the modal share of the car by increasing the modal share of more sustainable alternative modes and the occupancy rate of cars as shown in figure 3.2.

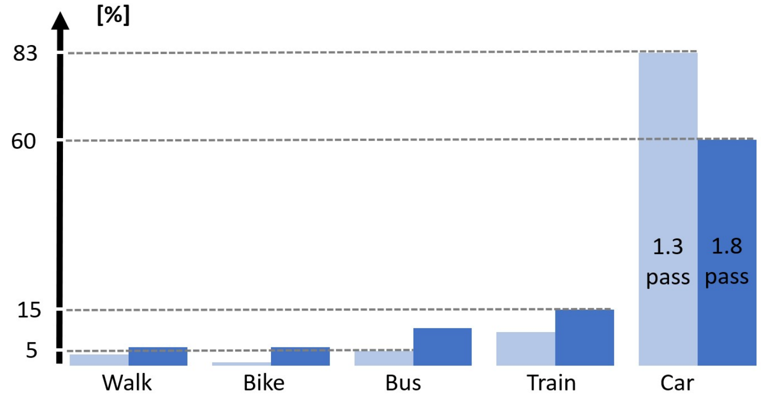

Figure 3.2: Modal share objectives for transport in Wallonia by 2030: 2017 in light blue 2030 in dark blue

Today, the passenger transportation demand is driven primarily by three trip purposes: leisure at 29%, shopping/services at 25%, and commuting at **20%**[26]. However, a more in-depth analysis is needed to assess the actual GHG emissions from this type of travel. Indeed, the distance traveled, the mode of transport chosen and its occupancy rate are all factors that influence the final emissions of these trips [25].

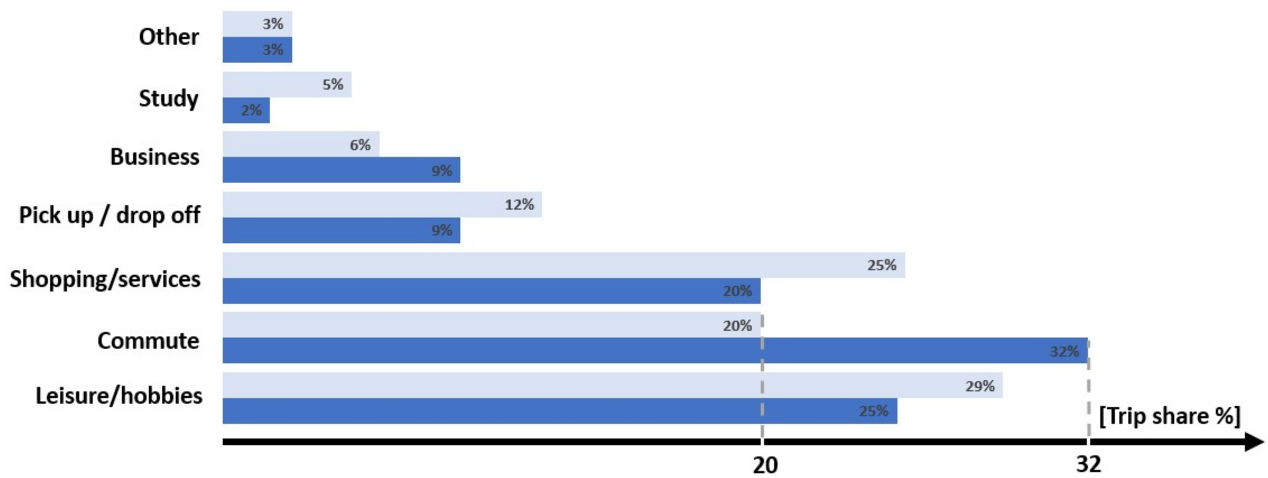

Figure 3.3: Trip share by purposes: trips share (light blue); GHG emissions share (dark blue)

The study from the SPF on mobility revealed that 65% of home-work trips in Belgium are made by car, followed by the bicycle at 11% and the train at 10%. This massive domination of the car in commute trips is even more pronounced for intra-Wallonia commute, where the modal share of the car reaches **83%**[25]. Moreover, home-to-work commutes are the longest, with an average distance of $21km$, and have the lowest car occupancy rate, with 1.05 passengers per vehicle. By comparison, leisure trips have an equivalent average distance of $18km$, but have a much higher occupancy rate with 1.53 passengers per vehicle [26].

This makes commuting to work the most emitting practice of private mobility accounting for **33%** of the total emissions due to passenger transport with **92%** of these practices emissions due to cars in Walloon Brabant. These trips are responsible for ∼4.2% of the overall GHG emissions in Belgium and about ∼**6.1%** in the Walloon Brabant.

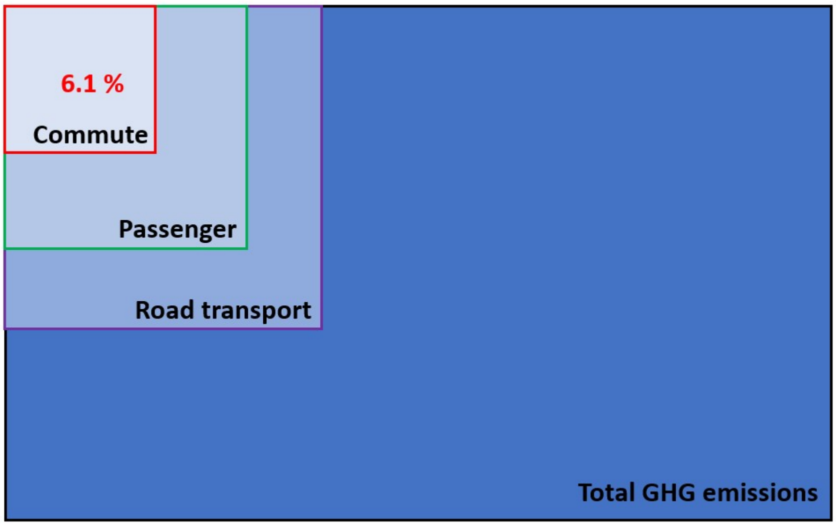

Figure 3.4: GHG emissions share of the commuting practice in Walloon Brabant

The amount of GHG emissions considered in this study case, including all the emissions due to commuting, only for the inhabitants of Walloon Brabant, is equal to **170.4 ktCO2**$_{eq}$ (CF. appendix C). Although the share of emissions considered is relatively modest at the Belgian scale (∼ 0.15%), it is sufficient to develop, test, and validate the proposed methodology and obtain relevant results at the Walloon Brabant level.

3.1 Setting the framework

The first two steps of the methodology developed in chapter 2 aim at setting up the framework necessary to analyze the level of social acceptance, the penetration rate and the effect on the reduction of GHG emissions of the practice changes in the population.

3.1.1 Creation of a representative database

Practice and individuals characterization

First, we characterized the individuals and their practice through nine factors classified into four categories according to the methodology presented in section 2.1. The characteristics selected and shown in figure 3.5 are those used by the Federal Public Services (SPF) for the climate survey.

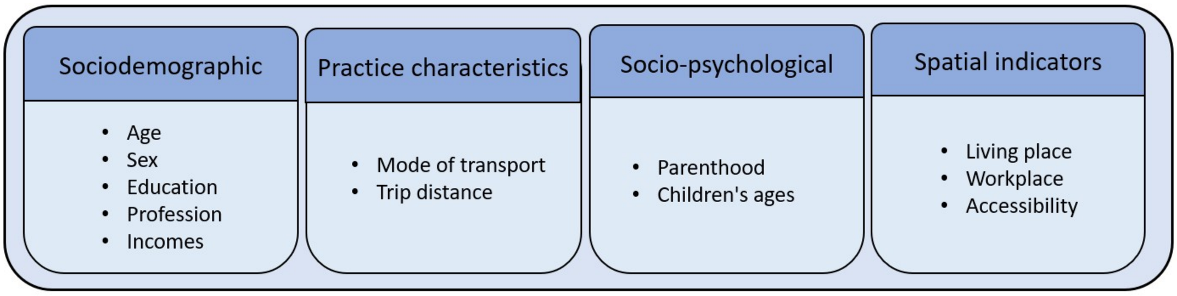

Figure 3.5: Practice and individual characteristics of commuting

The methodology used to determine the level of accessibility of each municipality is available in Appendix E.

Conduction of the survey

A survey is conducted to collect data on commuting to work and social acceptance of alternatives to cars in Walloon Brabant (CF. Appendix F). The population of interest consists of all workers living in Walloon Brabant aged 18 to 65, i.e. 165.000 people [12]. The net sample consists of 420 respondents who are part of the population being assessed which is consistent with the minimum sample size requirement (CF. formula 2.1). The net sample corresponds to the number of valid surveys (CF. 3.1.1) processed and used in the study case. By the conditions set out in section 2.1 we note a good representation in table 3.1 of gender and age. However, a weighting is necessary on the level of education due to an over-qualification of our sample with a gap of 10 points with the average population.

	Study raw sample	Walloon Brabant Population[1]
Sex		
Men	46%	52%
Women	54%	48%
Age		
18-25	12%	14%
25-35	15%	18%
35-45	25%	20%
45-55	23%	23%
55-65	20%	20%
Education		
Higher	66%	56%
Secondary	34%	44%
Commute distance		
< 7 [km]	16%	16%
7-15 [km]	14%	14%
15-30 [km]	39%	49%
30-60 [km]	27%	20%
> 60 [km]	3%	1%
Working region		
Walloon Brabant	5%	8%
Brussels-Capital	35%	38%
Wallonia apart from BW	19%	17%
Flanders	41%	37%

Table 3.1: Comparison of the study sample with the population

Weighting factors are used to ensure that the net sample is distributed in a representative manner and incomplete surveys are removed from the database, i.e only surveys that met the two following conditions are included in the database:

- At least 90% of the respondent characterization's questions (CF. appendix F) are complete and correct.
- The respondent has answered question *C1* (CF. appendix F) on the acceptance of alternatives.

[1]Data from the 2021 Walloon Brabant report [12]

3.1.2 Correlation analysis

Thanks to the characterization of individuals and their practices, correlation analysis can be performed. The correlation between selected individual characteristics and current mode of transportation as well as the willingness or not to switch modes is based on the weighted variance between the mean commuting modal share of the inhabitant of the Walloon Brabant and the modal share of the different social groups sharing common characteristics as developed in section 2.2.

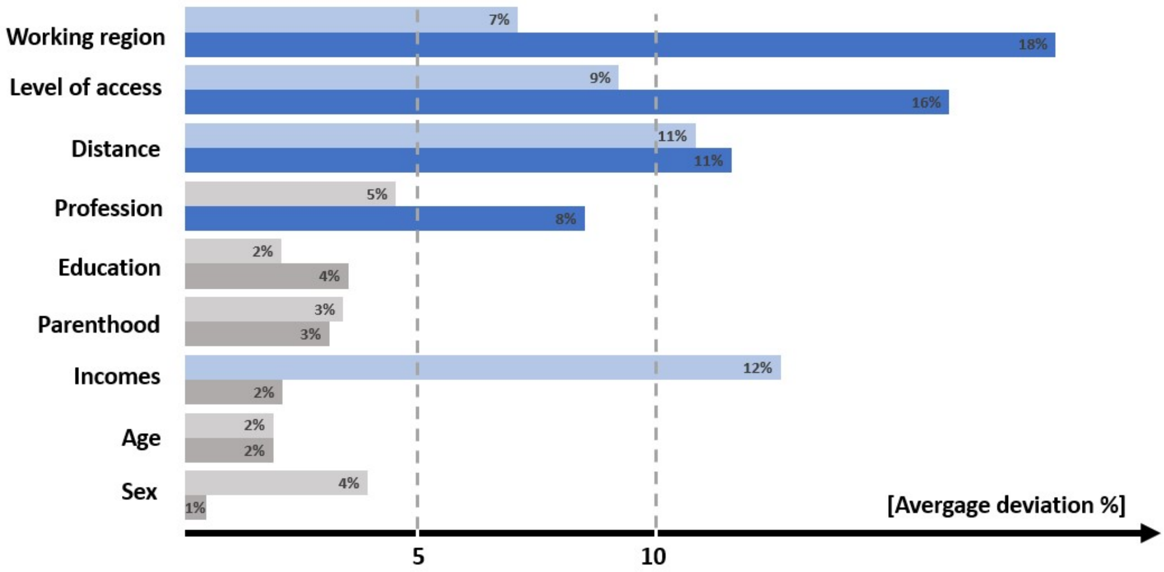

Figure 3.6: Correlation analysis between individual's characteristics and: the current practice of commuting (dark blue); the willingness to change the practice of commuting (light blue)

As we can see here above, the most impacting parameters regarding the current mobility are resulting from *Spacial indicators* (see section 2.1). The working region with a weighted variance of **18%** is, by far, the most influential parameter concerning current mobility. This means that the inhabitants of Walloon Brabant will travel differently if their workplace is located in Flanders, Wallonia, or the Brussels region. This can be explained on the one hand by the fact that the use of public transport is strongly correlated with the level of access to public transport (16%), which in turn is correlated with the region of work, and on the other hand by the particularly high congestion in the Brussels region [25].

However, when it comes to the acceptance of alternatives to cars we see that the level of income which is a *sociodemographic factor* is the most impacting factor with a weighted variance of **10.5%**. This gap between willingness and current practice can be explained by the lack of alternatives to the car available to the lower-income population locking their practice into a pattern beyond their opinion. This also shows that a significant portion of the population could make an important modal switch if convincing alternatives were offered. This finding is consistent with the study's findings that 37% of current motorists say they "can't" change their mode of transportation, while only 9% say they "don't want to" (CF. appendix A.2).

As a result of these findings and to ensure significant statistical differences[2], we will consider only the three characteristics with the highest level of correlation with current and future mobility, which are region of work, level of accessibility, and distance. This ensures that the observed impact of the characteristic on current and future practice reaches a sufficient level of significance and thus constitutes a real factor of social differentiation with respect to the practice studied.

3.2 General results

At first, the population is considered as belonging to a single social group. This allows us to identify the most popular alternative modes of transport and the main factors blocking their use.

3.2.1 Social acceptance of practice changes

The social acceptance of practice changes is assessed using the formula 2.4:

$$\%_{Penetration_{ij}} = \%_{Change_i} \cdot \%_{Alternative_k} \cdot \%_{Conditions_n} \cdot \%_{Gap}$$

Applied to this case study :

- $\%_{Penetration_{ij}}$: penetration rate of measure j encouraging a change of transport mode in group i.
- $\%_{Change_i}$: share of a group i in favor of any change of transport mode.
- $\%_{Alternative_k}$: share of the subgroup $\%_{Change_i}$ in favor of mode switching and use of mode k. In accordance with the existing and relevant transition measures, 7 alternatives to cars are proposed in the survey (CF. question *C2* in appendix F).

[2] A statistically significant difference, for example between men and women, is when the difference cannot (almost) be due to chance. Significant at the 95% confidence level means that there is a 5% probability that the difference is due to chance.

- $\%_{Conditions_n}$: share of the subgroup $\%_{Switch_i}$ in favor of the use of mode k under conditions n, relating to the factors blocking its current use. The 7 main blocking factors (CF. question *C3* in appendix F) were evaluated in the survey.

- $\%_{Gap}$: share of car trips actually replaced by the k mode. This factor has been estimated in the survey through a specific question (CF. question *D13* in appendix F) but can be refined if a still too large gap is observed between the opinion and the action in practice.

The general acceptance of alternatives to cars among the working population of Walloon Brabant is first analyzed by considering all driver workers as belonging to a single group. The study revealed that **62%** of this group favored changing their mode of transportation to commute to work.

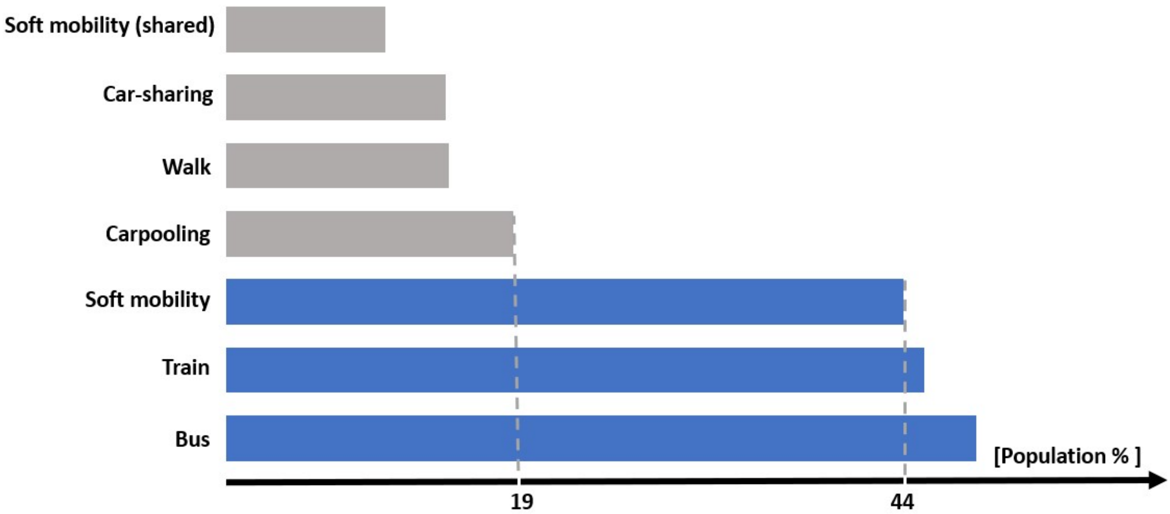

Figure 3.7: Popular alternative to cars in Walloon Brabant

Approximately **44%** of today's drivers favor using public transportation or soft mobility over driving to work. The main reasons for not doing so are, for more than half of the group, lack of infrastructure leading to lack of accessibility and lack of flexibility leading to lack of rapidity as we see in the graph 3.8. The survey also found that about **55%** of car trips would actually be replaced in practice, which represents the gap between opinion and action. It has been estimated by asking how many workdays a week they would actually see themselves commuting with an alternative mode to the car (see Appendix F question *D.13*).

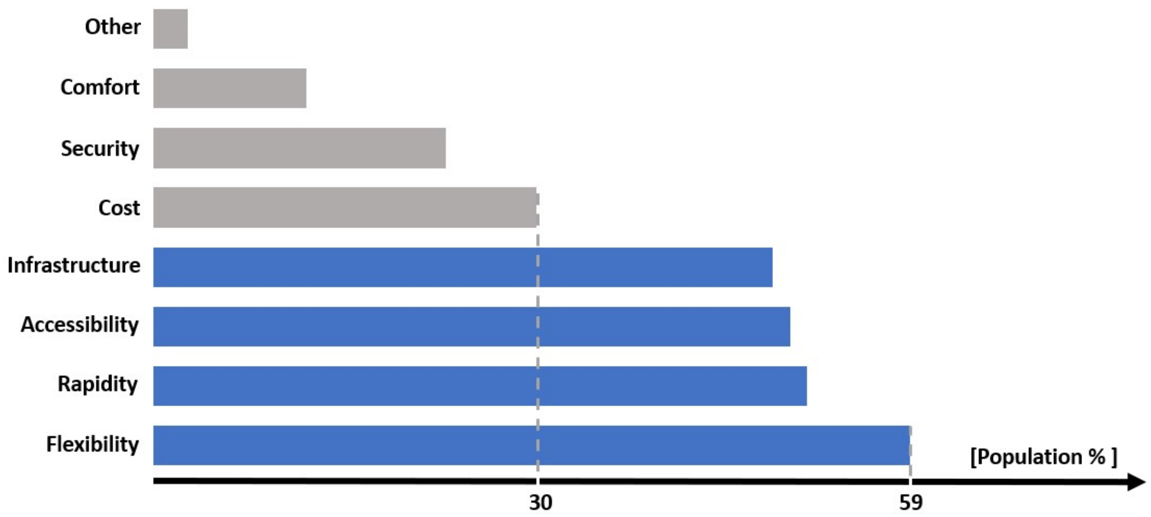

Figure 3.8: Factors blocking changes in commuting in Walloon Brabant

The social acceptance of the three most popular alternative modes to cars meeting the expectations of the population are obtained according to the methodology developed in section 2.4. The combination of these measures is also evaluated.

Transport mode	Acceptance	ME (95% CI)
Bus	15.3%	3.4%
Train	14.9%	3.6%
Soft modes	16.2%	3.4%
Combined	34%	6.2%

Table 3.2: Social acceptance specific to each mode

The combination of the three most popular alternatives observes a penetration rate of **35% ±6.2%** for a 95% confidence interval. We see that the final penetration rate is two times smaller than the general acceptance rate for mode change ($\sim$ 62%). This highlight the importance of refining questions to take into account the gap between the acceptance of a new practice and its actual integration into daily life as we did with the $\%_{Gap}$ rate .

3.2.2 GHG emissions' cut : first estimation

To evaluate the emissions reduction potential due to a change in practices we recall the function obtained in 2.7.

$$\text{GHG}_{ijk} = \sum^{i}\sum^{j}\sum^{k} \text{EUD}_{ij} \cdot \text{Footprint}_k$$

with :

- EUD_{ij}: The new final demand in km of a group i via mode j resulting from the considered practice change.
- Footprint_{jk} : GHG emissions of transportation mode j using energy source k in $gCO2_{eq}/km$.

First of all, by taking the mean carbon footprints (CF. appendix D) of the different modes of transport, and the current EUD of the population from the survey, we obtain total GHG emissions due to the current commute to work equal to **179.2 ktCO2**$_{eq}$. We note that there is a difference of less than 5% between these emissions obtained via our database and those found in the literature presented in the section 3 for the same level of detail (average over the whole population). Then, by taking the future EUD based on the acceptance rate of practice changes we obtain new total GHG emissions due to the practice. An emission cut of **27.7% ±6.4%** of current GHG emissions due to commuting to work in Walloon Brabant is expected if sufficient measures to develop public transport and smooth mobility are taken. At this stage, no precise measures are discussed or chosen, but some conclusions can already be drawn.

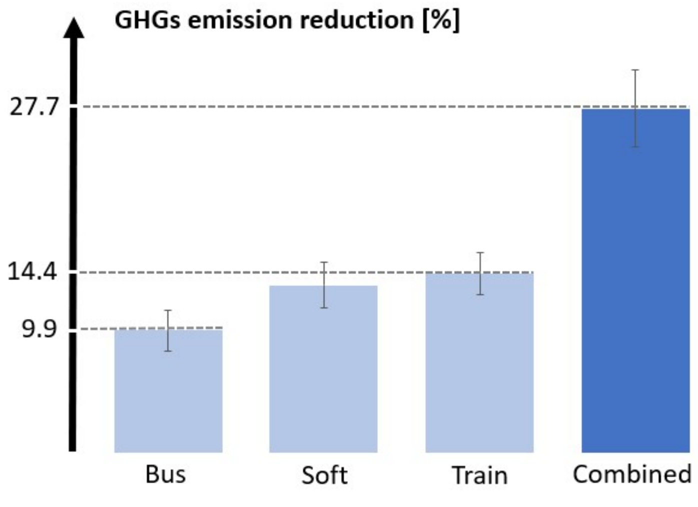

Figure 3.9: Maximum GHG emission reduction potential due to commuting in Walloon Brabant on a voluntary basis

First, it is found that the measures with the highest acceptance rate are not necessarily the ones with the greatest potential to reduce emissions from the practice. This will be important when selecting the most effective and profitable measures. Second, the margin of error of social acceptance and potential emission reduction has not increased. This is because public transport is a uniform fleet of the same vehicle, and the differences between the different light transport modes have little impact on the overall uncertainty because of their small carbon footprint (CF. appendix A.1).

Finally, we can assume that the emission reduction obtained for the combination of these three alternative practices represents the upper limit of potential GHG emissions reduction on a voluntary basis for the practice considered. Indeed, this first scenario, purely illustrative, evaluates the impact of an ideal offer of the three most popular alternatives to all workers living in the Walloon Brabant. However, the provision of all three modes at any location represents a significant oversizing of the mobility offer.

3.3 Measures selection

In order to obtain a realistic transition scenario, it is necessary to link potential changes in practices with appropriate measures to provide a transport offer that meets the specific needs and expectations of the population while minimizing the parallelism of equivalent services to minimize costs.

The survey revealed that the most popular alternatives to cars were public transport and soft modes of transportation. The selection of measures to provide a sufficient level of services depends on the population's expectations. It was evaluated in the study through the following criteria:

Public transports	
Cost	Half of the current price
Accessibility	15 minutes walk from a stop
Flexibility	Several times per hour
Rapidity	Maximum 1.5 slower than a car
Soft modes of transport	
Cost	Deductibility equivalent to a leasing car
Infrastructure	Isolated networks of bicycle paths
Rapidity	Maximum two times slower than car

Table 3.3: Ideal level of services expected by the population

Based on the expectations of the population and the conclusions of the final report of the Walloon Public Service (SPW) on the Walloon structuring network, relevant and realistic transition measures can be selected [23].

Measure 1: Structural bus network deployment and improvement

The current network partially meets expectations. Regarding accessibility 70% of the Walloon Brabant region currently has a level of service that is considered ideal (CF. Table 3.3) with a bus stop within a 1.5 km radius, less than 15min walking distance [22]. Regarding flexibility and correspondence, the level of services is clearly below expectations. In accordance with the final report of the structuring network conclusions, it is estimated that the implementation of 4 new rapid transit lines, as well as the improvement of 9 existing lines and the development of a FlexiTec service[3], would make it possible to reach the population's level of demand for public transit services in Wallonia.

Measure 2: Structural train network deployment

The current network partially meets expectations. Regarding flexibility 65% of the Walloon Brabant region currently has a level of service that is considered ideal with a minimum of two trains per hour [23]. Regarding accessibility and correspondence, the level of services is clearly below expectations. The RER project aims to upgrade the level of flexibility and connections within a perimeter of 30km around Brussels, including the Walloon Brabant [8]. However, the level of accessibility requiring the creation of new paths is not envisaged. Therefore, it is assumed that the bus network, as well as the soft mode path network, will allow reaching the stations in less than 15 minutes by other means than walking or driving.

Measure 3: Soft modes acquisition and dedicated networks deployment

The cycle track network of the Netherlands is taken as a reference [31] and it is considered that for an equivalent level of annual investment per capita the level of infrastructure allowing the use of soft transport modes will be sufficient. We assume that the public authorities invest as much per Walloon as our Dutch neighbors and based on the same distribution of public expenditure. The average depreciation cost of soft modes (a mix of scooters, bikes, and e-bikes) is added to get the total cost of the measure.

[3] On-demand bus service to underserved areas based on local needs

3.4 Results specific to measures

By assessing the specific needs of different social groups, it is possible to target their needs to select only the most relevant measures and thus avoid the parallelism of equivalent transport provision. This leads to two things. First, the average penetration rate increases due to the higher acceptance rate of measures specific to different subgroups. Second, the magnitude of the different measures is reduced, leading to a lower final cost.

3.4.1 Social acceptance of transition measures

First, we split the population into five groups by distance and region of work, the two most important factors influencing the practice 2.2. The standard deviation of the distances for people working in Brussels and in Wallonia (excluding Walloon Brabant) being low [26], we consider that only the work region allows differentiating these individuals. On the other hand, as the travel distances for people working in Walloon Brabant can vary greatly, three subgroups will be formed according to this distance. The acceptance rates are identified in the table below:

Working region	Distance	Popular Mode	Group	Acceptance	ME (95% CI)
Walloon Brabant	<10km	Soft modes	1	30.1%	4.5%
	10km to 20km	Soft & Bus	2	29%	4.5%
	> 20km	Bus	3	27.3%	4.4%
Wallonia	>20km	Bus	4	26.6%	3.8%
Brussels	>20km	Train	5	23.7%	3.6%

Table 3.4: Social acceptance specific to each group

We can see in the table 3.4 that the shorter the distance, the higher the acceptance rate. This can be explained by the fact that a short trip will generally take less time, and therefore will have less importance in everyday life. Second, there is a particular attraction to soft mobility. An explanation can be that it is the mode of transport closest to the car in terms of flexibility that represents the most important blocking factor to practice changes 3.8. In addition, the results obtained in the previous paragraph reinforce the acceptance of light transport modes as being particularly suitable for medium and short-distance trips.

3.4.2 GHG emissions' cut: second estimation

In the same way, as we did to evaluate the GHG emissions' cut in the oversized scenario 3.2.2 we obtain the potential reduction due to the new EUD. We can see below that an emission cut of **19.2% ±4.6%** of current emissions due to commuting to work in Walloon Brabant is expected if the measures discussed in section 3.3 to develop public transport and soft mobility are taken.

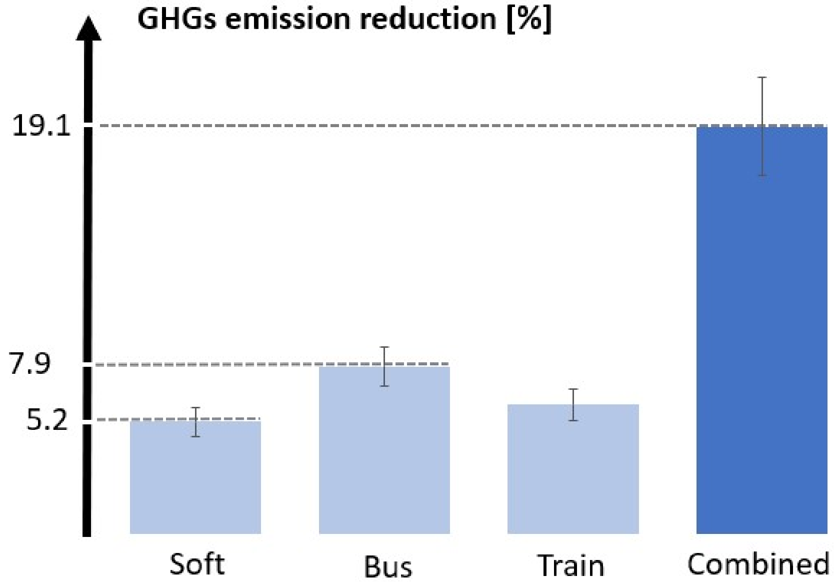

Figure 3.10: GHG emission reduction potential due to commuting in Walloon Brabant on a voluntary basis

First, we note that the proportion of the group in the population strongly constrains the reduction of emissions at the population level, which once again justifies the choice of limiting the number of subgroups. Indeed, a change of practice in a group responsible for a negligible share of emissions will also be negligible.

Secondly, we can see that the expected reduction in emissions increases with distance. This is because the emissions due to the practice are directly resulting from the mode footprint ($gCO2_{eq}/km$) and the distance traveled.

Finally, it can be seen that the expected emission reduction on a voluntary basis for this scenario is lower than the expected emission reduction for the parallel implementation of all the alternative modes considered. However, where the previous scenario represented a significant oversizing of the network, this one aims at optimizing its deployment and therefore reducing its costs.

3.5 Cost of measures estimation

Ideally, the costs of measures specific to the population's expectations and the region involved should be estimated by an agency with expertise in the field. However, we have no such means for this work. Therefore, an estimate of the cost of the measures needed to achieve the population's expected level of services is obtained by making certain assumptions described in Appendix A and using existing measures as a reference (CF. section 3.3). The calculation of the costs takes into account the acquisition of the vehicles (private or public), the operating costs of these vehicles (maintenance, PT drivers, energy, etc.), and the deployment of the necessary infrastructure (bicycle path, RER, etc.).

Measure 1: Structural bus network deployment and improvement

This first measure should be taken on a regional scale and cover the whole of Wallonia. This measure aims at deploying a structuring bus network to reach a sufficient level of service for a modal shift from car to bus for the home-work trips from the Walloon Brabant to Wallonia. The total estimated annual cost, based on the measure discussed in section 3.3, is between 10 and 15 M€/year [23]. According to the *H1* hypothesis (CF. appendix A), the amount paid by the Walloon Brabant is estimated to be proportional to the share of the population concerned by the measure, i.e. 11%.

The final estimated cost of the measure 1 for our case study is from **1 to 1.5** [**M€/year**] and aims to reduce **6.1% to 9.7%** of the emissions due to the commuting of the inhabitants of Walloon Brabant. This leads to a cost per ton of CO2 avoided from **57.5 to 137** [**€/tCO2eq**].

Measure 2: Structural train network deployment

This second measure is also on a regional scale but covers the region of Brussels capital. The reference cost is based on the RER project. This measure aims to improve the train's offer for trips to Brussels and is based on the current RER project. The total estimated annual cost (Capex and Opex) is between 43 and 70 [M€/year] for deploying and exploiting new infrastructure [8].

We use the *H1* and *H2* hypotheses (CF. appendix A) to estimate the budgetary share of the Walloon Brabant. The *H2* hypothesis allows to correct the cost estimation of the measure specifically aimed at a practice in proportion to the share of emissions due to this practice compared to the emissions of all the practices possibly impacted by the measure. In accordance with the RER deployment plan [8], the cost is divided between Flanders and Wallonia and then among the beneficiary municipalities in Wallonia, giving us a first ratio of 20% according to *H1*. Secondly, as the costs of the measure are mainly due to infrastructure costs, which will benefit all present and future passengers, we use hypothesis *H2* to obtain a second ratio specific to the share of train journeys made to go to or return from work, i.e. 30%.

The final estimated cost of the measure 2 for our case study is therefore from **2 to 3.6** [**M€/year**]. It aims at reducing **4.7% to 7.5%** of the emissions due to the commuting of the inhabitants of Walloon Brabant to Brussels. This leads to a cost per ton of CO2 avoided from **149 to 428** [**€/tCO2eq**].

Measure 3: Soft modes acquisition and dedicated networks deployment

This last measure, at the communal level, ensures a good connection of the whole network by overcoming the problem of the "last kilometer" [31]. The annual infrastructure cost for the deployment of a cycle track network equivalent to that of the Netherlands in Walloon Brabant is based on the dutch level of annual investment per capita in soft mobility ($\sim$ 20€/capita) and is estimated at $\sim$ 7.2[M€/year] [24]. In accordance with assumption *H2* (CF. appendix A) a correction ratio of 0.25 is added. In addition to the infrastructure cost, the vehicle acquisition cost[4], proportional to the concerned workers, is computed and estimated at $\sim$ 1.1 [M€/year].

The final estimated cost of the measure 3 for our case study is from **2.2 to 2.7**[**M€/year**] and aims to reduce **3.6% to 6.6%** of the emissions due to the commuting of the inhabitants of Walloon Brabant. This leads to a cost per ton of CO2 saved from **186 to 419** [**€/tCO2eq**]

[4]Considering a fleet of scooters (50%), bikes (25%), and e-bikes (25%) with a mean cost of 500€ and a lifetime of 3 years for e-modes and 6 years for bikes

3.6 Case study conclusion

In this case study, it was found that commuting to work for the inhabitants of Walloon Brabant was responsible for ∼**170 ktCO2$_{eq}$** and **6.1%** of the municipality's GHGs emissions. After analyzing the acceptance of alternative modes of transport to the car, we obtained that around **62%** of the workers favored a modal switch to public transport (bus and train) and soft mobility (scooter, bike and e-bike). They do not do so today mainly due to a lack of accessibility, flexibility, and sufficient infrastructure. It was found that **14.4% to 23.8%** of the greenhouse gas emissions of the practice can be reduced voluntarily provided that alternative modes meet the population's expectations. The factor of **3 to 4** between the general acceptance and the emission reduction expected is mainly due to an important gap between the opinion and the action. The carbon footprint of alternative modes, although much smaller than that of the car, also represents a limit to emission reductions.

We obtained that for a total cost of **5.2** [**M€/year**] **to 7.8** [**M€/year**] with a confidence interval of 95% the Walloon Brabant could reduce its emissions due to commuting to work of **14.5 % to 24 %**, which represent **25.8** [**ktCO2$_{eq}$**] **to 42.7** [**ktCO2$_{eq}$**] per year.

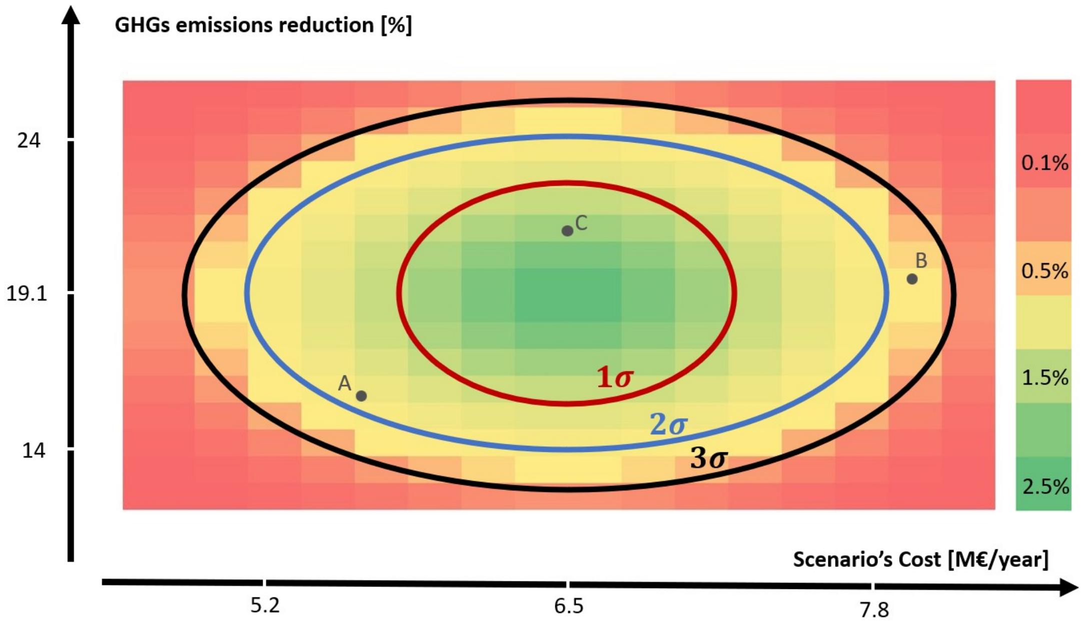

Figure 3.11: Multivariate Gaussian distribution of the emission's cut potential (y-axis) and the scenario's cost (x-axis): the 68%, 95%, and 99% confidence interval are respectively bounded in red, blue and black

This scenario leads to a cost per ton of CO2 avoided between **123 [€/tCO2] and 302 [€/tCO2]**, which is **6 to 8** times cheaper than a scenario of switching to electric cars (1000-1900 [€/tCO2][36]) and **3 to 4** times cheaper than a scenario of switching to plug-in hybrid cars (400-1400 [€/tCO2][36]).

The three points on the graph above are examples to facilitate the understanding of this graph. The first **point A** corresponds to a scenario where the cost per ton of $CO2_{eq}$ avoided would be around 200€. We observe that the cost of avoided emissions in this scenario results from a cost and a penetration rate of measures in the low range of estimates. This could, for example, correspond to a scenario where the soft transport fleet is mainly made up of low-cost vehicles (scooters and bicycles without electric assistance), but with a lower proportion of people taking the new bus routes than expected. The second **point B** corresponds to a scenario where the cost per ton of CO2 avoided is about 250€. We observe that the cost of avoided emissions in this scenario results from a cost in the high range of estimates. This could, for example, correspond to a scenario where the final cost of the RER is higher than estimated, but where the application of the different measures has the expected effect on the modal shift. Each of these scenarios could happen, however, we can say that scenario A is two times more likely to happen than scenario B and two times less likely to happen than scenario C.

It is clear that an investment in public transport and soft mobility is more profitable than switching to electric cars. However, the reduction of GHG emissions voluntarily remains limited. Therefore, it is essential to combine the implementation of such measures with incentives and disincentives to achieve significant changes in practice. Moreover, as this case study only deals with one practice covering a quarter of the daily trip's purposes we know that the emissions cut due to implementing these measures is likely to be much better. However, a similar study of other mobility-related practices is needed to prove and quantize this.

Chapter 4

Discussion and future work

This section presents ideas for improving the developed methodology and current energy system models. Proposals for improving the case study and ideas for application to other practices and sectors are also offered.

First, some improvements can be made to the case study. A specific evaluation of the cost of the imagined measures carried out by a competent authority would allow obtaining a more precise evaluation of the final cost of the scenario. However, history shows us that the final costs of public works are always very uncertain [8]. Also, a small-scale application of these measures would allow us to calibrate our correction factor between opinion and action to obtain an even more robust estimate of the expected GHG emissions reduction.

Second, following the proposed methodology, a similar study of all Belgian passenger mobility, which is responsible for 12.6% of national GHG emissions, can be carried out. The survey will have to be adapted to the different travel motives (leisure, shopping, education, etc.) and spread over the whole Belgian territory, but the methodology will remain the same. This will allow us to obtain a complete transition scenario for passenger mobility that considers the social acceptance of the proposed measures to ensure a good application among the population and thus an effective reduction of national GHG emissions. Such a study would also help to anticipate certain synergies between practices, such as the rebound effect. In the case of telecommuting, for example, there may be a partial shift in travel demand from commute trips to shopping and leisure trips as people have more time [16]. Moreover, the calculation of the costs of the scenario will be facilitated by the fact that many of the assumptions necessary for calculating the costs of a small-scale scenario will no longer be required (see appendix A).

In addition, similar studies can be considered for other sectors. For example, we know that domestic heating is responsible for 14% of national emissions [27] and that building renovation is the most important lever to reduce them [19]. However, it is currently difficult to assess which policy is most likely to lead to the maximum renovation of housing due to the lack of information regarding the social acceptance of these measures. A similar approach will allow comparing the different policies to maximize their actual effect, sometimes far from their potential effect.

Conclusion

Climate change is a major and complex challenge, from decarbonization to adaptation of demand through technological innovation. Our energy system, on which society is based, must be modified and our way of life will inevitably be impacted. The difficulty of considering the social dynamics underlying demand sometimes leads to the implementation of inefficient and uncertain transition policies [8].

In this work, we have developed a methodology to identify consumption dynamics specific to profiles of individuals representative of the population to assess the acceptance and effective penetration of transition measures in the population. This allowed us to robustly estimate the emission reduction relative to a transition scenario involving a behavior change and evaluate the cost of the latter per ton of $CO2_{eq}$ avoided. This allows us to compare different transition policies robustly and select the most cost-effective policies, but also the most likely to succeed, which was previously left to the discretion of the decision-maker(s).

The methodology presented has several advantages. First, the social acceptance survey preceding the work allows identifying the individual characteristics and the factors blocking and inciting the population to change their GHG emitting practices. Secondly, the correlation analysis between individual characteristics and energy consumption due to the practice allows us to identify the main factors influencing it and thus confirm or deny the relevance of certain present and future transition policies. In addition, the statistical analysis of the social acceptance of behavioral change allows us to evaluate the effective penetration of new practices in the population and thus determine the transition policies with the best chance of success. Finally, the robust attribution of costs and avoided emissions for the policies considered allows us to compare the policies according to three dimensions: environmental impact, cost, and social acceptance.

The case study revealed some interesting results. Firstly, it was found that more than **60%** of the car drivers responsible for 92% of the emissions due to commuting in the Walloon Brabant region are in favor of changing their mode of transport with train, bus, scooter, or e-bike. However, only **55%** of the distances would be effectively replaced by an alternative mode to the car on a voluntary basis. This highlights the large gap between potential and reality if convincing alternatives to the car were offered without a combination of incentives, disincentives, or constraints. Moreover, we found a cost per ton of $CO2_{eq}$ avoided between **123 €/tCO2$_{eq}$ and 302 €/tCO2$_{eq}$**, which is **3 to 8** times cheaper than a scenario of switching to electric cars (1000-1900 [€/tCO2][36]) or plug-in hybrid cars (400-1400 [€/tCO2][36]).

In addition, the factors most influencing car use were found to be the level of accessibility directly related to the region of residence and work, the distance, and the lack of infrastructure and flexibility. Contrary to one might think, income level does not currently influence car use. This can be explained by the lack of alternatives to the car and this is especially true in rural areas with poor public transport links. However, we also see that the low-income population would significantly shift to these alternatives if sufficient public transport services were provided everywhere.

In conclusion, a good transition scenario for mobility would be to improve the flexibility of existing public transport while developing their networks to enhance their accessibility to cover the transport demand on long (train) and medium (bus) distances. At the same time, roads should be developed for the use of soft modes of transport that allow easy access to the main public transport networks and cover the demand for transportation over short (scooters) and medium (e-bikes) distances to overcome the "last kilometer problem". Finally, a combination of economic incentives equivalent to the benefits of company cars and strong communication about these alternative modes will be needed to ensure maximum penetration of these measures and a minimum gap between opinion and action.

Appendix A

Appendix

A Costs estimation hypotheses

The cost of measures required to implement alternatives to reduce emissions from practice can be estimated based on existing similar measures. However, the costs available in the literature are generally sized for larger populations and are not specifically targeted at any particular practice. Moreover, it is rare for a measure to impact a single practice. Therefore, in order to best assess the costs of a measure related to changes in a particular practice, the following assumptions can be made:

- $\mathbf{H}_1$: the cost of the existing measure found in the literature is corrected in proportion to the ratio between the size of the population considered in the case study and the size of the population affected by the measure of reference.
- $\mathbf{H}_2$: the cost of the existing measure is corrected in proportion to the ratio between the share of emissions due to the considered practice and the total emissions affected by the measure. This strong assumption means that the cost of a measure impacting several practices is uniformly distributed according to the emissions related to these practices. This is not necessarily the case, but since the measures always apply to a set of practices, considering that only one of them will be affected would lead to an even larger error.
- $\mathbf{H}_3$: the investment costs per year are added to the annual operating costs to obtain an overall annual cost of the measure including its various specific costs.
- $\mathbf{H}_4$: The probability distributions of the costs of the measures are considered Gaussian due to lack of sufficient information. However, since the tendency is much more towards budget overruns than the opposite, the mean cost is multiplied by a standard safety factor of 1.5.

B Case study emissions calculation

$$\textbf{Considered emissions} = GHG_{BE} \cdot \%Sector \cdot \%PassMob \cdot \%Practice \cdot \%Population \quad (A.1)$$

$$= 116.6[MtCO2_{eq}] \cdot 23\% \cdot 55\% \cdot 33\% \cdot 3.5\% \quad (A.2)$$

$$= 170.4[ktCO2_{eq}] \quad (A.3)$$

With :

- GES_{BE} : Belgian emissions of greenhouse gases.
- $\%Pass$: share of national emissions due to passenger transport
- $\%Work$: share of passenger transport emissions due to commuting
- $\%_{PopBW}$: share of the population living in the Walloon Brabant

C Additional study case results

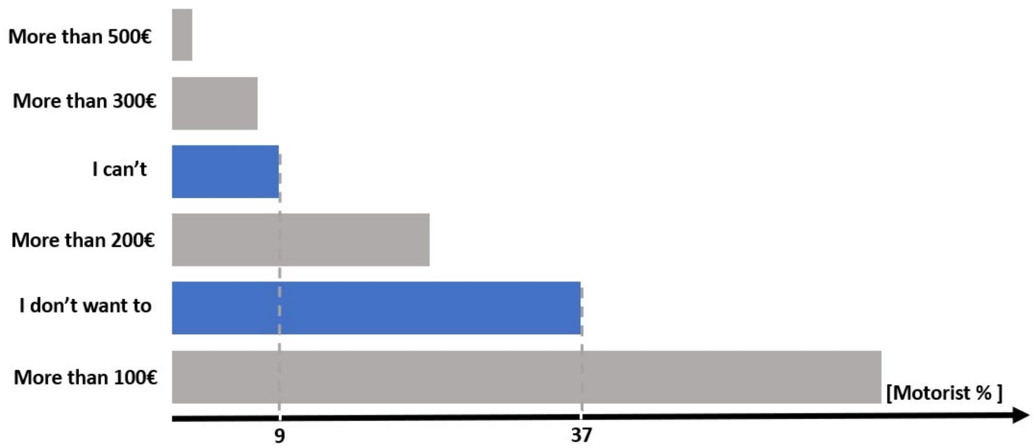

Figure A.1: Maximum increase in monthly transportation expenses to encourage a change in transportation mode (CF. appendix F question E.3)

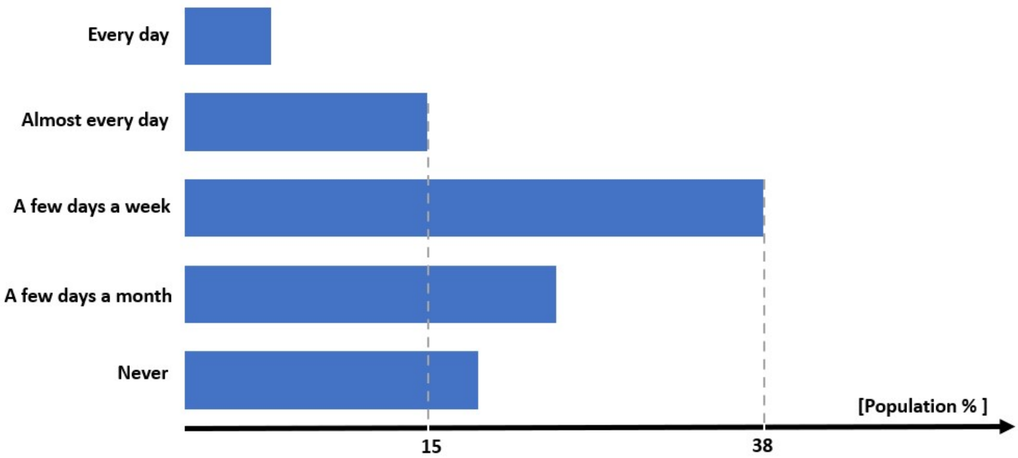

Figure A.2: Opinion on the optimal level of integration of telework (CF. appendix F question F.1)

D Robust assignment of transport modes carbon footprints

The emissions from commuting between individuals using the same mode of transport can vary according to the model used, due to the amount and type of energy the vehicle uses. The following section determines the average emissions of the modes of transport considered and, if necessary, assigns a standard deviation to them according to the variance observed within the fleet of vehicles considered.

Average carbon footprints

The $CO2_{eq}$ emissions related to using of a means of transport depend on different parameters. Indeed, the occupancy rate, and the number of emissions per kilometer traveled must be taken into account. This is why the emission rate of each mode will be defined in $gCO2_{eq}/km - pass$, that is, the amount of $CO2_{eq}$ in grams emitted to travel one kilometer per passenger. The methodology is based on results from the thesis of Gauthier Limpens [19]:

$$\mathbf{Footprint}_i = (\mathbf{Fuel}_{ji} \cdot \mathbf{CO2}_{directj} + \mathbf{Electricity}_i \cdot \mathbf{CO2}_{prod}) \tag{A.4}$$

With :

- Footprint$_i$: the carbon footprint of the mode of transport i in $[gCO2/km - pass]$

- Fuel_i : the fuel consumption j of the mode of transport i in natural condition of use in $[Wh/km - pass]$

- Electricity_i : the electricity consumption of the mode of transport i in $[Wh/km - pass]$

- $\text{CO2}_{directi}$: direct emissions from combustion in $[kgCO2/MWh_{fuel}]$

- CO2_{prod} : direct emissions from the production of electricity $[kgCO2/MWh_{fuel}]$

We choose not to consider the emissions due to the production and transport of fuels, because they are not, to date, taken into account in the calculation of the country's emissions. We note the interest in integrating these data into the models. However, this requires a complete redefinition of the sector's emissions and even more of the country, which is not the subject of this work.

A differentiation is made between public transport, light transport, and individual motorized transport. Indeed, public transport fleets are highly homogeneous as vehicles are always acquired in lots and constitute the whole fleet [22]. Also, the modes of light-assisted transport, whether scooters or bicycles, share equivalent technologies to date and show light variation in consumption per kilometer. We will therefore simply calculate the average carbon footprint of rail, bus, and light transport modes based on the characteristics of the different vehicles in these fleets and their share.

Mode	Ressources	Mode share [%]	Consumption [Wh/km-pass]	GWP_{op} [gCO2e/Wh]	Footprint [gCO2e/km-pass]
Train	Electricity	100	63	18.27	18.27
Bus	Diesel	75	265	71.55	66.0375
	Hybrid	25	198	49.5	
Scooter	Electricity	50	15	22.35	21.944
E-bike	Electricity	50	13.6	21.944	

Table A.1: Transport mode footprint[1]

[0]Data from Gauthier Limpens thesis [19]
[1]Data from Gauthier Limpens thesis [19]

The private motorized modes of transport constitute a less homogeneous group. Indeed, the Belgian car fleet is made up of more or less polluting vehicles depending mainly on the year of construction of the vehicle and the EURO standard relative to this year. Moreover, as shown in the graph above, a strong variation in emission standards is observed between private vehicles and company cars.

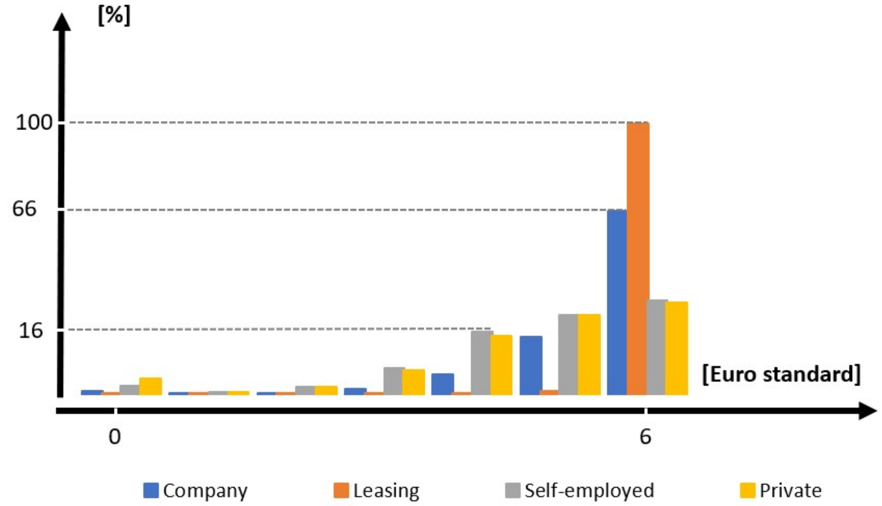

Figure A.3: Euro standards distributions by ownership

We obtain distributions specific to each ownership system by combining them with the mean footprint of the different EURO standards [13].

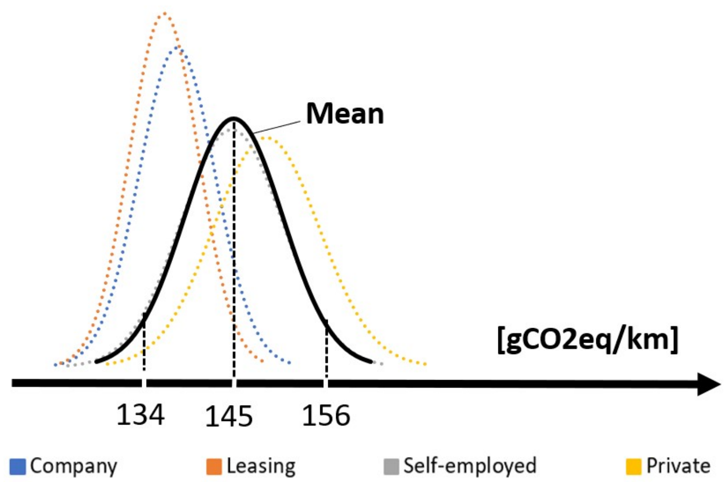

Figure A.4: Car footprint distributions by ownership

E Accessibility scores calculation

Accessibility to alternative modes of transport is one of the most important factors influencing the use or not of these modes and characterization of the trips related to this level of accessibility must be made. The methodology used below is based on the methodology developed by the SPM to evaluate the level of accessibility of the different municipalities in Belgium [26]. This calculation takes into account:

- The proximity of public transport stops (train, metro, streetcar, bus). The closer the stop, the greater its importance in the score.
- The importance of these stops is calculated on the basis of the number of vehicle passages, and the total number of passengers from each transport company.

Three different categories are determined according to different levels of access and the municipalities are ranked according to their accessibility scores.

Level of Access			**Level of Transit**		
Weak: 0	Average: 1	High: 2	Weak: 0	Average: 1	High: 2
No nearby train station and less than 100 bus stops	A nearby train station and or between 100 and 200 bus stops	A communal station and more than 200 stops	Less than 5000 boarding / getting off per day on weekdays	Between 5000 and 7000 boarding / getting off per day on weekdays	More than 7000 boarding / getting off per day on weekdays

Figure A.5: Access score criteria

As the case study and the data collection concern the inhabitants of Walloon Brabant, a distinction at the municipal level will only be made for the province of Walloon Brabant. Therefore, an average accessibility score is calculated and attributed to the municipalities of Flanders, Wallonia, and Brussels-Capital. A high accessibility score is given to all the municipalities of Brussels-Capital because of their very high accessibility level in proportion to Belgium, whereas an average accessibility score is given to all the cities of Flanders and Wallonia except for Walloon Brabant.

Brabant Wallon	Beauvechain	0
	Braine-l'Alleud	2
	Braine-le-Château	1
	Chastre	0
	Chaumont-Gistoux	0
	Court-Saint-Etienne	1
	Genappe	0
	Grez-Doiceau	0
	Hélécine	0
	Incourt	0
	Ittre	0
	Jodoigne	0
	La Hulpe	1
	Lasne	0
	Mont-Saint-Guibert	0
	Nivelles	2
	Orp-Jauche	0
	Ottignies-Louvain-la-Neuve	2
	Perwez	0
	Ramillies	0
	Rebecq	0
	Rixensart	1
	Tubize	2
	Villers-la-Ville	0
	Walhain	0
	Waterloo	1
	Wavre	1
Wallonie		1
Flandre		1
Bruxelles-Capitale		2

Figure A.6: Municipalities access score

Once the accessibility score of these different communes has been obtained, an accessibility score for the different trips can be calculated. A simple sum of the arrival and departure communes score is sufficient to classify these different trips and thus to attribute to the practices considered, the home-work trips, a characteristic relating to its level of accessibility.

$$\text{Trip access score} = \text{departure access score} + \text{arrival access score} \tag{A.5}$$

F Survey questionnaire

Partie A: Respondent characterization

A1. **Dans quelle région habitez-vous (lieu de résidence principale) ?**

A2. **Dans quelle commune habitez-vous ?**

A3. **Êtes-vous travailleur ?**

A4. **Dans quelle région travaillez-vous (principalement) ?**

A5. **Dans quelle commune travaillez vous ?**

A6. **Quelle distance sépare votre domicile et votre lieu de travail ?**

A7. **A quelle identité de genre appartenez-vous ?**

A8. **Quel âge avez-vous ?**

A9. **Avez-vous un ou plusieurs enfants, si oui quel âge ont-ils ?**

A10. **Quel niveau d'instruction maximum avez vous atteint ?**

A11. **Quel est votre niveau de revenu mensuelle (net) ?**

A12. **Quel statut professionel avez-vous ?**

Partie B: Mobility characterization

B1. **Quel est votre mode de transport principal d'ordre général ?**

B2. **Quel est votre mode de transport principal pour aller travailler ?**

B3. **Utilisez-vous parfois d'autres modes pour vous rendre au travail (plusieurs modes possibles) ?**

B4. **Quelle est l'année de mise en circulation de votre véhicule ?**

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B5. **Possédez-vous un véhicule de société ?**

Partie C: Social acceptance

C1. **Dans l'hypothèse où des mesures (économique, sécuritaire, accessibilité, etc.) facilitant l'intégration des autres modes de transport sont appliquées :**

Est-il envisageable de changer de mode de transport partiellement ou totalement ?

C2. **Lesquels pourriez-vous utiliser ?**

- Train ☐
- Metro, Bus, Tram ☐
- Léger particulier (Vélo, vélo électrique, trottinettes etc.) ☐
- Léger partagé (Vélo, vélo électrique, trottinettes etc.) ☐
- Marche ☐
- Voiture partagée ☐
- Co-voiturage ☐
- Aucun des modes proposés ☐

C3. **L'amélioration de quels composantes vous inciterait à utiliser ces autres modes de transport ?**

- Le confort ☐
- La flexibilité ☐
- Les infrastructures ☐
- L'accessibilité ☐
- Le coût ☐
- La sécurité ☐
- La rapidité ☐
- Aucune des mesures proposées ☐

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Je préfère ce mode de transport pour des raisons qui me sont propres (Empreinte carbone, habitudes, etc) ☐

Partie D: Level of requirement

D1. Quel niveau d'infrastructure jugez-vous idéal pour les modes de transport légers ?

- Bas : Rénovation des voiries existantes (trottoir et pistes cyclables) ☐
- Moyen : Rénovation et développement de nouvelles voiries ☐
- Elevé : Privatisation de voiries et développement de réseaux isolés de pistes cyclables ☐

D2. Quelle politique économique jugez-vous idéale pour les modes de transport légers privatifs ?

- Basse : Remboursement partiel du matériel ☐
- Moyenne : Remboursement total du matériel ☐
- Elevée : Déductibilité équivalente à une voiture de société ☐

D3. Quelle politique économique jugez-vous idéale pour les modes de transport légers partagés ?

- Basse : Coût du trajet égal aux transports en communs ☐
- Moyenne : Coût du trajet inférieur aux transports en communs ☐
- Elevée : gratuité ou quasi gratuité ☐

D4. Quel niveau d'accessibilité des modes de transports partagés jugez-vous idéal ?

- Bas : mode disponible à moins d' une demi-heure à pied ☐
- Moyen : mode disponible à moins de 15 minutes à pied ☐
- Elevé : mode disponible à moins de 5 minutes à pied ☐

D5. Quelle politique économique jugez-vous idéale pour les voitures partagées ?

- Basse : Coût équivalent à une voiture privative ☐
- Moyenne : Coût inférieure à une voiture privative ☐
- Elevée : Coût fortement inférieure à une voiture privative ☐

D6. Quel niveau d'infrastructures jugez-vous idéal pour la pratique du co-voiturage ?

- Bas : Déploiement d'aires de Co-voiturage dans différentes grandes villes ☐
- Moyen : Accès à des voiries prioritaires (ex: partagées avec Bus et taxi) ☐
- Elevé : Accès à des voiries privatisées (ex: bandes réservées au co-voiturage) ☐

D7. Quel niveau d'accessibilité jugez-vous idéal pour la pratique du co-voiturage ?

- Bas : Point de départ à moins de 1h à pied ☐
- Moyen : Point de départ à moins de 30 min à pied ☐
- Elevé : Point de départ à moins de 15 min à pied ☐

D8. Quel niveau de flexibilité jugez-vous idéal à la pratique du co-voiturage ?

- Bas : Plusieurs départs par jour aux heures de pointes ☐
- Moyen : Plusieurs départs par jour à toutes heures ☐
- Elevé : Plusieurs départ par heure à toutes heures ☐

D9. Quel niveau de flexibilité jugez-vous idéal à l'utilisation des transports en communs ?

- Bas : Départs plusieurs fois par jour ☐
- Moyen : Départs plusieurs fois par heure ☐
- Elevé : Départs plusieurs fois par demi-heure ☐

D10. Quel niveau d'accessibilité jugez-vous idéal à l'utilisation des transports en communs ?

- Bas : Point de départ à moins de 1h à pied ☐
- Moyen : Point de départ à moins de 30 min à pied ☐
- Elevé : Point de départ à moins de 15 min à pied ☐
- Très élevé : Point de départ à moins de 5 min à pied ☐

D11. Quelle politique économique jugez-vous idéale pour l'utilisation des transports en communs ?

- Basse : Prix actuel ☐
- Moyenne : 3/4 du prix actuel ☐
- Elevée: 1/2 du prix actuel ☐
- Très élevée : gratuité ou quasi gratuité ☐

D12. Quel niveau d'infrastructures jugez-vous idéal à la combinaison de plusieurs modes de transport ? (ex: vélo + train)

- Bas: Facilitation de la combinaison de divers moyens de transports [ex: parking (à voiture, moto, vélo, etc.) surveillé en gare] ☐
- Moyen : Adaptation des transports existants à la combinaison avec des mode "légers" (ex: Wagon pour vélo) ☐
- Elevé : Déploiement de réseaux destinés à la combinaison (ex: réseau de pistes cyclables + réseaux ferroviaires) ☐

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D13. **Dans quelles mesures utiliseriez-vous les moyens de transport suivants si le niveau de mesure que vous considérez idéal était éffectif ?**

	Jamais	Quelques jours par an (3-4 jours/mois)	Quelques jours par mois (5-10 jours/mois)	Quelques jours par semaine (2-4 jours semaines)	Tous le jours, à quelques exceptions près
Voiture	☐	☐	☐	☐	☐
Moto	☐	☐	☐	☐	☐
Scooter	☐	☐	☐	☐	☐
Train	☐	☐	☐	☐	☐
Metro, Bus, Tram	☐	☐	☐	☐	☐
Léger particulier (Vélo, vélo électrique, trottinettes etc.)	☐	☐	☐	☐	☐
Léger partagé (Vélo, vélo électrique, trottinettes etc.)	☐	☐	☐	☐	☐
Marche	☐	☐	☐	☐	☐
Voiture partagée	☐	☐	☐	☐	☐
Co-voiturage	☐	☐	☐	☐	☐

Partie E: Expenditure level and limit

E1. **Quel niveau de dépenses mensuelles en transport se rapproche le plus du vôtre ?**

- < 50 [€] ☐
- 50-100 [€] ☐
- 100-150 [€] ☐
- 150-200 [€] ☐
- 200-250 [€] ☐
- > 250 [€] ☐

E2. **Quelle part de ce budget en transports est, selon-vous, allouée au trajet domicile-travail ?**

- < 20 [%] ☐
- 20-40 [%] ☐
- 40-60 [%] ☐
- 60-80 [%] ☐
- 80-100 [%] ☐

E3. **Quel niveau de dépense mensuel en transports vous ferait changer de mode ?**

- >100 [€] ☐
- >200 [€] ☐
- >300 [€] ☐
- >500 [€] ☐
- Je ne peux pas changer de mode de transport ☐
- Je ne veux pas changer de mode de transport ☐

Partie F: Telework

F1. **Dans quelle mesure aimeriez vous intégrer le télé-travail / télé-enseignement à votre vie ?**

- Jamais ☐
- Quelques jours par mois (3-7 jours/mois) ☐
- Quelques jours par semaine (1-3 jours semaines) ☐
- Presque tous les jours (3-5 jours semaines) ☐
- Tous le jours, à quelques exceptions près ☐

Bibliography

[1] "Not In My Back Yard" syndrome. https://dictionary.cambridge.org/dictionary/english/nimby (2017), accessed: 2022-05-10

[2] Baxter, G., Sommerville, I.: Socio-technical systems: From design methods to systems engineering. Interacting with Computers 23(1), 4–17 (08 2010)

[3] Brand, C.: UK Transport Carbon Model: Reference Guide v1.0 (01 2010)

[4] Brand, C., Anable, J., Philips, I., Morton, C.: Transport energy air pollution model (team): Methodology guide (05 2019)

[5] Brand, C., Anable, J., Morton, C.: Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. Energy Efficiency 12(1), 187–207 (Jan 2019)

[6] Brand, C., Dons, E., Int Panis, E.A.B.: The climate change mitigation effects of daily active travel in cities. Transportation Research Part D: Transport and Environment 93 (2021)

[7] Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., Paroussos, L., Fragkiadakis, K., Tsani, S., Karkatsoulis, P., Höglund-Isaksson, L., Winiwarter, W., Purohit, P., Gomez Sanabria, A., Frank, S., Kesting, M.: EU Reference scenario 2016 -Energy, transport and GHG emissions Trends to 2030 (07 2016)

[8] Cour des comptes: Réseau express régional : mise en oeuvre et financement. https://www.ccrek.be/Docs/2017_03_RER_MiseEnOeuvreEtFinancement.pdf (2017)

[9] Epprecht, N., von Wirth, T., Stünzi, C., Blumer, Y.B.: Anticipating transitions beyond the current mobility regimes: How acceptability matters. Futures 60, 30–40 (2014)

[10] European Commission: Eurostat. glossary: Final energy consumption, accessed: 2021-10-11

[11] European Economic and Social Committee: What conditions are needed for the energy and low-carbon transition to be socially acceptable? (2022), https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/what-conditions-are-needed, accessed: 2022-02-09

[12] Fondation Économique et Sociale du Brabant wallon: Le Brabant wallon en chiffres. https://www.inbw.be/sites/default/files/publications/bw_en_chiffres_2021_pages.light_.pdf (2021)

[13] Fédération Belge de l'Automobile et du Cycle: Parc automobile belge : Répartition du parc belge des voitures par classe environnementale. https://www.febiac.be/public/statistics.aspx?FID=23&lang=FR (2019), accessed: 2022-03-15

[14] H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S.: Sixth Assessment Report WGI : physical science basis of the climate change. https://www.ipcc.ch/report/ar6/wg1/ (2022)

[15] Hofman, E.: Social acceptance of renewable energy (2021), https://climatepolicyinfohub.eu/social-acceptance-renewable-energy, accessed: 2021-09-11

[16] Hook, A., Court, V., Sovacool, B.K., Sorrell, S.: A systematic review of the energy and climate impacts of teleworking. Environmental Research Letters 15(9), 093003 (aug 2020)

[17] Li, F., Trutnevyte, E., Strachan, N.: A review of socio-technical energy transition (stet) models. Technological Forecasting and Social Change 100, 290–305 (08 2015)

[18] Limpens, G.: Generating energy transition pathways: application to belgium (06 2021)

[19] Limpens, G., Moret, S., Jeanmart, H., Maréchal, F.: Energyscope td: A novel open-source model for regional energy systems. Applied Energy 255, 113729 (2019)

[20] Lipschutz, R.: Practicing energy, or energy consumption as social practice (2015), https://escholarship.org/uc/item/1vs503px

[21] Malone, H., Nicholl, H., Coyne, I.: Fundamentals of estimating sample size. Nurse Researcher Volume 23, 21–25 (05 2016)

[22] Opérateur de Transport de Wallonie: Tec network maps (2021), https://www.letec.be/View/TEC_network_maps/1135, accessed: 2021-11-10

[23] Province du Brabant Wallon: Rapport final : Réseau structurant de transport public, liaisons structurantes et recommandations. http://mobilite.wallonie.be/files/eDocsMobilite/Outils/Plans%20de%20mobilit%C3%A9/BW_axes_TC_structurants_et_recommandations_201903.pdf (2019)

[24] Service public de Wallonie: Évaluation économique de la pratique du vélo en Wallonie. http://mobilite.wallonie.be/files/eDocsMobilite/politiques%20de%20mobilit%C3%A9/wallonie%20cyclable/%C3%A9conomie/Evaluation%20%C3%A9conomique%20de%20la%20pratique%20du%20v%C3%A9lo%20en%20Wallonie_resume.pdf (2015)

[25] Service Public Fédéral de la Mobilité et des Transport: Diagnostic fédéral sur les déplacements domicile-travail. https://mobilit.belgium.be/fr/mobilite/domicile_travail (2017)

[26] Service Public Fédéral de la Mobilité et des Transport: Monitor : Enquête nationale sur la mobilité et la sécurité routière. https://mobilit.belgium.be/fr/mobilite/mobilite_en_chiffres/enquetes_sur_la_mobilite_des_belges/monitor (2017)

[27] Service Public Fédéral de l'Environnement: Émissions des gaz à effet de serre belge par secteur (2021), https://climat.be/en-belgique/climat-et-emissions/emissions-des-gaz-a-effet-de-serre/emissions-par-secteur, accessed: 2022-04-17

[28] Service Public Fédéral de l'Environnement Wallon: Rapport sur l'état de l'environnement wallon. http://etat.environnement.wallonie.be/home/Infographies.html (2018)

[29] Service Public Fédéral de l'Environnement Wallon: Etat de l'Environnement Wallon : Emissions de Gaz à effet de serre. http://etat.environnement.wallonie.be/contents/indicatorsheets/AIR%201.html (2022), accessed: 2022-05-04

[30] Service Public fédéral Santé publique, Sécurité de la chaîne alimentaire et Environnement: Enquête sur le climat. https://climat.be/en-belgique/communication-et-education/enquetes-sur-le-climat (2022)

[31] Service Public Wallon de la Mobilité et du transport: Stratégie Régionale de Mobilité. http://mobilite.wallonie.be/home/politiques-de-mobilite/politique-de-mobilite-regionale-wallonne/

strategie-regionale-de-mobilite.html#:~:text=La%20mise%20en%20%C5%93uvre%20de,du%20plan%20air%20climat%20%C3%A9nergie. (2019)

[32] Shove, E., Walker, G.: What is energy for? social practice and energy demand. Theory, Culture Society 31, 41–58 (08 2014)

[33] Sulikova, S., Brand, C.: Investigating what makes people walk or cycle using a socio-ecological approach in seven european cities. Transportation Research Part F: Traffic Psychology and Behaviour 83, 351–381 (2021)

[34] Thompson, P., Liu, Y.: Understandings of margin of error (01 2005)

[35] United Nations Framework Convention on Climate Change: COP26 : Glasgow Climate Pact and Outcomes. https://ukcop26.org/the-conference/cop26-outcomes/ (2021)

[36] van Vliet, O., Brouwer, A., Kuramochi, T., van den Broek, M., Faaij, A.: Energy use, cost and co2 emissions of electric cars. Journal of Power Sources 196, 2298–2310 (01 2015)

[37] Wikipedia contributors: Weighted arithmetic mean — Wikipedia, the free encyclopedia (2022), https://en.wikipedia.org/w/index.php?title=Weighted_arithmetic_mean&oldid=1100253243, [Online; accessed 15-August-2022]

[38] Wüstenhagen, R., Wolsink, M., Bürer, M.J.: Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy 35(5), 2683–2691 (2007)

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**