UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ
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FERNANDO CESAR CUZINSKY

IDENTIFYING THE ROADMAP FOR PASSENGER TRANSPORTATION IN CURITIBA BY MEANS OF LCA AND MATHEMATICAL OPTIMIZATION

DISSERTAÇÃO

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IDENTIFYING THE ROADMAP FOR PASSENGER TRANSPORTATION IN CURITIBA BY MEANS OF LCA AND MATHEMATICAL OPTIMIZATION

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A Dissertação de Mestrado intitulada: **Identifying the roadmap for passenger transportation in Curitiba by means of LCA and mathematical optimization**, defendida em sessão pública pelo Candidato **Fernando Cesar Cuzinsky**, no dia 15 de fevereiro de 2019, foi julgada para a obtenção do título de Mestre em Engenharia, área de concentração: Engenharia de Manufatura, e aprovada em sua forma final, pelo Programa de Pós-Graduação em Engenharia Mecânica e de Materiais – PPGEM.

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Curitiba, _____de _______________de 20___.

Carimbo e assinatura do Coordenador do Programa

____

À Carine, minha esposa e companheira. Quem me deu suporte e motivação durante todo o trabalho. E, ao nosso filho, Matheus.

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A Deus, gratidão por tudo!

“We are what we repeatedly do, therefore excellence is not an act, but a habit.”

Will Durant, 1926

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RESUMO

Na intenção de definir as prioridades das estratégias de mitigação das mudanças climáticas nas cidades, este trabalho propõe rotas estratégicas para transporte de passageiros para a cidade de Curitiba entre 2017 e 2035. Foi proposta uma estrutura integrada que combina cenários de backcasting, Avaliação do Ciclo de Vida (ACV) e otimização matemática. A rota quantitativa para transporte de passageiros foi modelado como uma Programação Linear Inteira Mista (PLIM). Os impactos ambientais analisados foram o Potencial de Aquecimento Global (GWP20 e GWP100) e o Potencial de Temperatura Global (GTP100). Verificou-se que, para ambas as rotas analisadas, o projeto do metrô não precisa ser implementado e os ônibus urbanos podem suprir a demanda de transporte. Se uma melhoria ocorrer no transporte público, aumentando sua participação no transporte de passageiros, o GWP100 pode ser 28% menor em 2035, em comparação com o cenário base que é definido pelo impacto GWP100. Esta pesquisa produz um modelo para estimar os impactos das cidades e desenvolver rotas quantitativas para reduzir as mudanças climáticas no transporte de passageiros. Além disso, os presentes resultados proveem dois roteiros para o transporte público e individual, para Curitiba.

Palavras chaves: Avaliação do Ciclo de Vida; Programação Linear Inteira Mista; Planejamento urbano; Rotas estratégicas.

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ABSTRACT

In order to set the priorities of strategies for climate change mitigation in cities, this work proposes roadmaps for passenger transportation for the city of Curitiba between 2017 and 2035. We suggested an integrated approach that combines backcasting scenarios, Life Cycle Assessment (LCA) and mathematical optimization to prioritize the activities and develop the roadmaps. The quantitative roadmap for passenger transportation was modeled as a mixed-integer linear programming (MILP). Global Warming Potential and Global Temperature Potential impacts were analyzed. From our approach it was found that for both roadmaps, subway does not need to be implemented, and urban buses can supply the transportation demand. Whether an improvement would occur in public transportation, increasing its participation in passenger transportation, the Global Warming Potential for 100 years can be 28% lower in 2035 compared to the baseline scenario. This baseline is also defined by GWP100 impact. This research yields a model to estimate the cities' impacts and to develop quantitative roadmaps to reduce the climate change for passenger transportation. In addition, the present findings provide two roadmaps for public and individual transportation for Curitiba.

Key Words: Life Cycle Assessment; Mixed-Integer Linear Programming; Urban Planning; Roadmap.

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ABBREVIATIONS

AFOLU	Agriculture, forestry and other land use
ANP	Agência nacional de petróleo, gás e biocombustíveis
BAU	Business as usual
BEV	Battery electric vehicle (plug-in)
BR	Brazil
BRT	Bus rapid transit
DFO	Problems without derivatives
GHG	Greenhouse gases
GLO	Global
GNC	Compressed Natural Gas
G-O	Global optimization
GTP100	Global Temperature Potential for 100 years
GWP100	Global Warming Potential for 100 years
GWP20	Global Warming Potential for 20 years
HEVp	Hybrid Electric Vehicle powered by petrol
IAP	Instituto Ambiental do Paraná
IBGE	Instituto brasileiro de geografia e estatísticas
InT	Individual transportation
IP	Integer programming
IPCC	Intergovernmental Panel of Climate Change
IPPU	Industrial processes and product use
IPPUC	Instituto de pesquisa e planejamento urbano de Curitiba
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCP	Linear complementary problem
LP	Linear programming
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MIP	Mixed-integer programming
NEW	New alternative technology
NLP	Nonlinear programming
PuT	Public transportation
RoW	Rest of the world
SO	Specific objective
URBS	Urbanização de Curitiba S.A.

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1 INTRODUCTION

1.1 CONTEXT AND RESEARCH QUESTION

Cities have great potential to reduce the Greenhouse Gases (GHG) emissions due to their privileged position in fostering the participation of citizens and building partnerships with local stakeholders (KONA et al., 2016, p. 5). A joint action of all cities enable the reduction of global GHG emissions by 47% in 2050; where buildings, transport and waste management are the core pollutants at city level (ERICKSON; TEMPEST, 2014, p. 4). However, the efforts of city governments are still insufficient to achieve the GHG reduction target stated by the Covenant of Mayors (KONA et al., 2016, p. 25). Thus, in order to improve the efficiency of actions against the climate change, the governments must focus on urban planning (KERN; ALBER, 2009, p. 190). These governments should use tools and methods to prioritize the programs and strategies that minimize the environmental impacts and maximize the co-benefits (FLOATER et al., 2016, p. 6). A useful way to assess and prioritize the strategies is to develop visions of desirable futures through the scenarios development.

Planning through scenarios enables the governments to assess the strategies and determine the coherent actions. Scenarios link the technical and participative planning into a systematic and integrated framework (CHAKRABORTY; MCMILLAN, 2015, p. 27). In general, scenarios emphasize on defining the issues, identifying the key drivers, stakeholders, trends, constraints and other relevant issues in a systematic way and ranking these items by importance (AMER; DAIM; JETTER, 2013, p. 26). Based on the perspective, scenarios are classified between extrapolative or normative. Extrapolative scenarios extend present trends, and normative scenarios look backward from the desirable future (ROPER, 2011, p. 31). The question “how can a specific target be reached?” guides the normative approach (BÖRJESON et al., 2006, p. 725). This approach is applicable to develop a sustainable future. In addition, normative scenarios are directed to the goal and policies planning (AMER; DAIM; JETTER, 2013, p. 26).

Backcasting is a normative scenario that planners have applied in many sectors to plan sustainable futures. Phdungsilp (2011, p. 708) suggests this approach in urban planning toward sustainable cities. Backcasting is favored when the problems have long-term complex issues, huge changes and when dominant trends are part of the problem (DREBORG, 1996, p. 816).

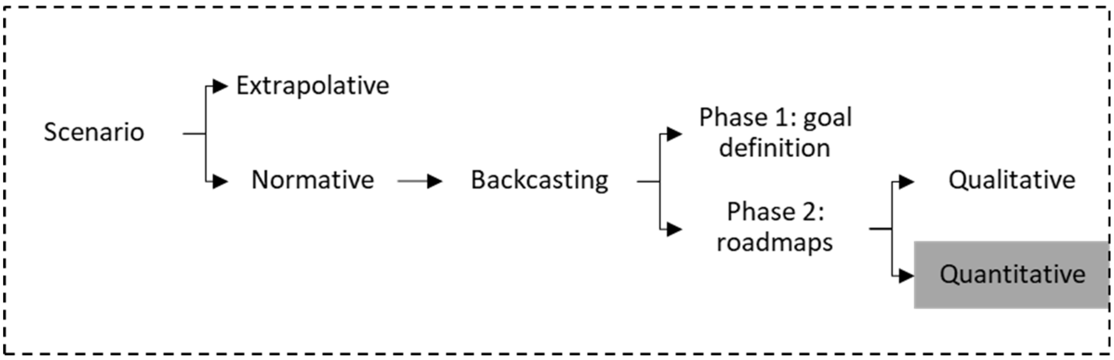
Gomi, K.; Ochi, Y.; Matsuoka, Y. divide the backcasting into two phases. First, the goal is described, while in the second phase the *roadmaps* to achieve the goal from the current situation are identified (GOMI; OCHI; MATSUOKA, 2011, p. 853). These roadmaps are as important the goal itself (QUIST; VERGRAGT, 2006, p. 1034). In addition, from the modelling viewpoint, the first phase uses static models and in the second phase, the roadmaps are developed by dynamic models, where the trends in each year are the constraints (GOMI; OCHI; MATSUOKA, 2011, p. 853).

Roadmaps can be classified as qualitative or quantitative. Workshops, interviews, Delphi method and other participative approaches are qualitative roadmaps. Quantitative roadmaps employ analytic techniques that take into account exogenous variables and parameters that describe the socio-technologic variables, demands and other variables.

Despite the qualitative roadmaps being usually applied (HOLMBERG, 1998; PHDUNGSILP, 2011; QUIST, 2007; ROBINSON, 1990; SHARMINA, 2017; VERGRAGT; QUIST, 2011), affirmations based exclusively on stakeholders opinions are the major problem in developing roadmaps (VERGRAGT; QUIST, 2011, p. 750). When mainly scenarios are developed to reduce the greenhouse gases emissions, since the quantitative data are the core of the problem (GOMI; OCHI; MATSUOKA, 2011, p. 853). Moreover, it is suggested to governments take actions based on quantitative analysis (ASHINA et al., 2012, p. 597). Therefore, this study focuses on quantitative roadmaps.

Figure 1 clarifies the context of this study.

Figure 1 –The context of this research



In order to develop roadmaps the exogenous variables, parameters and trends are defined, and then the quantitative analysis identify the paths. Different policies determine these input data. There are current three models of quantitative roadmaps (ASHINA et al., 2012; GOMI; OCHI; MATSUOKA, 2011; WEN et al., 2017).

Gomi, Ochi and Matsuoka (2011) have developed the first model of quantitative roadmaps of backcasting. The process to identify the roadmaps is formulated as an algorithm for discontinuous nonlinear problem. The process is iterative and the stakeholder opinion at each iteration is analyzed to identify the appropriate roadmap. The model presented by the authors has the intention to facilitate discussions on low-carbon policies. However, an optimum solution is not found. Moreover, the model is not user-friendly (GOMI; OCHI; MATSUOKA, 2011, p. 870).

Wen and colleagues (2017) have applied the same model developed by Gomi, K.; Ochi, Y. and Matsuoka, Y. (2011) to identify the roadmaps in the China's power industry in the years of 2020 and 2030.

A different approach was presented by Ashina and colleagues (ASHINA et al., 2012). They identified optimums roadmaps for Japan through the mathematical optimization. The problem was considered to involve multi-periods and thus mixed-integer programming problem was used for formulation. The objective function was to minimize the total costs of technologies. A great contribution of this research is the consideration of technology penetration based on consumer preference.

As presented above, the mathematic optimization seems to better solve the problem of identify an optimum quantitative roadmap that takes into account different policies to achieve the desirable future. Thus, mathematical optimization is applied here to the city of Curitiba, focusing on the sector Transportation of passengers.

Therefore, based on what were previous stated and on the idea of reducing the greenhouse gases in the transportation sector, in Curitiba, the following research question addresses this research:

Is it possible to identify an optimum quantitative roadmap to the sector of transportation of passengers, in Curitiba, to reduce the greenhouse gas emissions for a long-term planning?

This research intends to answer this question by characterizing an adequate optimization model. In the sequence, an integrated framework is suggested. This framework was applied to the city of Curitiba (Brazil), and then this work delivers a roadmap to the transportation of passengers.

1.2 OBJECTIVES

The general objective of this research is to identify through mathematical optimization the roadmap to reduce the greenhouse gases emission for the sector of transportation of passengers, in Curitiba.

From the perspective of backcasting, mathematical optimization and life cycle assessment, the specific objectives of this study are:

SO 1. Identify the optimization method to solve the problem of quantitative roadmap;

SO 2. Suggest an integrated framework to identify the priority sectors in environmental impacts, and then build the roadmap for the sector of transportation of passengers;

SO 3. Apply the framework suggested in the City of Curitiba (Brazil), from the period of 2017 to 2035, assuming 2016 as a base-year.

1.3 RESEARCH SCOPE AND BOUNDS

This research is limited to suggesting a model to develop roadmaps in the context of backcasting scenarios, and to test this model in the city of Curitiba, specifically in the sector of transportation of passengers. Information such as: life cycle assessment database, population growth, and studies on the potential technologies in the future are the inputs in the study case.

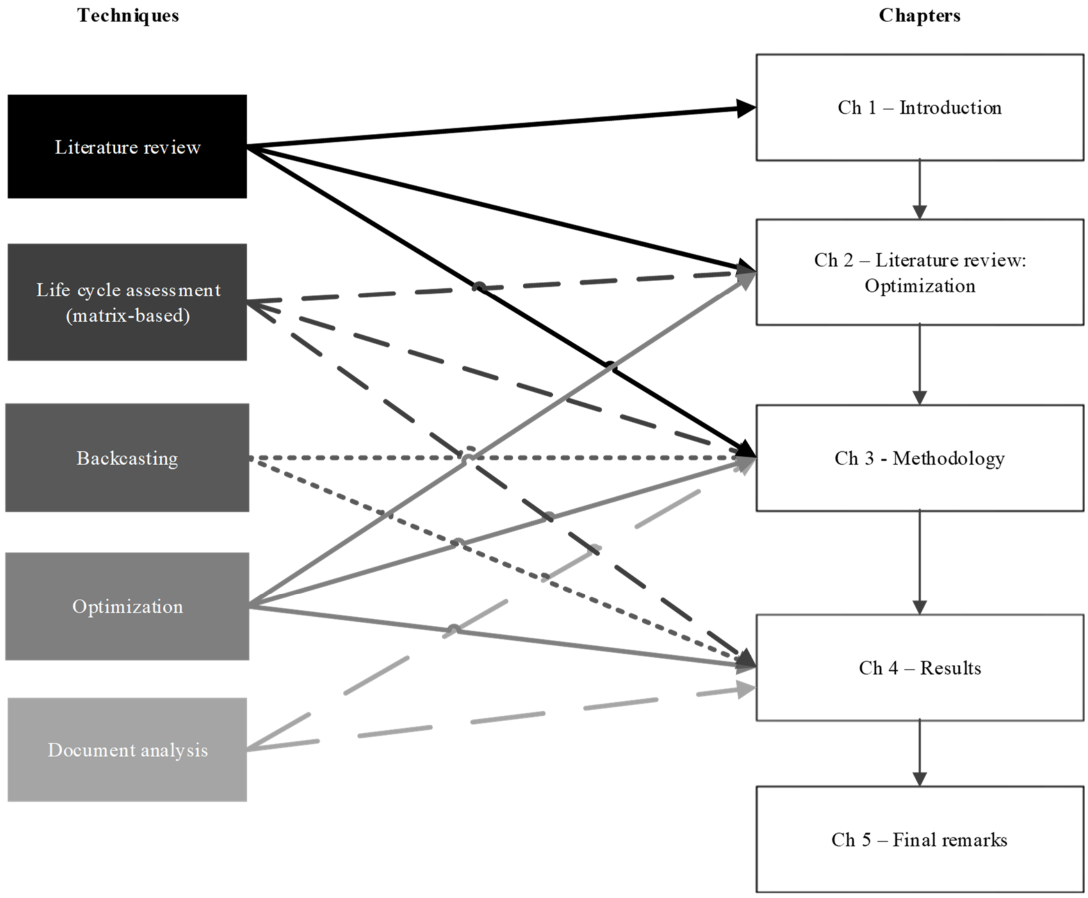
On the other hand, it is NOT the intention of this study to:

- Suggest a new model of backcasting;
- Judge the most appropriate backcasting model;
- Compare the level of GHG emissions estimated in this study with other public studies;
- Judge the currently existing public policies to reduce the GHG emissions.

1.4 STRUCTURE OF THIS DISSERTATION

The interrelationships between research techniques and the corresponding chapters of this dissertation are shown in Figure 2.

Figure 2 – Interrelationships between techniques and chapters of this dissertation.



Notes: Ch: chapter

This dissertation has five chapters. The first chapter has introduced how to prioritize the strategies over the GHG reduction, using the backcasting approach, and stated the problem addressed by this research. Focusing on how to solve this problem, the research question, objectives and research scope were presented.

Chapter 2 presents the literature review of optimization problems. First, it gives reasons why mathematical optimization is a way to model quantitatively develop the roadmap in backcasting approach. Then, the author states the problem from the viewpoint of optimization. Finally, the types of problems in optimization are characterized and an optimization method is suggested. This chapter addresses the specific objective 1 (SO 1).

Chapter 3 presents an integrated systematic framework, which combines the model proposed to develop the roadmap and other tools and methods such as matrix-based life cycle assessment and contribution analysis. This approach achieves the specific objective 2 (SO 2).

Chapter 4 presents the results found (SO3), describes the data, and discusses the outcomes.

Chapter 5 sums up the main findings of the study and shows the final discussion and implications of this research.

2 LITERATURE REVIEW: OPTIMIZATION AS A WAY TO DEVELOP QUANTITATIVE ROADMAP

The general goal of this study is to find the appropriate roadmap to reduce the greenhouse gases emission in cities, under specific conditions. These characteristic can be translated as follows:

- "appropriate roadmap" can be translated as optimum roadmap;
- "Reduce" can be interpreted as minimize;
- "Specific conditions" can be interpreted as constraints.

These characteristics are found in the mathematical optimization. Optimization techniques deal with several complex constraints and with several input data (ARORA, 2004, p. 5). Thus, it is reasonable to search the solution for the problem stated in Section 1.1 in the optimization field.

The objective of this chapter is to identify an optimization method to solve the problem of optimum roadmap. First, from the viewpoint of optimization, the characteristics of the problem are given, and then the types of optimization problems are reviewed. Finally, a solution method is identified.

2.1 STATEMENT OF THE OPTIMIZATION PROBLEM

This study seeks to identify a more appropriate roadmap to achieve the target of greenhouse gases emission in the city level; in other words, the concern is to find the optimum roadmap that minimizes greenhouse gases emission over the years, taking into account trends such as energy demand, population growth and market penetration. These trends are constraints that make it difficult to find a solution by simply applying conventional decision analysis. To deal with this challenge, optimization techniques are chosen.

From the viewpoint of optimization, it is necessary to know the characteristics of the problem in order to choose the most appropriate set of methods to solve it. In engineering problems, the practitioner is looking to minimize some factors (e.g. costs, material and emissions) or to maximize others, such as profit. These two different types of objectives are respectively called minimization and maximization problem. These objectives are called objective functions, which involve variables named design variables. Besides the objective functions, the existence of constraints determine if the problem is constrained or unconstrained. The nature of objective functions and constraints indicates whether the problem is linear or nonlinear; and, the nature of the design variables determines if discrete, continuous or both types of variables are in the problem (RAO, 2009, p. 6–9).

Based on the factors mentioned above, this problem can be characterized as a problem of minimization.

The objective function that governs the environmental impact is modeled through the matrix-based approach developed by Heijungs and Suh (2002). The authors considered the demand vector as the only variable, which represents the amount of a product in the period. Therefore, the objective function is a linear Equation.

The constraints included in the problem are considered linear, since the problem does not take into account neither time nor spatial differentiation. In addition, the constraints are exclusively demands of energy, products and environmental targets.

In backcasting, the concern is to set the desirable scenario and determine the roadmaps. These roadmaps describe the socio-technology transitions over the years. Therefore, this problem can be characterized as a multi-period problem.

The variables presented in this problem are both continuous and discrete. The former exists in all environmental impact equations and constraints, which are dependent on production amount. The latter exists to describe different conditions over different periods, i.e., due to the nature of multi-period (CUZINSKY, 2018).

As aforementioned, the problem has the characteristics presented in Table 1.

Table 1 – Characterization of the optimization problem

Condition	**Characteristic**
Reduce the GHG emissions over the years	Problem of minimization
The environmental impact has a linear dependence on amount produced	Linear objective function
Constrains are modeled as demands and environmental targets.	Linear constraints
Different periods under analysis	Multi-period problem
Different conditions under analysis	Discrete variables
The production amount is a continuous variable	Continuous variable

After characterization, it is possible to review the classification of problems in optimization literature.

2.2 OPTIMIZATION PROBLEMS

Optimization techniques currently can be applied to a broad range of problems; nevertheless, no single method can solve all types of problems efficiently, hence scientists have developed a range of optimization methods. The classical methods are useful in finding the optimum solution of continuous and differentiable functions, but problems are usually more complex and need methods that are more advanced (RAO, 2009, p. 63). For complex problems, metaheuristic methods exist, such as: genetic algorithm, simulated annealing, colony optimization, neural network-based optimization and fuzzy optimization.

The problems can be classified based on the nature of their factors (RAO, 2009), see Table 2. The problem can be constrained or unconstrained. The designer has to analyze if the problem is dynamic on time. If the time is continuous, the physical structure determine if the problem is an optimal control or not. In addition, the designer must take into account the linearity of the Equations involved, i.e., constraints and objective function. Moreover, if the problem treats uncertainties in values, the problem has a probabilistic nature, otherwise is a deterministic. In some problems the variables cannot be separated, which characterize the separability of the functions. The designer also need to analyze if the problem only deals with one objective or more.

Table 2 – Nature of factors of the optimization problems

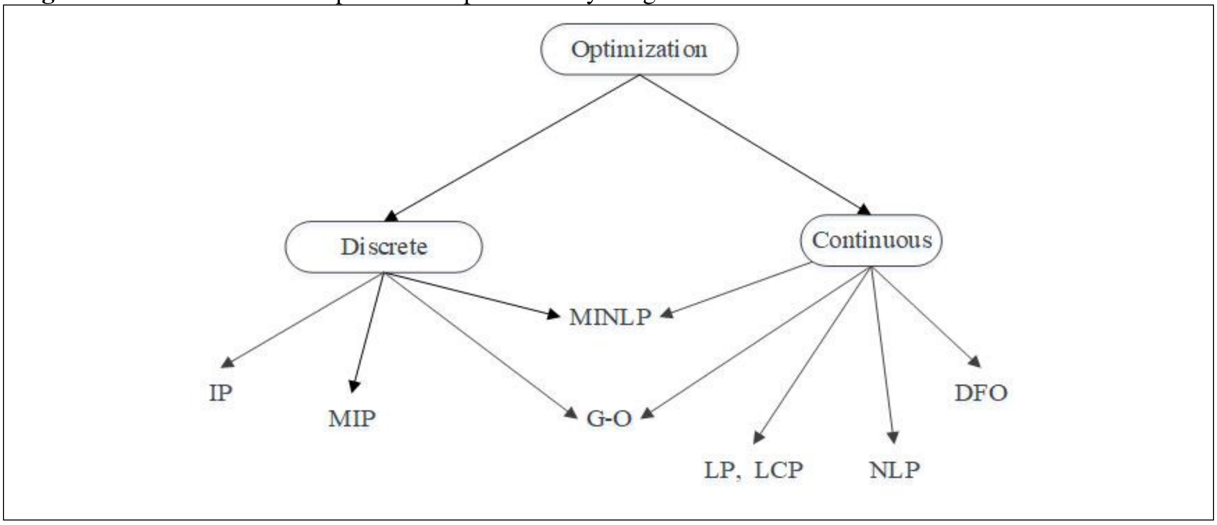
Factors	Options
Existence of constraints	Constrained or unconstrained
Nature of design variables	Static or dynamic optimization problem
Nature of physical structure of the problem	Optimal or non-optimal control
Nature of equations involved	Linear, nonlinear, quadratic or geometric programming problem
Nature of variables	Discrete or real
Deterministic nature	Deterministic or stochastic
Separability of the functions	Separable or non-separable
Number of objectives	Single or multi-objective problem

Source: Adapted from (RAO, 2009)

Most of problems have simultaneously many characteristic presented in Table 2. For example, a problem can use uncertainty to identify the optimum solution for two objectives (multi-objective). The variables are discrete and real variables, and the functions are nonlinear.

Biegler and Grossmann (2004) proposed a classification (see Figure 3) for the usual problems in chemistry processes. The authors inferred that the problems involve either deterministic or uncertainty optimization. The former falls either discrete or continuous variables or dynamic modelling. Then the problems with continuous variables are linear programming (LP), nonlinear programming (NLP) and problems without derivatives (DFO). An important subclass of LP is the linear complementary problem (LCP). For those problems with discrete variables, the integer problems (IP) arise, and when both discrete and continuous variables exist, the problem is a Mixed-Integer Programming (MIP), which can be linear or nonlinear. The authors also comment the existence of global optimization (G-O).

Figure 3 – Classification of optimization presented by Biegler and Grossmann

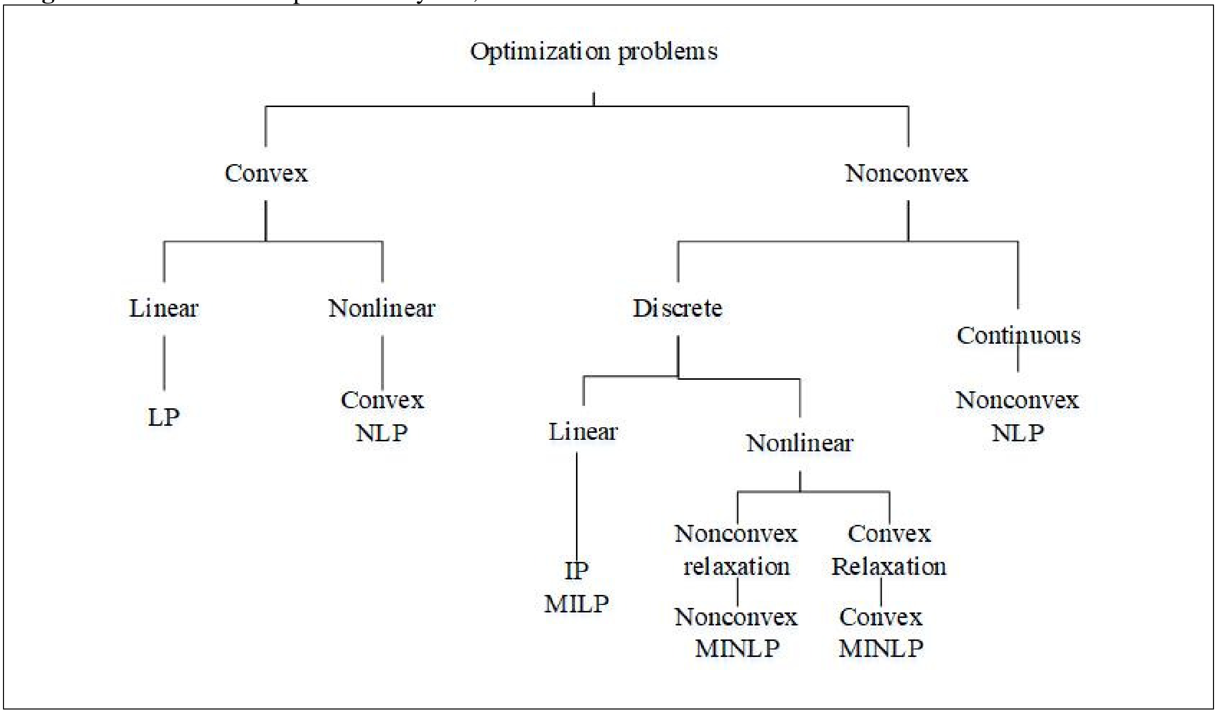


Source: Adapted from (BIEGLER; GROSSMANN, 2004, p. 1170)

The authors also mentioned that optimization problems can be represented by steady-state or dynamic models. Steady state model considers the problem as static, which means that there is no time differentiation. On the other hand, in dynamic model, the time is considered. If the time is discrete, the problem falls into multi-period programing (MIP) optimization problem, while for the case of continuous time the problem is an optimal control problem (BIEGLER; GROSSMANN, 2004).

Another factor of the problem that must be part of the classification is whether the problem is convex or non-convex (LIN; TSAI; YU, 2012). An optimization problem is convex if the set and the objective function are convex otherwise the problem is non-convex. The classification suggested by Lin and colleagues is presented in Figure 4.

Figure 4 – Classification presented by Lin, Tsai and Yu

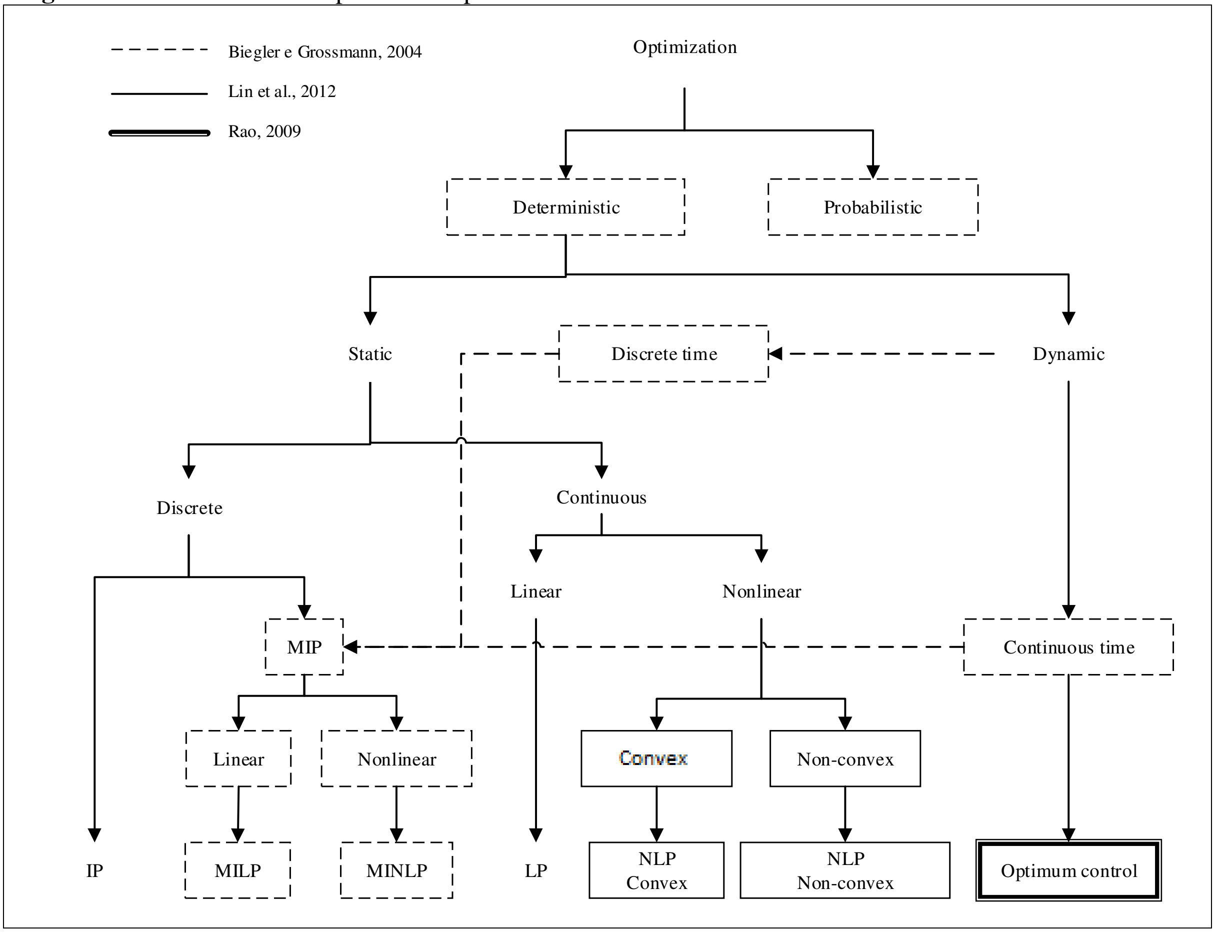


Source: (LIN; TSAI; YU, 2012, p. 3)

When the problem has both discrete and continuous variables, there is the mixed-integer programming problems. In this class of problems, the concept of relaxation is important. Relaxation is a process of loose one or more constraints of the problem. In this process, the feasible region grows in size. When the constraint is relaxed all variables are allowed to be real continuous variables (SIOSHANSI; CONEJO, 2017, p. 153). Whether the set and the functions in the relaxed problem for nonlinear problems are still nonconvex, the problem has a nonconvex relaxation. This characteristic is also addressed by Lin and colleagues (LIN; TSAI; YU, 2012, p. 3) to differ nonconvex MINLP and convex MINLP problems.

Based on the factors above, Figure 5 presents the optimization problem in a systematic classification. This classification is a compilation of the problems presented by the last works described above. In Figure 5, classification without lines are common to the three works analyzed. Problems can be either deterministic or probabilistic. The latter considers that problems have uncertainty about the parameters that are described by stochastic (random or probabilistic). The basic idea in stochastic programming is to convert the stochastic problem into an equivalent deterministic problem (RAO, 2009, p. 632). The input and the outcome of this approach are stochastic variables. Despite the existence of significant uncertainty in real world problems it is often adequate to assume that the system is deterministic (SIOSHANSI; CONEJO, 2017, p. 13). As this research will not deal with statistic, only deterministic problems are addressed.

Figure 5 – Classification of optimization problems



Notes: IP: Integer programming; MIP: Mixed-integer programming; MILP: Mixed-integer linear programming; MINLP: Mixed-integer nonlinear programming; LP: Linear programming; NLP: Nonlinear programming

The nature of the problem will define whether the static or the dynamic optimization must be applied. Whether the parameters of the problem do not change over time or over the trajectory, the problem is a static optimization, otherwise the problem is dynamic (RAO, 2009, p. 16). Typical applications of dynamic optimization include production planning, controlling and scheduling (BIEGLER; GROSSMANN, 2004, p. 1182). Dynamic optimization deals with either discrete or continuous time. For discrete time, the problem can be treat as mixed integer programming (MIP) problem, and for continuous time with optimum control. MIP also can solve dynamic optimization.

In static problems, design variables can assume discrete and continuous variables. Discrete variables can be pure discrete, integer, linked integer or binary variables (ARORA, 2004, p. 513). When the problem only deals with integer variables then it has Integer Programming (IP); otherwise, it is a Mixed-Integer Programming (MIP), which can be Mixed-Integer Linear Programming (MILP) or Mixed-Integer Nonlinear Programming (MINLP) depending on the nature of the Equations. MIP problems are non-convex. MINLP problems can be divided into their nature of relaxation that are either non-convex relaxation or convex relaxation (LIN; TSAI; YU, 2012, p. 3). Convex MINLP involves minimizing a convex objective function over a feasible region that is convex when the discrete variables are relaxed as continuous variables. In nonconvex MINLP the objective function and/or the continuous relaxation of the feasible region are not convex (TRESPALACIOS; GROSSMANN, 2014, p. 991).

When the variables are continuous and the objective functions and constrains are linear then Linear Programming (LP) arises. This kind is also a convex problem. This problem first appeared in practical use in 1930 to optimal allocation of resources. Nowadays, the algorithms available can deal with a large quantity of constraints in LP. Nevertheless, when the Equations are nonlinear then Nonlinear Programming (NLP) arises and can be convex (Convex NLP) or non-convex (Non-convex NLP). Convex NLP without constraints and differentiable can be efficiently solved by classical search methods such as Newton's methods and conjugated direction methods (RAO, 2009, p. 80). When the problem falls into the Non-convex NLP, which are those without derivatives, methods make use of heuristic approaches and artificial neural networks (BAÑOS et al., 2011, p. 2). The heuristic methods are usually solved by transforming the original nonconvex problem into a convex problem and then solved it to obtain the global optimum (LIN; TSAI; YU, 2012, p. 4). Genetic algorithm, simulated annealing, tabu search, ant colony optimization and particle swarm optimization are some of the heuristic methods.

Another characteristic of the problem is the number of objectives. The optimization project can have single or multiple objectives. Multiple objective optimization is useful to analyze the behavior between tradeoffs, e.g. costs and environmental impact. The best known technique to solve multi-objective optimization problems is the ε-constraint method (EHRGOTT, 2015, p. 98). In this approach, while optimizing an objective the other objectives are set as constraints. The solution represented by points can be represented as a Pareto curve, these points are the Pareto optimal solution (HAIMES; LASDON; WISMER, 1971). This approach enable the decision-makers to have a holistic view of the tradeoffs involved.

Engineering problems usually fall into the classification presented in Figure 5. The Table 3 shows the characteristics of the optimization problems.

Table 3 – Characteristics of optimization problems

	Design variable		Equations		Discrete time	Cont time	Derivative
	Cont	Discrete	Linear	Nonlinear			
IP		x	x				
MILP	x	x	x		x		X
MINLP	x	x	x	x	x		X
LP	x		x				X
Convex NLP	x			x			X
Non-convex NLP	x			x			
Optimal Control	x	x	x	x		x	x

Now it is possible to compare the characteristics of the problem addressed in this research (see Chapter 2.1) to the classification above (Table 3). The objective function (Equation 1) and the constraints are both linear. As the problem deals with multi-period, the variables are discrete and continuous. In addition, as linear Equation it has derivative. Therefore, it is possible to affirm that the research problem lies on the Mixed-Integer Linear Programming (MILP) problem.

In the field of backcasting, Ashina and colleagues (2012) have developed the only study that has applied MILP; however, they did not considered different conditions for the same period. On the other hand, the application of MILP in multi-period problems when the conditions are considered (binary variables) are present in the field of energy planning (AHMADI et al., 2015; HENDRICKSON; NIKOLIC; RAKAS, 2016; MIRZAESMAEELI et al., 2010; ZHANG et al., 2012). Into these studies, binary, discrete and continuous variables are applied to deal with the distinct conditions for each year. Nevertheless, these studies did not specify the method used to solve the problem.

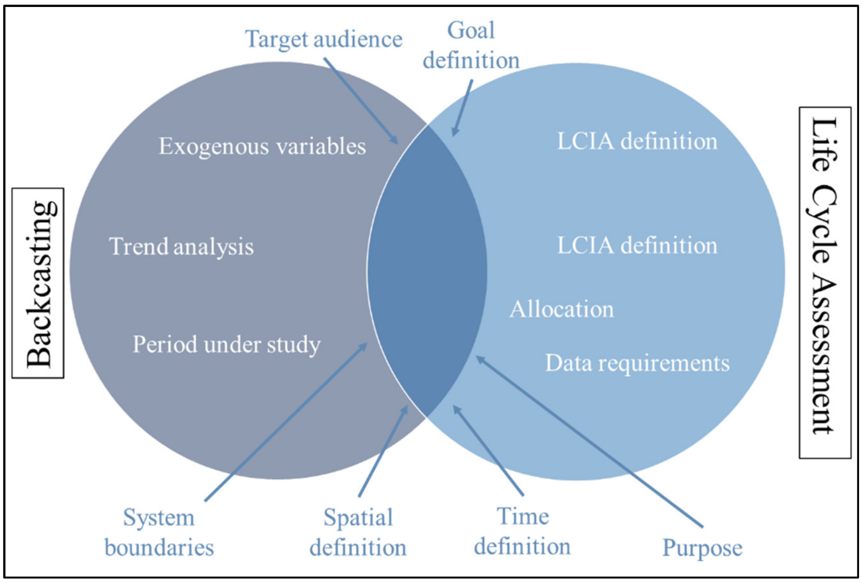
3 METHODOLOGY: AN INTEGRATED APPROACH

To identify the quantitative roadmaps by mathematical optimization, it was firstly necessary to specify the targets, trends and exogenous conditions of the problem. In order to do so, this chapter describes a systematic framework that was used to set the desirable future and the process to identify the optimum roadmap under the circumstances adopted.

The novelty of this research is to identify the quantitative roadmap by the application of mixed-integer linear programming (MILP) in a multi-period problem for the transportation sector of passengers in Curitiba.

The first step of the backcasting approach and Life Cycle Assessment present some similarities. At this step, the goal definition of the study, its audience, spatial definition and other factors are similar in both tools. However, each approach has other specific issues to be defined, as illustrated in Figure 6.

Figure 6 – Common characteristics between backcasting and life cycle assessment in their first step

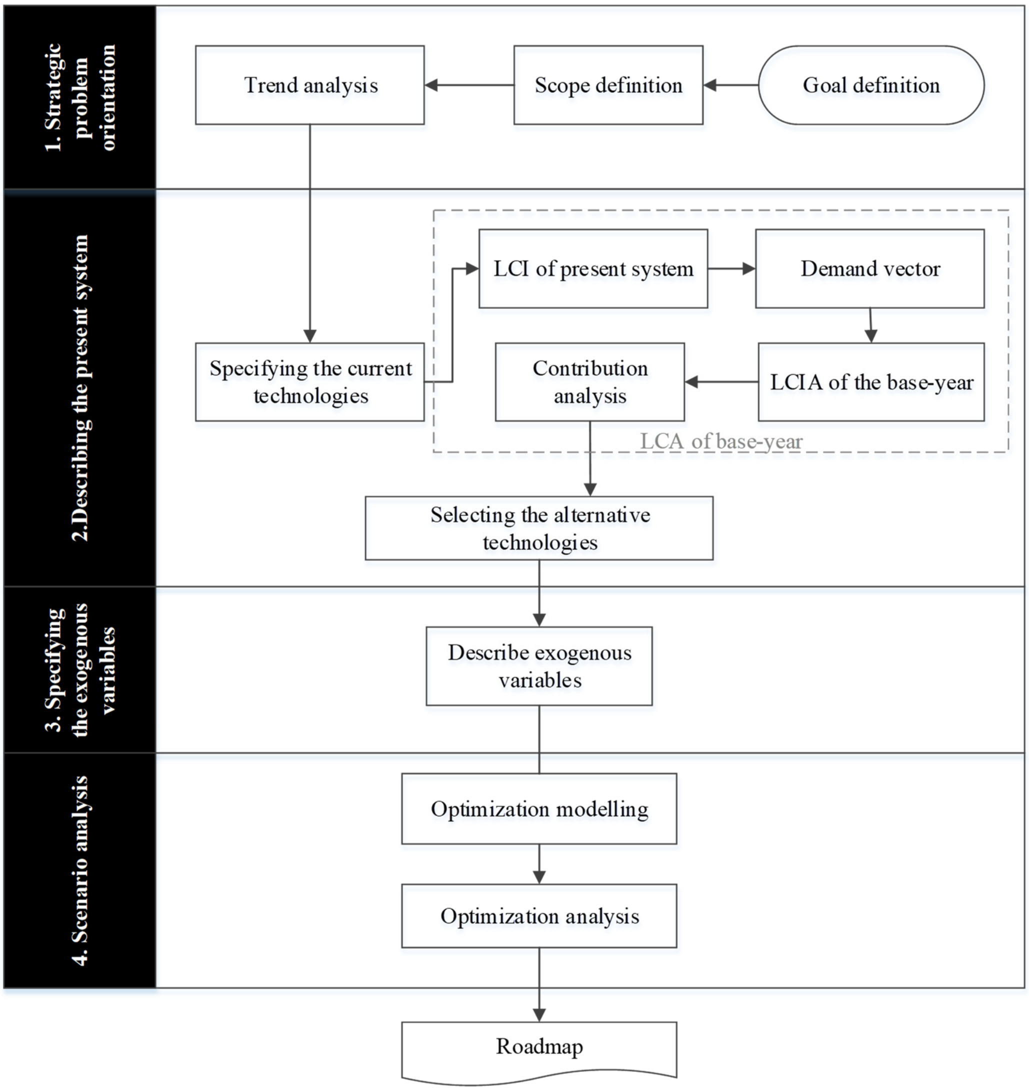


The four-step framework used in this research to identify the quantitative roadmap was based on backcasting developed by Robinson (1990). This backcasting method has been widely applied.

To facilitate the communication with the Life Cycle Assessment practitioner, some modifications in the Robinson's methodology were done. In addition, the steps 1 and 2 of the original backcasting method were joined in the first step, named "Strategic problem orientation", which also embraced the goal and scope of the Life Cycle Assessment , defined by the standards NBR ISO 14040 and 14044 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2014). Although the backcasting approach suggests as the last step the policy recommendations, it was omitted here, due to the fact that a board of specialists would be necessary. Figure 7 shows the framework applied in this research.

The systematic framework starts with the goal definition and finishes with the discussion of the quantitative roadmap obtained. In addition to the MILP optimization problem, other tools and methods were part of the framework, such as document analysis in the process of gathering data, matrix-based Life Cycle Assessment (LCA) to estimate the environmental impacts and contribution analysis to determine the priorities.

Figure 7 – An integrated framework applied in this research to identify the roadmaps to reduce the GHG emission



3.1 STRATEGIC PROBLEM ORIENTATION

The aim of this step was to explore the problem from a systematic viewpoint, looking for possible problem definitions, environmental issues, opportunities and possible solutions (DUIN, 2016, p. 136). In this step it was listed the information required both from Life Cycle Assessment and Backcasting approaches.

3.1.1 Goal Definition

The aim of this research, by means of LCA and backcasting was to identify the roadmaps of passenger transportation in Curitiba, to reduce the GHG, from 2017 to 2035, assuming 2016 as a base-year. To accomplish this goal, the following objectives were set:

- Estimate the Climate Change impacts of Curitiba in the base-year;
- Estimate the unitary impact of Global Warming Potential (100years) for passengers' vehicles;
- Model the problem of passenger transportation as a Mixed-Integer Linear Programming.

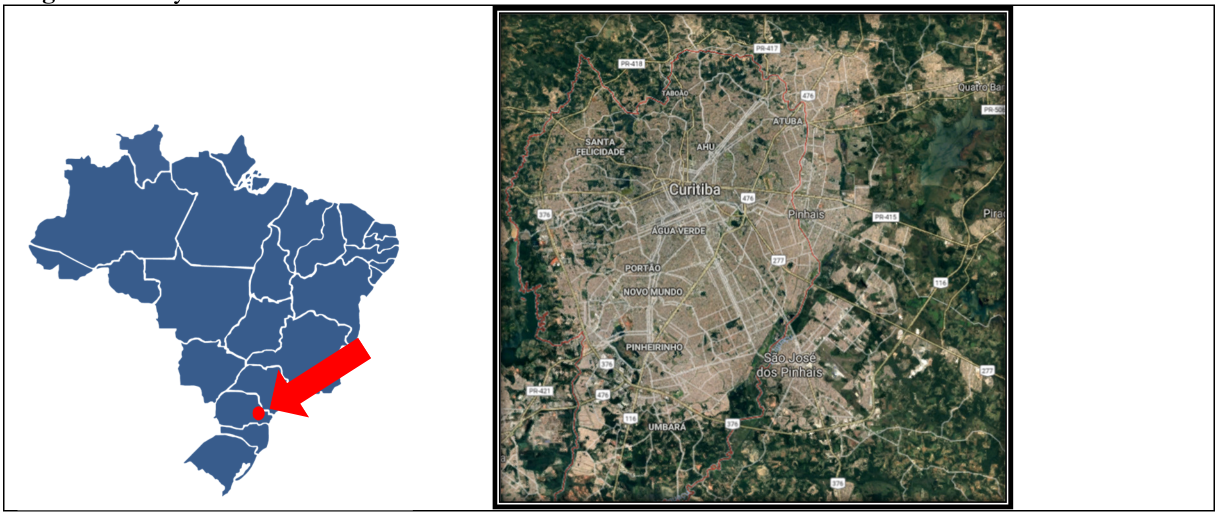
3.1.2 Scope Definition

3.1.2.1 Product system: Curitiba

In this research, it was applied the concept of product system from a different viewpoint. Instead of focus on the products, it was defined the city of Curitiba (Brazil) as the system product, and its borders as the system boundaries.

The city of Curitiba was the product system. Curitiba is the capital city of Paraná State, stablished in March, 29th of 1963, located in the west of the state (Figure 8). The total area is 435 km², and is 934 m above the sea. The estimated population of the city in 2018 is 1.9 million. Services and commerce activities are the key to the Curitiba's economy, followed by industry.

Figure 8 – City of Curitiba

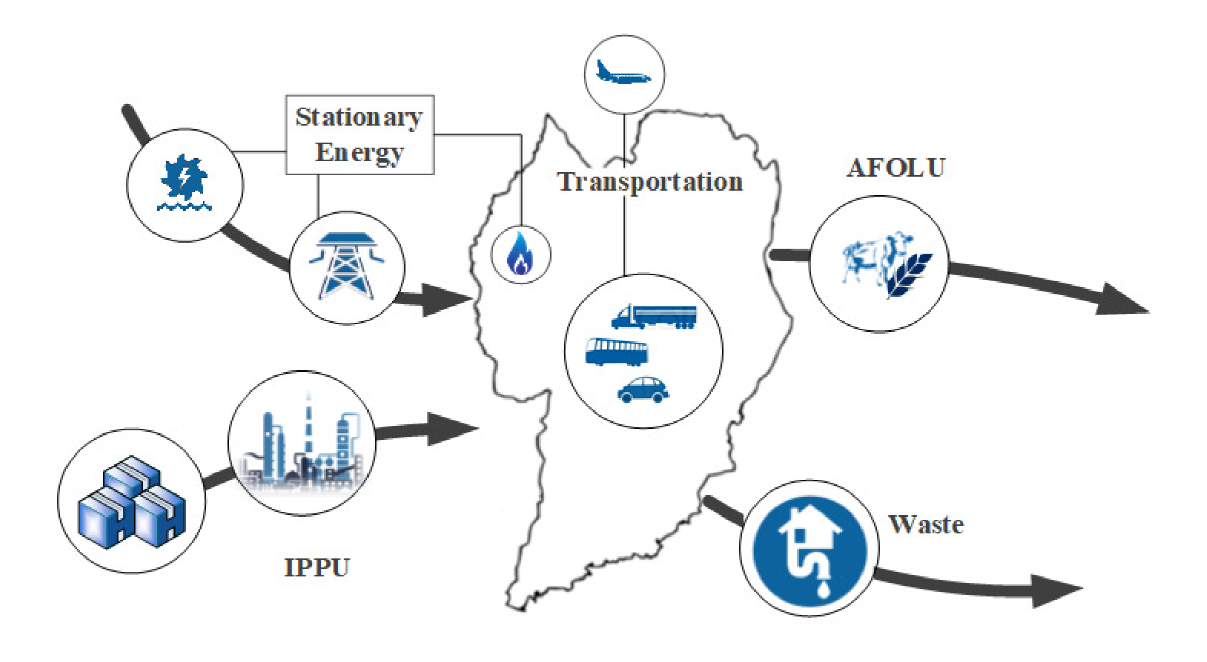


Despite of been known as the “Brazil’s green capital” (THE GUARDIAN, 2018), the city faces many environmental issues as many other cities. Curitiba is also recognized by its transportation system, having the world’s first bus rapid transit (BRT) network. This system moves people with efficiency. However, mobility remains an issue in the city. Due to the population growth and the increase number of vehicles, new solutions are welcome.

3.1.2.2 System boundaries and emission sources

As previous mentioned, the political borders defined the boundaries where the urban activities happen. For each product or service that took place within the city, distinct life-cycle phases were considered in accordance with data available. The scope of the greenhouse gases emission adopted is described in the Figure 9.

Figure 9 – Scope of greenhouse emissions adopted in this research



Notes: The emissions from sectors before the city were based on consumption. Within the city boundaries were based on operation and use. Sectors after the city's borders, had their emissions counted based on their production.

The greenhouse gas emissions for Stationary Energy mostly occurred outside of the city's borders, with exception to the emission from heat generated from natural gas and heavy fuel oil that were assumed to occur in the city. The sector Industrial Process and Product Use (IPPU) supplied raw materials for the industries in Curitiba. The emissions for transport for these raw materials were not considered. The food consumed in the city was also unconsidered in this research due to the lack of data for public domain. Despite been important, these emissions would not be high as the individual transportation and energy emissions.

Emissions from Transportation mostly were in the city. However, the emission from airplane were based on the fuel commercialized in the city in the base year. The sectors of Agriculture, Forestry and Land Use (AFOLU) and Waste had their emissions based on production, such as wastewater generated in the city.

3.1.2.3 Life cycle impact assessment methods and categories

The potential impacts of Climate Change were analyzed through the Intergovernmental Panel of Climate Change (IPCC) methodology (MYHRE et al., 2013). To the base-year (2016), the impact categories of Global Warming Potential for 20 years (GWP20), Global Warming Potential for 100 years (GWP100) and Global Temperature Potential for 100 years (GTP100) were analyzed, as recommended (FRISCHKNECHT; JOLLIET, 2016).

For optimization purpose, only GWP100 was analyzed, because it has been the default metric used as a characterization factor in life cycle impact assessment methods (FRISCHKNECHT; JOLLIET, 2016, p. 59).

3.1.2.4 Data requirements and quality

Demands of each activity were important to define the demand vector. Demand vector is represented by values that defined the quantity used or consumed of each activities in the city. Table 4 lists the desirable data for demand.

Table 4 – Data requirement for demands

Description	Ideal data
Activity	Equal to the activity in the city
Technology	The same of operating in the city
Year	2016 for base-year and dynamic for optimization purpose
Geography	City of Curitiba

3.1.2.5 Allocation

The raw data found both for demand vector and environmental inventories did not suffered the any allocation procedure. Since, they did not present problems of double counting. However, the database used in this research (*ecoinvent v.4 cut-off*, described better in sequence) takes into account allocation.

This database considers allocation cut-off by classification, cut-off in short, which is a system model methodology applied in the database. The production of materials is allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes (ECOINVENT, 2018).

3.1.2.6 Temporal

The roadmap was determined for 2017-2035 period, but the base-year was 2016. The base-year was the most recent one with data available. The target year was selected based on Curitiba 2035 (CURITIBA: SENAI/PR, 2017) and other studies that describe the possible development of technologies (COPPE; FETRANSPOR, 2012; DE SOUZA et al., 2018; EPE, 2016). In addition, the target year should be far enough in the future to achieve the necessary changes but close enough that the stakeholders can easily envision it (GOMI; OCHI;MATSUOKA, 2011, p. 854).

3.1.3 Trend Analysis

Population growth for Curitiba, the trends of technologies for individual and public transportation, number of vehicles per person, and other trends were adopted and implemented to develop the roadmaps. These trends are described in Step 3.

3.2 DESCRIBING THE PRESENT SYSTEM

3.2.1 Current Technologies

The roadmap must be anchored to a description of present system being studied; tied to the goals and constraints (ROBINSON, 1990, p. 828).

In order to facilitate the process of gathering data for all activities that were present in the base-year, it was applied the methodology suggested by the Global Protocol for Community-Scale Greenhouse Gases Inventory (FONG et al., 2015). This protocol have been used by many cities’ governments around the world, such as Auckland (New Zealand), Belo Horizonte (Brazil), Boston (United States), Curitiba (Brazil) and others (CDP, 2016). In accordance with this guideline, the activities that took place within the city were classified as sectors, subsectors and subcategories. Table 5 lists the classification of sectors and subsectors analyzed. The subcategories are the activities, e.g., urban bus or wastewater treatment.

Table 5 – Classification of sectors, subsectors

Sectors	Subsectors
Stationary energy	Residential buildings Commercial and institutional buildings and facilities Manufacturing industries and construction Energy industries Agriculture, forestry, and fishing activities Non-specified sources Fugitive emissions from mining, processing, storage, and transportation of coal Fugitive emissions from oil and natural gas systems
Transportation	On-road Railways Waterborne navigation Aviation Off-road
Waste	Solid Waste disposal Biological treatment of waste Incineration and open burning Wastewater treatment and discharge
Industrial process and product use (IPPU)	Industrial processes Product use
Agriculture, forestry and other land use (AFOLU)	Livestock Land Aggregate sources and non-CO2 emission sources on land
Other scope 3	

Source: (FONG et al., 2015, p. 10)

Using the classification presented in Table 5, the technologies operating in the base year found are described in sequence by sector.

3.2.1.1 Stationary energy

Only few energy sources were consumed within the city boundaries. Moreover, there was no electricity power plants in the city in the base-year. Therefore, it was only found data for some sources of energy for Curitiba. These sources of energy fed distinct subsectors, as listed in Table 6.

Table 6 – Stationary energy considered in the analysis

Sub-sector	Subcategory	Considered[1]
Residential buildings	Electricity	Yes
	Natural gas	Yes
Commercial and institutional buildings and facilities	Electricity	Yes
	Natural gas	Yes
Public services	Electricity	Yes
Manufacturing industries and construction	Electricity	Yes
	Natural gas	Yes
	Heavy fuel oil	Yes
	Kerosene	Yes
Energy industries	Electricity	Yes
Agriculture, forestry, and fishing activities	Electricity	Yes
Non-specified sources	Liquefied Petroleum Gas	Yes

Note: [1] If the subcategory was considered in the environmental impact calculation

The subcategory electricity represents the Brazilian national grid that involves all types of electricity sources, such as thermal, hydraulic, wind, solar and others.

3.2.1.2 Transportation

The data collected embraced only on-road and aviation sectors. A train for freight transportation system crossing the city was operational in the base-year, but the data for this subsector was unavailable. The activities considered are described in the Table 7. The subcategories considered were defined based on available data.

Table 7 – Subsectors and activities in the base-year in the transportation sector

Sub-sector	Subcategory	Unit	Considered[1]
On Road	Motorcycle	Unit	Yes
	Passenger car, petrol	Unit	Yes
	Passenger car, ethanol	Unit	Yes
	Light commercial vehicles	Unit	Yes
	Urban bus, unspecified	Unit	Yes
	Lorry semi-light (PBT > 3.5t <6t)	Unit	Yes
	Lorry, light (PBT ≥ 6t. < 10 t)	Unit	Yes
	Lorry, medium (PBT ≥ 10 t. < 15 t)	Unit	Yes
	Lorry, semi-heavy (PBT ≥ 15 t.; PBTC < 40 t.)	Unit	Yes
	Lorry, heavy (PBT ≥ 15 t.; PBTC ≥ 40 t.)	Unit	Yes
	Ethanol hydrated (consumption)	L	Yes
	Petrol with 25% of anhydrous ethanol	L	Yes
	Diesel with 7% of biodiesel	L	Yes

Aviation	Aviation, kerosene	L	Yes
	Aviation, petrol	L	Yes

Note: [1] If the subcategory was considered in the environmental impact calculation

3.2.1.3 Waste

Wastewater and solid waste disposal were considered. The respective activities are listed in Table 8. The data came from the water supply company, SANEPAR (2017) and from a third-party project report (INTERNATIONAL FINANCE CORPORATION, 2015). Although the author has required additional information for the environmental department of the city government concerning the solid waste management, he had never had any answer.

Table 8 – Subsectors and activities considered for the waste sector

Sub-sector	**Sub-category**	**Considered[1]**
Solid waste disposal	Residential and commercial	Yes
	Waste from municipal cleaning service	Yes
	Hazardous	Yes
	Construction waste	Yes
	Wastes from river (cleaning service)	No
	Indirect wastes	No
Wastewater treatment and discharge	Residential and commercial	Yes

Note: [1] If the subcategory was considered in the environmental impact calculation

Wastes from river and indirect wastes were unconsidered due to their unknown composition.

3.2.1.4 Industrial process and product use (IPPU)

Product use for individual purpose was not considered, neither the food supplied. The impacts for industrial process were based on the raw materials consumed by the companies. However, the emission to transport these materials were also not considered. Table 9 lists the products consumed by industrial processes. Almost all information were from the Paraná Institute of Environment (IAP, 2018), just tap water (SANEPAR, 2017) and asphalt (ANP, 2016).

Table 9 – Products consumed in the Industrial Process and Product Use (IPPU) sector

Material	Cons	Material	Cons	Material	Cons[1]
2-ethyl anthraquinone	No	Hydrogen peroxide	Yes	Nitrogen	Yes
Acetic acid	Yes	Insurable tires	No	Sand	Yes
Acrylic	Yes	Leather, fabrics, etc.	No	Sodium acid pyrophosphate	No
Aluminum	Yes	MDF	Yes	Sodium cyanide	Yes
Ammonia anhydrous	Yes	Metal (unspecified)	Yes	Sodium hydroxide	Yes
Aromatic solvent	Yes	Metal parts	Yes	Stabilizers	No
Asphalt	Yes	Muriatic acid	No	Steel (bars)	Yes
Cast iron	Yes	Nitric acid	Yes	Steel plates	Yes
Caustic soda	Yes	Ortho-cyclohexyl acetate	No	Sulfur	Yes
Cement	Yes	Paper	Yes	Sulfuric acid	Yes
Cupper	Yes	Paraffin	Yes	Tap water	Yes
Degreaser	Yes	Pine knot	No	Welding components	No
Demineralized water	No	Pine wood	Yes	Wires, steel	Yes
Electrostatic paint waste	No	Plastic parts	Yes	Wood	Yes
Fabrics, acrylic	No	Plastic, various	Yes	Zinc anode	No
Gravel	Yes	Pork carcass	Yes	Zinc oxide	Yes
Gum of pine resin	No	Rubber profile	Yes		

Note: [1] If the subcategory was considered in the environmental impact calculation

Two reasons justified the non-consideration of the information listed in Table 9. First, the amount for each product was actually low and applying the cut-off criteria by mass, these materials were not considered. Second, no *ecoinvent* dataset was available for products not considered (NO, in Table 9).

3.2.1.5 Agriculture, forestry and other land use (AFOLU)

Curitiba as an industrial city, did not have many agriculture and forestry activities in the base-year, thus few activities were documented, as shown in Table 10. All information came from IBGE (BRASIL, 2016).

Table 10 – Agriculture, Forestry and Land Use (AFOLU) activities present in the base-year

Sub-sector	Subcategory	Cons[1]
Agriculture	Maize (grain)	Yes
	Beans (grain)	No
Livestock	Milk	Yes

Table 10 – Agriculture, Forestry and Land Use (AFOLU) activities present in the base-year (continued)

Sub-sector	Subcategory	Cons[1]
	Horse	No
	Wool	No
	Honey	No
	Cattle for slaughtering	Yes
	Swine	Yes
	Sheep for slaughtering	Yes

Note: [1] If the subcategory was considered in the environmental impact calculation

Beans, wool, horse and milk are activities/products without datasets in the *ecoinvent* database, therefore they were unconsidered. They could be adapted as other culture, e.g. soybeans; however, the amount produced was low to justify the modification.

3.2.2 Life Cycle Inventory (LCI) Of The Base-Year

In order to analyze the potential environmental impact of the city, in the base-year, through the Life Cycle Assessment, it was necessary to know the environmental inventory of an activity during its life cycle. In this research, the life cycle database *ecoinvent v.3.4 cut-off* (WERNET et al., 2016) was used when available.

The activities (subcategories) operating in the city in the base year were connected to the datasets available in the database, as shown in Table 11. These datasets were preferably in the sequence Brazil (BR), Rest of the World (RoW), and finally Global (GLO). This approach was also used by Chiumento (2016).

For the subsector “On-road”, in Transportation sector, some adaptations were necessary, as follows.

Table 11 – Links between activities and datasets

Subsector	Activity	Dataset	Geo	Unit	Connection
Sector: Stationary Energy					
Residential buildings	Electricity	market for electricity, low voltage	BR	kWh	Direct
	Natural gas	heat production, natural gas, at boiler atmospheric non-modulating <100kw	RoW	MJ	Direct
Commercial and institutional buildings and facilities	Electricity	market for electricity, low voltage	BR	kWh	Direct
	Natural gas	heat production, natural gas, at boiler atmospheric non-modulating <100kw	RoW	MJ	Direct
Public services	Electricity	market for electricity, low voltage	BR	kWh	Direct
Manufacturing industries and construction	Electricity	electricity, high voltage, production mix	BR	kWh	Direct
	Natural gas	heat production, natural gas, at boiler atmospheric non-modulating <100kw	RoW	MJ	Direct
	Heavy fuel oil	heat and power co-generation, oil	BR	MJ	Direct
	Kerosene	market for kerosene	RoW	kg	Direct
Energy industries	Electricity	electricity, high voltage, production mix	BR	kWh	Direct
Agriculture, forestry, and fishing activities	Electricity	market for electricity, low voltage	BR	kWh	Direct
Non-specified sources	Liquefied petroleum gas	market for liquefied petroleum gas	RoW	Kg	Direct
sector: transportation					
On Road	Motorcycle	transport, motorcycle, use phase	BR	person*km	Adapted
	Passenger car, petrol	transport, passenger car, petrol – use phase	BR	person*km	Adapted
	Passenger car, ethanol	transport, passenger car, ethanol – use phase	BR	person*km	Adapted
	Light commercial vehicles	transport, freight, light commercial vehicle -use phase	BR	metric ton*km	Adapted
	Urban bus	transport, urban bus, use phase	BR	person*km	Adapted
	Lorry semi-light (PBT > 3.5t <6t) Lorry semi-light (PBT > 3.5t <6t) Lorry, light (PBT ≥ 6t. < 10 t) Lorry, medium (PBT ≥ 10 t. < 15 t)	market for transport, lorry, unspecified, use phase, BR	BR	metric ton*km	New

Table 11 – Links between activities and *ecoinvent* datasets (continued)

Subsector	Activity	Dataset	Geo	Unit	Connection
	Lorry, semi-heavy (PBT ≥ 15 t.; PBTC < 40 t.) Lorry, heavy (PBT ≥ 15 t.; PBTC ≥ 40 t.)	market for transport, lorry, unspecified, use phase, BR	BR	metric ton*km	New
Aviation	Aviation, kerosene	market for kerosene	RoW	kg	Direct
	Aviation, petrol	market for petrol, unleaded	RoW	kg	Direct
Sector: Waste					
Solid waste disposal	Residential and commercial	treatment of municipal solid waste, sanitary landfill	RoW	Kg	Direct
	Indirect				None
	Municipal waste	treatment of municipal solid waste, sanitary landfill	RoW	kg	Direct
	Hazardous waste	market for hazardous waste, for underground deposit	GLO	Kg	Direct
	Illegal disposal and construction waste	market for waste concrete	RoW	Kg	Direct
Wastewater treatment and discharge	Residential and commercial	market for wastewater, from residence	RoW	m^3	Direct
Sector: Industrial Process and Product Use (IPPU)					
Product use	Metal (unspecified)	market for steel, unalloyed	GLO	kg	Direct
	Sodium cyanide	market for sodium cyanide	GLO	kg	Direct
	Degrease	market for solvent, organic	GLO	kg	Direct
	Sodium hydroxide	market for sodium hydroxide, without water, in 50% solution state	GLO	kg	Direct
	Steel wire	market for wire drawing, steel	GLO	kg	Direct
	Steel sheets	market for hot rolling, steel	GLO	kg	Direct
	Plastic pieces	market for extrusion of plastic sheets and thermoforming, inline	GLO	kg	Direct
	Metallic pieces	market for steel, unalloyed	GLO	kg	Direct

Table 11 – Links between activities and *ecoinvent* datasets (continued)

Subsector	Activity	Dataset	Geo	Unit	Connection
	Rubber wires	market for synthetic rubber	GLO	kg	Direct
	Aluminum	market for aluminum, cast alloy	GLO	kg	Direct
	Hydrogen peroxide	market for hydrogen peroxide, without water, in 50% solution state	GLO	kg	Direct
	Acetic acid	market for acetic acid, without water, in 98% solution state	GLO	kg	Direct
	Aromatic solvent	market for solvent, organic	GLO	kg	Direct
	Nitric acid	market for nitric acid, without water, in 50% solution state	GLO	kg	Direct
	Sulfuric acid	market for sulfuric acid	GLO	kg	Direct
	Nitrogen	market for nitrogen, liquid	RoW	kg	Direct
	Sodium hydroxide	market for sodium hydroxide, without water, in 50% solution state	GLO	kg	Direct
	Ammonia	market for ammonia, liquid	RoW	kg	Direct
	Cement	market for cement, portland	RoW	kg	Direct
	Gravel	market for gravel, crushed	RoW	kg	Direct
	Sand	market for sand	GLO	kg	Direct
	Acrylic	market for polymethyl methacrylate, sheet	GLO	kg	Direct
	Sulfur	market for sulfur	GLO	kg	Direct
	Paraffin	market for paraffin	GLO	kg	Direct
	Zinc oxide	market for zinc oxide	GLO	kg	Direct
	Copper	market for copper	GLO	kg	Direct
	Paper, unspecified	paper production, newsprint, recycled	RoW	kg	Direct
	Plastic, unspecified	market for injection moulding	GLO	kg	Direct
	Pine wood	market for roundwood, eucalyptus ssp. from sustainable forest management, under bark	GLO	m3	Direct
	Wood, unspecified	market for sawnwood, board, softwood, raw, dried (u=20%)	GLO	m3	Direct
	MDF wood board	market for medium density fibreboard	GLO	m3	Direct
	Swine	market for swine for slaughtering, live weight	GLO	kg	Direct

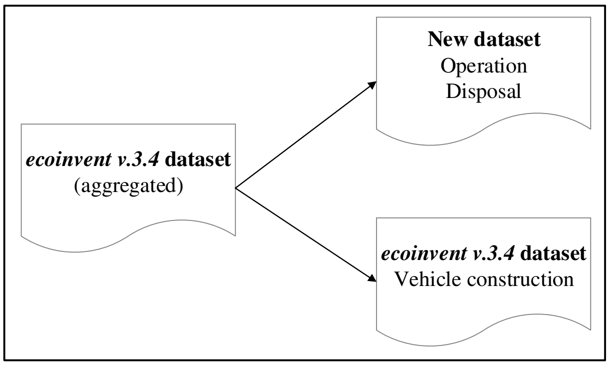
Table 11 – Links between activities and *ecoinvent* datasets (continued)

Subsector	Activity	Dataset	Geo	Unit	Connection
	Steel bars	market for steel, unalloyed	GLO	kg	Direct
	Iron	market for cast iron	GLO	kg	Direct
	Tap water	market group for tap water	GLO	kg	Direct
	Asphalt	market for mastic asphalt	GLO	kg	Direct
Sector: Agriculture, Forestry and Other Land Use (AFOLU)					
Land	Maize (grain)	market for maize grain	GLO	Kg	Direct
Livestock	Cattle for slaughtering	cattle for slaughtering, live weight to generic market for red meat, live weight	GLO	Kg	Direct
	Swine	swine production	Row	Kg	Direct
	Sheep	market for sheep for slaughtering, live weight	GLO	Kg	Direct
	Milk	market for milk	GLO	Kg	Direct

3.2.2.1 Datasets for Transportation/On-road

Firstly, in the base-year the emission of Transportation had to have only the operation emission, because it was assumed that the impact of vehicle production were counted in previous year. As in the *ecoinvent* database, the transport datasets aggregate the whole vehicle life cycle, i.e., construction, use and disposal. It was needed to separate the vehicle construction from the operation and disposal emissions. Figure 10 illustrates this methodology.

Figure 10 – Disaggregation strategy applied for some datasets



The new dataset has the economic and environmental flows (HEIJUNGS; SUH, 2002, p. 15) for the operation and disposal phase. These data were documented in M.S. Excel, as illustrated in the Figure 11. The same signal convention of the *ecoinvent* was adopted (WEIDEMA et al., 2013). Activity name refers to the new name created. Unit Name represent the unit of functional units of the reference flow in this dataset. 'Based on' field expresses the original dataset from the *ecoinvent* database. All relevant 'Considerations' were also documented in the spreadsheet. 'Economic' and "Environmental' data list the name of flows and their characteristics. All datasets created or adapted are described in Appendix A1.

Figure 11 – Spreadsheet structure utilized to document the new datasets

Activity name transport, passenger car, petrol, use phase
UnitName km
Based on 11742 - transport, passenger car, small size, petrol, EURO 5, RoW

Consideration The emissions are considered the same as the original dataset

Economic

ProductName	Geography	UnitName	Amount
transport, passenger car, petrol, use phase	BR	km	1
market for petrol, 15% ETBE additive by volume, \	GLO	kg	-0.06581197
market for road	RoW	m*year	-0.0006966
market for brake wear emissions, passenger car	GLO	kg	0.00000577
market for passenger car maintenance	GLO	unit	-0.00000645
market for road wear emissions, passenger car	GLO	kg	0.0000127
market for tyre wear emissions, passenger car	GLO	kg	0.0000743

Environmental

ElementaryFlow Name	Compartment	Subcompartment	UnitName	Amount
1-Pentene	air	urban air close to grc	kg	1.96E-08
2-Methyl pentane	air	urban air close to grc	kg	7.42E-06
Acetaldehyde	air	urban air close to grc	kg	1.33E-07
Acetone	air	urban air close to grc	kg	1.09E-07

Table 12 lists the data modified from original dataset in the new ones.

Table 12 – Data modified in the new datasets

Activities	Economic	Environmental
Passenger car, petrol	Fuel consumption in kg/km	None
Passenger car, ethanol	Fuel consumption in kg/km	All emissions
Motorcycle	Fuel consumption in kg/km	None
Urban bus	Fuel consumption in kg/p*km Type fuel consumed (diesel + biodiesel)	Carbon dioxide, fossil and non-fossil Carbon monoxide, fossil and non-fossil Methane, fossil and non-fossil

Fuel consumption for all vehicles in the base-year was obtain from an estimative of real operation observed in Brazil (BRASIL, 2013). The amount of biodiesel in diesel were 7%, as better explained in Step 3.

The emissions for passenger car, ethanol were based on 2007 values for passenger car, flex fuel technology operating with ethanol (CETESB, 2016, p. 180).

For diesel cycle engines, the amount of fossil and non-fossil emissions were calculated as a function of the amount of biodiesel in the fuel composition, through the Equation (1) and (2).

$$E^{new}_{fossil}=(1-b)*E^{original}_{fossil} \quad (1)$$

$$E^{new}_{non\text{-}fossil}=b*E^{original}_{fossil} \quad (2)$$

Where:

E^{new}_{fossil}: New amount of fossil emission E in kg, due to the biodiesel in the fuel composition.

$E^{original}_{fossil}$: The amount of fossil emission in the original dataset in kg, when only fossil fuel was consumed.

$E^{new}_{non\text{-}fossil}$: New amount of non-fossil emission E in kg, due to the biodiesel in the fuel composition.

b: amount of biodiesel in the diesel composition, e.g. for diesel B7, b=0.07 (or 7%) of biodiesel.

These emissions were Carbon dioxide (fossil and non-fossil), Carbon monoxide (fossil and non-fossil) and Methane (fossil and non-fossil).

For freight transportation, it was necessary to build a “market for” dataset that considered the different capacities of lorries. The amount of each type of vehicle in the dataset were estimated based on the quantity this vehicle in the Brazilian fleet. In addition, for each type of lorry a new dataset were built. The Table 13 lists the type of lorries and the modifications done in economic or environmental exchanges, i.e. data modified in new datasets from the original dataset.

Table 13 – Data modified in new datasets of freight transportation

Lorry (capacity)	Economic	Environmental
3.5-7.5 metric ton 7.5-16 metric ton 16-32 metric ton >32 metric ton	Fuel consumption in kg/metric ton*km Type fuel consumed (diesel + biodiesel)	Carbon dioxide, fossil and non-fossil Carbon monoxide, fossil and non-fossil Methane, fossil and non-fossil

For Transportation activities, some datasets were adapted or created followed the methodology presented in Section 3. Table 14 lists the name of these datasets. These datasets are described in detail in Appendix A1.

Table 14 – New datasets

Activity	Dataset
Passenger car, petrol	transport, passenger car, petrol, use phase
Passenger car, ethanol	transport, passenger car, ethanol, use phase
Motorcycle	transport, motorcycle, use phase
Urban bus	transport, urban bus, B7, use phase
	market for transport, freight, lorry - use phase, BR
	transport, freight, lorry 3.5-7.5 metric ton, EURO3 - use phase
Lorry	transport, freight, lorry 7.5-16 metric ton, EURO3 - use phase
	transport, freight, lorry 16-32 metric ton, EURO3 - use phase
	transport, freight, lorry >32 metric ton, EURO3 - use phase
Light commercial vehicle, diesel	transport, freight, light commercial vehicle - use phase

It is relevant to point that for diesel-based technology it was assumed that 7% of diesel composition was biodiesel from soybean, as it was the amount ruled in 2016 (BRASIL, 2014). The *ecoinvent* dataset named ‘esterification of soybean oil, BR’ represented this biodiesel in all suitable dataset.

In freight transportation, a new dataset, titled in this research as “market for transport, freight, lorry, unspecified / [BR]’ was used to estimate the emissions from lorries operation within the city in 2016. This dataset represented the share of distinct types of lorry in the national fleet (CNT, 2017, n. Table 1.4.1.3.7). Table 15 shows these relative amount per lorry type, expressed by its load capacity, and their correspondent dataset.

Table 15 – National fleet of freight transport vehicles

Type of lorry		National fleet
Semi-light weight	transport, freight, lorry 3.5-7.5 metric ton, EURO3 - use phase	6.95%
Light and medium weight	transport, freight, lorry 7.5-16 metric ton, EURO3 - use phase	34.37%
Semi-heavy weight	transport, freight, lorry 16-32 metric ton, EURO3 - use phase	28.64%
Heavy weight	transport, freight, lorry >32 metric ton, EURO3 - use phase	30.04%
		Total: 100%

Source: (CNT, 2017, n. Table 1.4.1.3.7).

3.2.3 Demand Vector

To perform the Life Cycle Assessment of the city, the whole amount demanded of each activity, by the city, in the base-year (2016), were documented as a vector, i.e., a demand vector. The units of this vector must be align with the units of the respective dataset. To convert these units and adapt the data to the scope of emissions (Figure 9), some mathematic manipulation were done, as described in sequence by sectors.

3.2.3.1 Stationary energy

The demands of electricity, kerosene for lighting and liquefied petroleum gas were based on the amount consumed in the city in the base-year, assuming that all amount commercialized were consumed within the city boundaries.

For heavy fuel oil and natural gas, it was assumed that all amount of natural gas and heavy fuel oil commercialized in the city were consumed in the city, consequently it was estimated the heat generated. To do so, these fuels were converted to heat used in the city. The conversion of fuel-to-heat were based on the technologies documented in the datasets of *ecoinvent v.3.4 cut-off* (WERNET et al., 2016) and listed in Table 16.

Table 16 – Conversion of fuel consumed into heat generated in the city in the base-year

Activity: Natural gas		
ecoinvent dataset name / geography	heat production, natural gas, at boiler atmospheric non-modulating <100kW / RoW	
Amount demanded: 0.03 m³/MJ		
	Fuel consumed (m³)	Heat generated (MJ)
Residential Buildings	5.13 E+6	188.87 E+6
Commercial and institutional buildings and facilities	5.22 E+6	192.18 E+6
Manufacturing industries and construction	4.54 E+6	1,670.98 E+6
Activity: Heavy fuel oil		
ecoinvent dataset name / geography	heat and power co-generation, oil / BR	
Amount demanded: 0.01 kg/MJ		
	Fuel consumed (kg)	Heat generated (MJ)
Residential Buildings	4.4380 E+4	4.44E+06

3.2.3.2 Transportation

3.2.3.2.1 Aviation subsector

For aviation sub-sector, the demand vector were based simply on consumption of kerosene and fuel for aviation (Table 17).

Table 17 – Demands for aviation subsector

Sub-sector	**Activity**	**Amount [kg]**
Aviation	Consumption of kerosene	1,689,630
	Consumption of petrol for aviation	449,901

Source: (ANP, 2016)

3.2.3.2.2 On-road subsector

Two different data were available for the on-road subsector: fleet registered and fuel commercialized in the city in the base year. The former came from the state department of transportation (DETRAN - PR, 2018) and municipal department of transportation (URBS, 2018), later came from national agency of petrol, gas and biofuel (ANP, 2016).

Applying the Equations (3) to (7), it was possible to estimate the appropriate functional unit1. These Equations were based on '*Emissões veiculares no estado de São Paulo, 2016'* (CETESB, 2017) and on the *Inventário Nacional de Emissões Atmosféricas por Veículos Automotores Rodoviários: Relatório Final* (BRASIL, 2013).

The total consumption of a fuel was the sum of this fuel consumed by the different types of vehicles (v), as demonstrated by Equation (3).

$$C_f = \sum_v Fr_{v,f} . \overline{Iu_{v,f}} . \frac{1}{\overline{Ql_{v,f}}} \qquad \forall\, v, f \qquad (3)$$

Where:

C_f: Consumption of fuel (f), in liters (L)

$Fr_{v,f}$: Fleet of vehicles (v) of fuel (f), in number of units

$\overline{Iu_{v,f}}$: Average of intensity of use of vehicle (v) of fuel (f), in kilometers (km)

$\overline{Ql_{v,f}}$: Avarege consumption of fuel of vehicle type (v) of fuel (f), in kilometers per liter (km/L)

The intensity of use and the consumption of fuel are dependent of the model-year of the vehicle (BRASIL, 2013); however, as these information were unavailable it was assumed the average age of the fleet of type of vehicle (v) for the city. By doing so, it was possible to estimate the ($\overline{Ql_{v,f}}$) and ($\overline{Iu_{v,f}}$). Fuel consumed per kilometers for cars, and motorcycle came from the report 'Inventário Nacional de Emissões Atmosféricas por Veículos Automotores Rodoviários: Relatório Final' (BRASIL, 2013), and are listed in Table 57 and Table 58 (Attachments) respectively. Intensity of use came for the same report and the values are in Table 56 (Attachments). The average age of the fleet are listed in Table 18. Then, the intensity

[1] Functional unit is the quantitative flow of a system product to use as a reference unit, e.g., 1 kwh of electricity.

of use per year and the consumption rate of fuel for each type of vehicle were obtained based on the average age of the fleet, as listed in Table 19.

Table 18 – Average age of fleet in the base-year

Activity	Average age of fleet (years)	Source
Passenger Car		
Ethanol		
Petrol	9	(SINDIPEÇAS, 2016)
Motorcycle		
Light commercial vehicles		
Lorry	13	(CNT, 2017, n. Table 1.6.1.2.)

Table 19 – Intensity of use and consumption of on-road transportation activities

Activity	Intensity of use (km)	Consumption rate (km/L)
Passenger Car		
Ethanol	14600 [a]	7.8[b]
Petrol		11.7[b]
Motorcycle	8400 [a]	37.09[c]
Light commercial vehicles	16400 [a]	9.5[d]
Lorry	98553 [a]	--
Urban bus*	110,875,685 [e]	2.08 [f]

Source: [a](BRASIL, 2013, n. Table 34) , [b](BRASIL, 2013, n. Table 24), [c](BRASIL, 2013, n. Table 25), [d](BRASIL, 2013, n. Table 26), [e](URBS, 2016), [f](URBS, 2017)

The amount of each fuel consumed (Table 20) by transportation activities were supplied by National Agency of Petroleum, Gas and Biofuel (ANP).

Table 20 – Fuel commercialized in Curitiba in the base-year

Fuel	Amount (L)
Ethanol	207,782,186
Petrol	726,206,631
Diesel	374,702,422
Aviation kerosene	2,060,524
Aviation, petrol	580,518

Source: (ANP, 2016)

a. Petrol

Equation (4) expresses the petrol consumed in the city. It was assumed that all petrol commercialized in the city was consumed by cars and motorcycles in the city. In addition, it was considered that all passenger cars were flex fuel technology, since vehicles with petrol technology represent 4% of the national fleet (CNT, 2017). Vehicles powered exclusively by petrol or ethanol have distinct efficiency when compared to flex fuel engines (BRASIL, 2014). For motorcycle, was considered that all fleet are petrol-based technology.

$$C_{petrol} = C_{petrol,\ cars} + C_{motorcycle} \tag{4}$$

b. Ethanol

It was considered that ethanol was consumed by flex fuel-based passenger cars. Applying the Equation (3) was possible to estimate the functional unit (km) for these vehicles. Where the average consumption of fuel ($\overline{Ql_{v,f}}$) came from Table 57 (Attachments), assuming the average age of fleet.

c. Diesel

Urban bus and freight transport by lorry were responsible for total amount of diesel consumed, see Equation (5), and this amount is the same reported by ANP (ANP, 2016) as commercialized in the city in base year.

$$C_{diesel} = C_{diesel,\ urban\ bus} + C_{diesel,\ lorry} \tag{5}$$

- Urban bus

The consumption of diesel by urban bus was determined by Equation (6). The department of transport (URBS) supplied the total of distance traveled by year (Iu_v) and the average fuel consumption per kilometer ($\overline{Ql_v}$).

$$C_{diesel,\ urban\ bus} = Iu_v \cdot \frac{1}{\overline{Ql_v}} \qquad \text{v: urban bus} \tag{6}$$

The functional unit (person*km) was estimated by Equation (7). The number of passenger transported (p) in 2016 and the distance of a trip (d) were considered. In accordance with the URBS (2018), 551,786,195 passengers were transported in 2016. Moovit (2016) reported that the average distance traveled by passenger by transit was 7 km in Curitiba.

$. f_{urban\ bus} = d \cdot p$ (7)

- Freight transport by lorry

To estimate the functional unit of freight transport by lorry in 2016, firstly the weight average consumption ($\overline{Ql_{v,f}}$) of these vehicles were obtained, considering the data informed by each dataset (WERNET et al., 2016) , as described in Table 21. The average consumption was 0.041 ($kg.metric\ ton^{-1}.km^{-1}$), or 0.0480 ($L.metric\ ton^{-1}.km^{-1}$) , if the density of diesel is considered equal to 0.853 (kg/L).

Table 21 – Average consumption of freight by lorry transportation

Type of lorry	National fleet	Consumption[1] (kg/metric ton*km)
transport, freight, lorry 3.5-7.5 metric ton, EURO3 - use phase	6.95%	0.111
transport, freight, lorry 7.5-16 metric ton, EURO3 - use phase	34.37%	0.048
transport, freight, lorry 16-32 metric ton, EURO3 - use phase	28.64%	0.038
transport, freight, lorry >32 metric ton, EURO3 - use phase	30.04%	0.020

Note: [1](WERNET et al., 2016)

Using the Equations (3), the amount of diesel was obtained. Then, diving the fuel consumed by the weight average consumption, the functional unit arises and is equal to 6.69 E+09 (metric ton.km).

3.2.3.3 Waste

The amount of waste generated and treated in the city in the base year was directly obtained from two annual reports, only converting the units. SANEPAR (2017) supplied the amount of wastewater, and IFC project (2015) supplied values for solid waste, as described in Table 22.

Table 22 – Waste generated in the city in the base-year

Sub-sector	Sub-category	Considered
Solid waste disposal	Residential and commercial	Yes
	Indirect	No
	Waste from municipal cleaning service	Yes
	Hazardous	Yes
	Wastes from river	No
	Illegal disposal and construction waste	Yes
Wastewater treatment and discharge	Residential and commercial	Yes

The wastes from river and indirect wastes were not considered due to the unknown composition of these wastes. The data of "Illegal disposal and construction waste" supplied by the IFC (2015) was simply adopted as market for waste concrete. "Waste from municipal cleaning service" was admitted as municipal waste sent to the sanitary landfill.

3.2.3.4 IPPU

The city of Curitiba has few industries within its jurisdiction division, the industrial parks are situated in the neighbor cities. Therefore, it was possible to gather the data of product consumed by the industries situated in Curitiba. Through the approach suggested by Zortea and Cybis (2014), this research collected the data supplied by 'Instituto Ambiental do Paraná (IAP)' on the reports of environmental statements of operation. Most products were already in the correct unit; for those that were not, the conversion factors presented in Table 23 were applied.

Table 23 – Conversion factors used for IPPU sector in the base-year

Description	Factor	Source
Density of low carbon steel (kg/m³)	7860	(CHIAVERINI, 1977)
Linear density of rubber unspecified (kg/m)	0.10	(ENGINEERING TOOL BOX, 2018)
Volume of a round wood (m³)	0.11	*Estimated*
Thickness of a MDF board (m)	0.03	*Estimated*

3.2.3.5 AFOLU

For this sector, the data were only available for products produced. Hence, the emissions were based on production instead of consumption. The information of livestock and land production were obtained by the IBGE (BRASIL, 2016), as listed in Table 24.

Table 24 – AFOLU products obtained in the base-year

Subsector	Sub-category
Land	Maize (grain)
	Beans (grain)
Livestock	Milk
	Honey bee
	Wool
	Cattle for slaughtering
	Horses
	Swine
	Sheep

Some considerations were done to convert the raw data to the right unit. These conversion factor are represented in Table 25.

Table 25 - Conversion factors used for AFOLU sector in the base-year

Description	Factor	Source
Density of milk (kg/L)	1032	(EMBRAPA, 2018)
Average weight of a cattle (kg)	360	(IMEA, 2018)
Average weight of a swine (kg)	120	(DE OLIVEIRA, 2011, p. 12)
Average weight of a sheep (kg)	150	(CRIAR E PLANTAR, 2018)

3.2.4 Life Cycle Impact Assessment Of The Base Year

Each dataset in the database has an activity vector, which is partitioned into technosphere vector 'A' and environmental vector 'B'. When many activities are jointed, arises the technosphere matrix 'A' and environmental matrix 'B' and hence the database (for more details see Heijungs and Suh (2002)). Applying the linear algebra it was possible to calculate the environmental impact of a system process, defined by Equation (8).

$$H = \mathbf{QBA}^{-1} f \qquad (8)$$

Where (**Q**) is the characterization matrix that has the characterization factors for each impact category due to elementary flow in (**B**). The economic flows are expressed in (**A**). The demand vector (**f**), represents the amount of each activity demanded, which is determined by the approach described in Section 3.2.3 (HEIJUNGS; SUH, 2002, p. 174).

In this research, the matrices (A), (B) and (Q) were provided by *the ecoinvent v. 3.4 cut-off database,* and the mathematic calculations were performed in Python v.3.6.

3.2.5 Contribution Analysis

The results obtained by life cycle impact assessment provided the information of total environmental impact of the city in the base-year. However, the interest was to known which sectors and their activities were the most pollutants. This was done by contribution analysis.

The outcome of this step was a list of most pollutant activities in the city in the base-year by sector. Through the Equation (9) was possible to investigate the contribution of an activity, a sector and subsector (HEIJUNGS; SUH, 2002, p. 175).

$$h_l(P_a)=\sum_{\forall k}\sum_{j\in Pa}\sum_{\forall i} q_{l,k} b_{k,j} \left(\mathbf{A}^{-1}\right)_{j,i} f_i \qquad \begin{matrix}\forall\, i, j \in \mathbf{A} \\ \forall\, l \in \mathbf{Q} \\ \forall\, k \in \mathbf{B}\end{matrix} \qquad (9)$$

Where:

$h_l(P_a)$: Environmental impact 'l' of an activity 'P_a', e.g. kg of CO_2 eq. (GWP 100a);
$q_{l,k}$: The characterization factor that links the intervention k with the impact category 'l';
$b_{k,j}$: Environmental exchange 'k' of the activity 'j';
$\left(\mathbf{A}^{-1}\right)_{j,i}$: Technosphere exchange 'i' of the activity 'j';

The outcomes of this step provided the information to select the alternative technologies in the next step, which were used in the optimization step to identify the quantitative roadmap.

As is documented in the Section 4 (Results) the sector of "Transportation" presented the highest contribution for the three impact categories analyzed. Therefore, this sector was the priority, hence all the methodological steps presented in sequence focused on this sector. In addition, this research addressed the transportation of passengers, which was divided in Public Transportation (PuT) and Individual Transportation (InT).

3.2.6 Selecting Alternative Technologies

Afforded with the priorities given by the outcomes in the previous step, it was possible to determine alternative technologies for Public Transportation (PuT) and Individual Transportation (InT) of passengers, which composed the roadmaps. These alternatives were chosen whether the environmental data were available, following the same sequence of Section 3.1.2.iv (BR, RoW and GLO).

3.2.6.1 Life cycle assessment of the alternative technologies

With the alternatives defined, the process of gathering data were done following the same linear algebra approach described in Section 3.2.4 (Life Cycle Impact Assessment Of The Base Year).

Then, the unitary impact of each alternative technology was obtained through the matrix-based LCA, implemented in Python. These unitary impacts were expressed in kg of carbon dioxide per functional unit (e.g., kg CO2 eq./ person*km-1) for the Global Warming Potential for a hundred years – GWP100a (IPCC, 2013). These information were used in the optimization modeling.

3.2.6.2 Additional data for the alternative technologies

For the On-road subsector, the capacity of passengers per vehicle were obtained. For railway subsector, the data for subway such as, capacity of passengers, number of stages of construction, capacity of operation and length of rail in each stage were obtained from public reports.

3.3 SPECIFYING THE EXOGENOUS VARIABLES

Exogenous variables described part of the world that was not included in the backcasting itself, but must be specified in order to develop consistent roadmap (ROBINSON, 1990, p. 830). Exogenous variables formed the constraints in the optimization problem that are described further in Section "Step 4.a". These data were extrapolated to match the longer time horizon of the backcasting analysis. This approach is usual in backcasting approach (ROBINSON, 1990, p. 831).

The exogenous variables concerning the passenger transportation were:

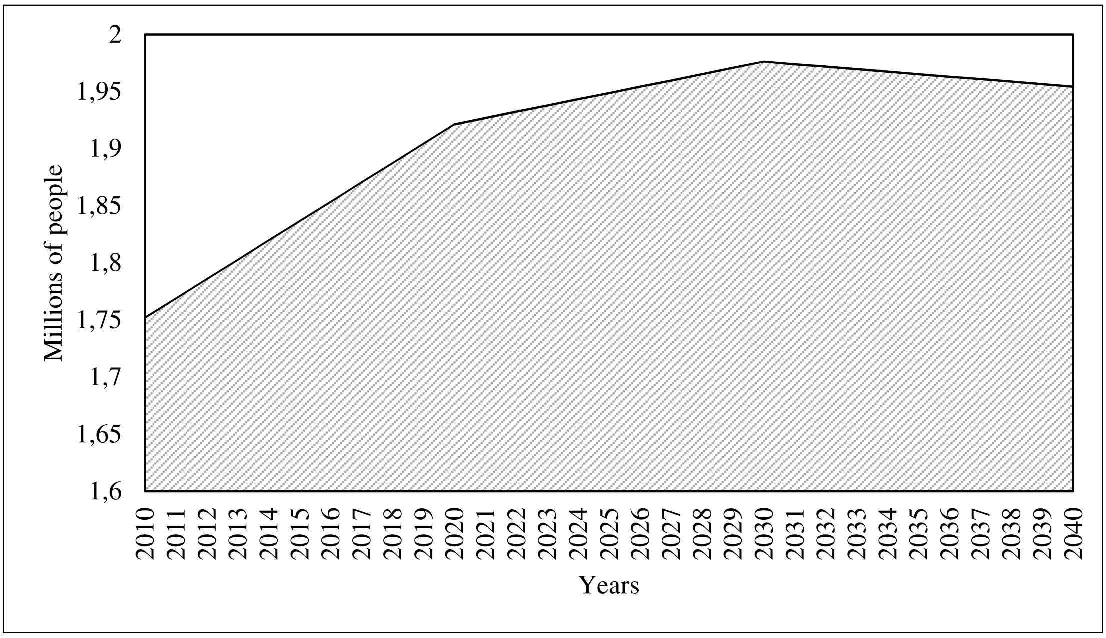
3.3.1 Population Growth, Mobile Population And The Demands For Public And Individual Transportation

Through the data from Brazilian Institute of Geography and Statistics (IBGE) and Institute of Economic and Social Development of Paraná (IPARDES) it is possible to estimate the population in Curitiba up to 2040. The Table 26 lists the data and their source. Figure 12 shows the population using linear interpolation between the years from Table 26.

Table 26 – Population estimated in the period

Year	Population [millions of people]	Growth	Source
2010	1.75	--	(BRASIL, 2010)
2020	1.92	0.9%	
2030	1.98	0.3%	(IPARDES, 2017, p. 7)
2040	1.95	-0.1%	

Figure 12 – Population estimated



A third-party study in cooperation with the Institute of Research and Urban Planning of Curitiba (IPPUC, in Portuguese), shows that 77% of population in metropolitan area of Curitiba are mobile (IPPUC, 2017, p. 91), i.e., people that do at least one travel by any modal.

The same report specifies the number of travels done by passengers in Public Transportation (PuT) or Individual Transportation (InT). Then, applying the distance traveled in each choice, it is possible to estimate how much one passenger moves in a year, in kilometers. Table 27 summarizes these data.

Table 27 – Characteristics of passengers in Curitiba

Data	**Unit**	**Value**
Mobile population (MP)[1]	% of population	77%
Number of travels for people in mobile population[1]	travels/person	2.76
Travels by PuT[1]	travel/person	0.69
Travels by InT[1]	travel/person	1.38
Average millage per trip using PuT[2]	km/travel.day.person	7.00
Average millage per trip using InT[3]	km/travel.day.person	5.00
Total mileage using PuT	km/year.person	1763
Total mileage using InT	km/year.person	2518

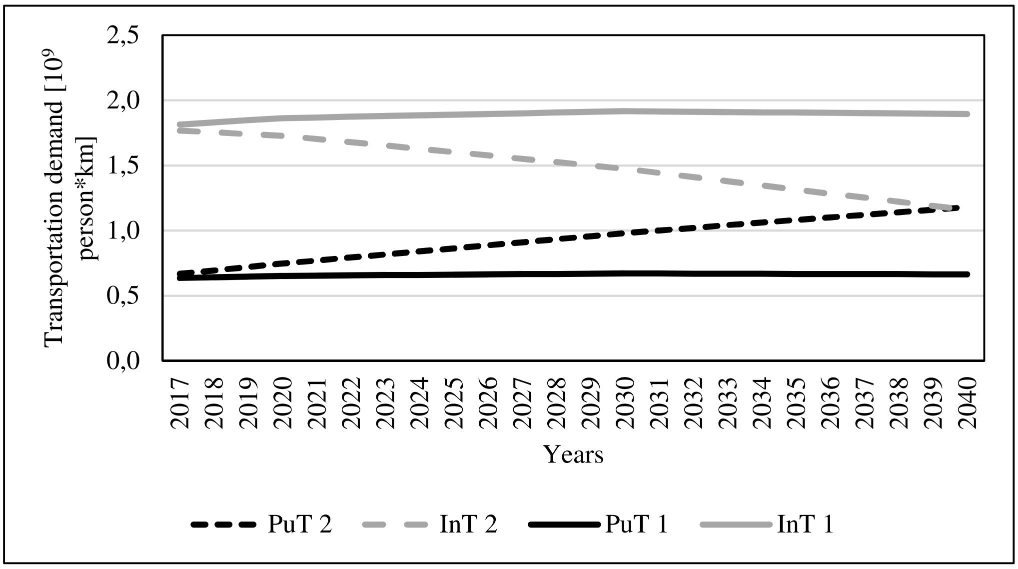
Notes: [1](IPPUC, 2017); [2](MOOVIT, 2016); [3](SÃO PAULO, 2015, p. 22)

Two scenarios were analyzed in this research. For the first scenario, the share of mobile population using PuT and InT are kept unchanged and equal 25% and 50% respectively (IPPUC, 2017, p. 77). In scenario 2, the percentage change to 40.5% and 34.5% by 2040 for

PuT and InT respectively. This increment in mobile population using PuT represent the best region observed in Curitiba in 2016 (IPPUC, 2017).

Multiplying the share of mobile population using PuT or InT for the population estimated, and for the mileage traveled, arise the demand of passenger transportation, as described in Figure 13.

Figure 13 – Estimative of transportation of passengers demand



The changes suggested in scenario two decrease the demand of people transiting in the city.

3.3.2 Vehicles Per Person

In order to maintain the quality in the public transportation, it was assumed that the same ratio of bus per person of the base-year (2016) has been maintained. This simple approach imply that the demand at the peak hours is fully supplied. This simplicity it was also supposed to the individual transportation. Assuming that the population do not change its culture in the sense of vehicles per person over the years.

Thus, the ratio of vehicles per person were calculated by Equation (10). The ratios were 334 people/bus and 0.36 cars/person. These information involve the amount of vehicles needed in the peak demand.

$$r_i = \frac{Pop^0}{Fr_i^0} \quad , \quad i{:}PuT, InT \qquad (10)$$

Where:

r_i: ratio of person/vehicle

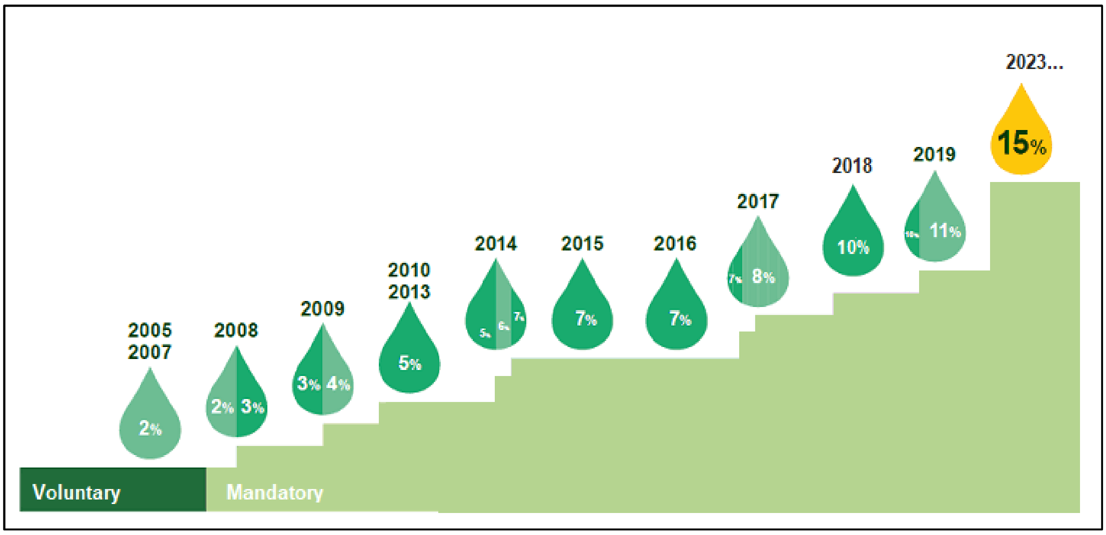
Fr_i^0: Fleet of vehicle of subcategory *i* in the base-year, in amount of vehicles

Pop^0: Population in the base-year, in number of person.

3.3.3 Biodiesel Composition In Diesel Fuel

In the 2016 (base-year) 7% of the diesel fuel was composed by biodiesel. This amount increased today to 10%. Rule by the Law 13.263/16 (BRASIL, 2016), in 2023, 15% of biodiesel will be mandatory in the diesel composition. Figure 14 illustrates the evolution of biodiesel percentage.

Figure 14 – Biodiesel required in the diesel composition

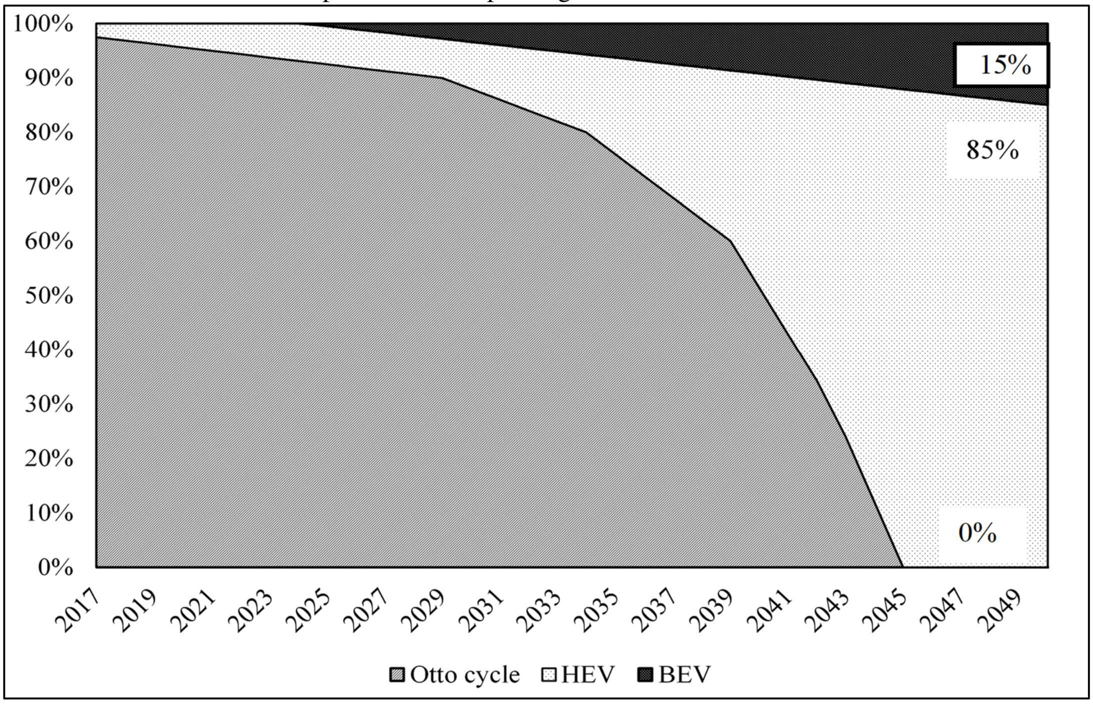


Source: (UBRABIO, 2018)

3.3.4 Trends For Individual Transportation Vehicles

The trends for individual transportation is built on the report of Energy Demand in 2050 in Brazil (EPE, 2016), which is a well done forecast of energy in Brazil, including the estimated fleet of lightweight vehicles. Figure 15 demonstrate the perspectives for new sales of each type of vehicles.

Figure 15 – Estimative of market penetration for passenger cars



Source: (EPE, 2016, p. 109)

3.4 Scenario Analysis

3.4.1 Optimization

At this step, the quantitative roadmaps were developed. This process was carried out by mathematical optimization considering the problem as a Mixed-Integer Linear Programming (MILP) problem due to its characteristics of multi-period, linear Equations and discrete, binary and continuous variables, as reviewed in Section 2.

The model was implemented in IBM ILOG CPLEX Optimization Studio®, version 12.8.0.0, educational license, and the post-processing results were executed in Python 3.6. The learning process demanded a huge effort and time. By doing so, I was able to implement the model and obtained the results.

The model were analyzed for two distinct scenarios.

Scenario 1: the percentage of population that use Public Transportation (PuT) or Individual Transportation (InT) were kept fixed over the years.

Scenario 2: The percentage of population that use PuT or InT varied along the period. The percentage for PuT increases, reaching the highest value observed in the Curitiba neighborhood in the base-year (2016), and for Individual Transportation the value was the smallest observed.

These two scenarios defined distinct values of constraint, consequently, the data were considered as exogenous variables.

3.4.2 Problem Statement

Indices

v	Passenger car
b	Urban bus
t	Year-calendar, in [years]
m	Describe the year-model of vehicles, in [years]
e	Stage of the subway project

Sets

BAU	Vehicles with business-as-usual technology
NEW	Vehicles with alternative technologies
$\mathcal{O}$	Vehicles with Otto cycle engine
$\mathcal{N}$	Alternative technologies

Continuous variable

x_t	Operational capacity of the subway in the year-calendar (t), in [person*km]

Integer variable

$S_{c,t}$	Number of passenger cars (c) commercialized in the year-calendar (t), expressed in [units].
$S_{b,t}$	Number of urban bus (b) commercialized in the year-calendar (t), expressed in [units].

Binary variable

$y_{e,t}$	Decision to build the stage (e) of the subway in the year-calendar (t). 1 if the stage is built, 0 otherwise.
$z_{e,t}$	Decision if the stage (e) of the subway is operational in the year-calendar (t). 1 if it is operational, 0 otherwise.

Parameters

t_b	Base-year in [years]
h_{InT}	Total impact of individual transportation, in [kg of CO_2 eq.]
$h_{v,t}^{sales}$	Impact due to vehicles (v) commercialized in the city, in year-calendar (t), in [kg of CO_2 eq.].
$h_{v,t}^{operation}$	Impact of operation of vehicles (v) in the year-calendar (t), expressed in [kg of CO_2 eq.].
$I_v^{operation}$	Unitary impact of operation, in [kg of CO_2 eq./pkm]
Pe_v	Capacity of people per vehicle (v)., in [number of passengers/vehicle]
I_v^{sales}	Unitary impact of sale/production, in [kg of CO_2 eq./unit]
$Fr_{v,t}^0$	Initial fleet of vehicle (v), in BAU, remaining in the year-calendar (t), in [units]
Use_t^0	Intensity of use of BAU vehicles in the year-calendar (t), in [km/year]
$Use_{v,m}$	Intensity of vehicle (v), of year-model (m) in the year calendar (t), in [km/year]
W_t	Disposal curve in the year-calendar (t) *[unidimensional]*
$Fr_v^{initial}$	Number of vehicles (v) in 2016, in [units]
C_t^{Otto}	Percentage of vehicle with Otto cycle commercialized in the year-calendar (t) *[unidimensional]*
$C_{n,t}$	Percentage of market penetration of vehicle (n) belonging to NEW in the year-calendar (t), *[unidimensional]*
R_t	Minimum number of vehicles in the year calendar (t), due to the ratio of vehicles/person [units]
D_t^{InT}	Demand for individual transportation, in [pkm]

3.4.2.1 Objective function

The objective function focus on minimizing the total Global Warming Potential (GWP100) impact (h_{total}). Decisions involving the sales of passenger cars ($S_{c,t}$), urban bus ($S_{b,t}$), and the decision to build the subway were taken into account. Thus the objective function (Equation 11) is the sum of impacts for Individual Transportation (InT), on-road Public Transportation (PuT) and the impacts of subway.

Impacts of InT and on-road PuT are composed by impacts of sales and operation. The impacts of sales always happened when new vehicles were sold in the city, Equations (12) and (16). The impacts of operation (Equations (13) and (17)) are the multiplication of the unitary impact of each vehicle for passenger's capacity, for the distance traveled by each type of vehicle.

$$\min h_{total} = \underbrace{\sum_t \sum_c \left(h_{c,t}^{sales} + h_{c,t}^{operation}\right)}_{\text{Impacts of InT}} + \underbrace{\sum_t \sum_b \left(h_{b,t}^{sales} + h_{b,t}^{operation}\right)}_{\text{Impacts of PuT-on-road}} + \underbrace{\sum_{t=tb}^{T} I^{construction} . \sum_{e=1}^{E} k_e . y_{e,t}}_{\text{contruction impacts for subway}} + \underbrace{\sum_{t=tb}^{T} \sum_{e=1}^{E} I^{train} . NbTrain_e . y_{e,t}}_{\text{aquision impacts for trains}} + \underbrace{\sum_{t=tb}^{T} \sum_{e=1}^{E} I_{operation}^{subway} . x_t}_{\text{operation impacts of subway}} \quad (11)$$

$$h_{c,t}^{sales} = I_c^{sales} . S_{c,t} \qquad \forall\, c, t \qquad (12)$$

$$h_{c,t}^{operation} = I_c^{operation} . Pe_c . \left(Fc_{c,t}^0 . Ucar_t^0 + \sum_{m=tb}^{t} Ucar_{c,m} . S_{c,m} . WC_t \right) \qquad \forall\, v, t \qquad (13)$$

$$Fc_{c,t}^0 = Fc_c^{initial} . WC_{t=t+mi} \qquad \forall\, v, t \qquad (14)$$

$$WC_t = 1 - \exp(-\exp(1.798 - 0.137 * t)) \qquad \forall\, v, t \qquad (15)$$

$$h_{b,t}^{sales} = I_b^{sales} . S_{b,t} \qquad \forall\, v, t \qquad (16)$$

$$h_{b,t}^{operation} = I_b^{operation} . Pe_b . \left(Fb_{b,t}^0 . Ubus_t^0 + \sum_{m=tb}^{t} Ubus_{b,m} . S_{b,m} . WB_{t=m}) \right) \qquad \forall\, v, t \qquad (17)$$

$$WB_t = \frac{1}{(1 + \exp(0.16.(t-19.1)))} + \frac{1}{(1 + \exp(0.16.(t+19.1)))} \qquad (18)$$

The right part of operation impact Equations (Equations (13) and (17)), between parentheses, represent the total distance traveled by vehicles (c or b), in kilometers. Where ($Fc_{c,t}^0$ and $Fb_{b,t}^0$) are the remaining number of vehicles from the base-year (2016) in the calendar-year (t), and ($Ucar_t^0$ and $Ubus_t^0$) are the intensity of use in kilometers of the initial fleet that is dependent of the age of the initial fleet. The summation is the distance traveled by each model (m) of vehicle in the calendar-year (t). ($S_{c,m}$ and $S_{b,m}$) are the number of vehicle (c) or (b) sold in the year-model (m), and (WC_t) is the disposal curve applied to the model-year (m) for passenger cars, and (WB_t) the disposal curve applied to urban bus. Both curves were given by Brasil (BRASIL, 2014, p. 86).

The end-of-life impacts were not considered.

3.4.2.2 Constraints

3.4.2.2.1 Individual transportation

The Equation (19) imposes that the sales of vehicles (o) equipped with Otto cycle engine decrease along the years. The share of sales of this were expressed by (C_t^{Otto}). The summation in the right side represents the number of all vehicles (c) sold in the year-calendar (t). O is the set of vehicles with Otto cycle engine, which comprehended petrol and ethanol technologies. Equation (20) certifies the market penetration of other technologies, i.e. Compressed Natural Gas (CNG), hybrid electric vehicle (HEVp) and Plug-in Battery Electric Vehicle (BEV). Where $\mathcal{N}$ is the set of alternative technologies, which involved passenger cars with Compressed Natural Gas (CNG), Hybrid Electric Vehicle powered by petrol (HEVp) and Plug-in Battery Electric Vehicle (BEV).

Another consideration was to keep the same ratio of vehicle per person along the years. Equation (21) represents it.

$$S_{o,t} \leq C_t^{Otto} . \sum_{v} S_{c,t} \qquad \forall\, c, t \quad o \in \mathcal{O} \tag{19}$$

$$S_{n,t} \leq C_{n,t} . \sum_{c} S_{c,t} \qquad \forall\, c, t \quad n \in \mathcal{N} \tag{20}$$

$$\sum_{v} \left[Fr_{c,t}^{0} + \sum_{m=tb}^{t} S_{c,t} . WC_m \right] \geq R_t \qquad \forall\, c, t \tag{21}$$

3.4.2.2.2 Public transportation – on-road

From 2018 to 2020, the business-as-usual (BAU) technologies are partially replaced with the rate (τ) in vehicles per year. This trend is modelling by constraint (22). After 2021, the remaining vehicles are disposal, following the Equation (23).

Vehicles equipped with new technologies, defined by the set NEW, have their fleet operating in the city, in the year-calendar (t) limited by the percentage (C_b) of the total fleet, as defined in Equation (24). The left side of Equation (24) represent the fleet of vehicles (n) in the year-calendar (t). The summation in the right side is the total number of vehicles operation in the city in the year-calendar (t).

Similar to the individual transportation, the ration of people per vehicle was maintained, ensuring that the system can support the peak demand. Constraint (25) modeled it.

$$Fb_{b,t}^{0} = Fb_{b}^{initial} - \tau . t \qquad \forall\, b \in BAU,\ t \leq 2020 \tag{22}$$

$$Fb_{b,t}^{0} = Fb_{b,t=2020}^{0} . WB_t \qquad \forall\, b \in BAU,\ t \geq 2021 \tag{23}$$

$$\sum_{m=tb}^{t} S_{n,m}.W_{t=m} \leq C_b.\sum_{b}\left[Fb_{b,t}^{0} + \sum_{m=tb}^{t} S_{b,m}.WB_{t=m}\right] \qquad \forall\, n \in NEW \quad \forall\, b,t \qquad (24)$$

$$\sum_{b}\left[Fb_{b,t}^{0} + \sum_{m=tb}^{t} S_{b,m}.WB_{t=m}\right] \geq R_t \qquad \forall\, b,t \qquad (25)$$

3.4.2.2.3 Public transportation – railway

As mentioned before, though the subway stage (e) is operational in the year-calendar (t) it can operate below the capacity of that stage (Equation (26)). The binary variable $z_{e,t}$ affirm if the stage (e) is operational in the year-calendar (t). If it is operational, $z_{e,t}$ equal 1, otherwise is zero. Therefore, from Equation (26), the maximum operational capacity (the summation) increases as soon as the stages are built. The stage (e) can only start to operate after passed the lead-time (l) needed to construct the railways of the stage (e). Constraints (27) to (29) model this condition to stages 1, 2 and 3 respectively. Moreover, the next stage can only be built whether the previous stage is already built. This condition is modeled by Equations (30) and (31). The construction of each stage can only start once, as described by Equation (32).

$$x_t \leq PTr_t \sum_{e} C_e\, k_e z_{e,t} \qquad \forall\, t,\, e \qquad (26)$$

$$z_{e,t} \leq z_{e,\,t-1} + y_{e,t-l_1} \qquad \forall\, t \geq t_b + l_1,\; e = 1, t > 1 \qquad (27)$$

$$z_{e,t} \leq z_{e,\,t-1} + y_{e,t-l_1} \qquad \forall\, t \geq t_b + l_1 + l_2\,,\; e = 2, t > 1 \qquad (28)$$

$$z_{e,t} \leq z_{e,\,t-1} + y_{e,t-l_1} \qquad \forall\, t \geq t_b + l_1 + l_2 + l_3\,,\; e = 3, t > 1 \qquad (29)$$

$$y_{e,t} \leq y_{e-1,\,t-l_1} \qquad \forall\, t \geq t_b + l_1\,,\; e > 1 \qquad (30)$$

$$y_{e,t} \leq y_{e-1,\,t-l_2} \qquad \forall\, t \geq t_b + l_1 + l_2,\; e > 2 \qquad (31)$$

$$\sum_{e} y_{e,t} \leq 1 \qquad \forall\, t,\, e \qquad (32)$$

3.4.2.2.4 Transportation demand

The vehicles (c) operating in the city in the year-calendar (t) must to satisfy the demand for that year for individual transportation. This demand was expressed in person*km that is a transportation unit, and determined by Equation (33).

The number of vehicles (b) and the subway system operating in the city, in the year-calendar (t), must to supply the demand of public transportation, defined by constraint (34) and expressed in person*km.

$$\sum_{v} Pe_{c} \cdot \left(Fc^{0}_{c,t} \cdot Ucar^{0}_{c,t} + \sum_{m=tb}^{t} Ucar_{c,m} \cdot S_{c,m} \cdot WC_{t} \right) \geq D_{t}^{InT} \qquad \forall\, c, t \qquad (33)$$

$$x_{t} + \sum_{b} Pe_{b} \left\{ Fb^{0}_{b,t} \cdot Ubus^{0}_{b,t} + \sum_{m=tb}^{t} Ubus_{t,m} S_{v,m} WB_{t} \right\} \geq D_{t}^{PuT} \qquad \forall\, b, t \qquad (34)$$

3.4.2.2.5 Variable constraints

Finally, the variable of sales ($S_{c,t}$) must be positive and integer, rule by constraint (35).

$$S_{c,t} \geq 0,\ S_{c,t} \in \mathbb{Z}^{+} \qquad (35)$$

$$S_{b,t} \geq 0,\ S_{b,t} \in \mathbb{Z}^{+} \qquad (36)$$

$$y_{e,t} = \{0,1\},\ z_{e,t} = \{0,1\},\ x_{t} \in \mathbb{R}^{+} \qquad \forall\, t, e \qquad (37)$$

As aforementioned, the equations (1) to (37) defined the mathematical model of Mixed Integer Linear Programming (MILP) proposed. The computational results of such model are explored in Chapter 4.

4 RESULTS

Through the considerations and approaches described in the previous section, the following results were obtained.

4.1 BASE YEAR

4.1.1 Demand Vector

The amount of all activities demanded in the city in 2016 (base-year) were displayed as a vector in Table 28.

Table 28 – Demand vector in the base-year

Dataset Name	Unit	Amount
transport, motorcycle, use phase	p*km	1.04E+09
transport, passenger car, petrol	p*km	8.17E+09
transport, passenger car, ethanol	p*km	1.62E+09
transport, freight, light commercial vehicle -use phase	metric ton*km	0.00E+00
transport, urban bus, use phase	p*km	3.86E+09
market for transport, lorry, unspecify, use phase, BR	metric ton*km	6.69E+09
market for kerosene	kg	1.69E+06
market for petrol, unleaded	kg	4.50E+05
market for electricity, low voltage	kWh	1.49E+09
heat production, natural gas, at boiler atmospheric non-modulating <100kW	MJ	1.89E+08
market for electricity, low voltage	kWh	1.31E+09
heat production, natural gas, at boiler atmospheric non-modulating <100kW	MJ	1.92E+08
market for electricity, low voltage	kWh	3.77E+08
electricity, high voltage, production mix	kWh	1.32E+09
heat production, natural gas, at boiler atmospheric non-modulating <100kW	MJ	1.67E+09
heat and power co-generation, oil	MJ	4.44E+06
market for kerosene	kg	8.82E+04
electricity, high voltage, production mix	kWh	1.16E+07
market for electricity, low voltage	kWh	1.29E+06
market for liquefied petroleum gas	kg	8.58E+07
treatment of municipal solid waste, sanitary landfill	kg	-5.28E+08
market for hazardous waste, for underground deposit	kg	-3.80E+04
treatment of municipal solid waste, sanitary landfill	kg	-8.12E+07
treatment of municipal solid waste, sanitary landfill	kg	-8.12E+07
market for waste concrete	kg	-1.50E+07

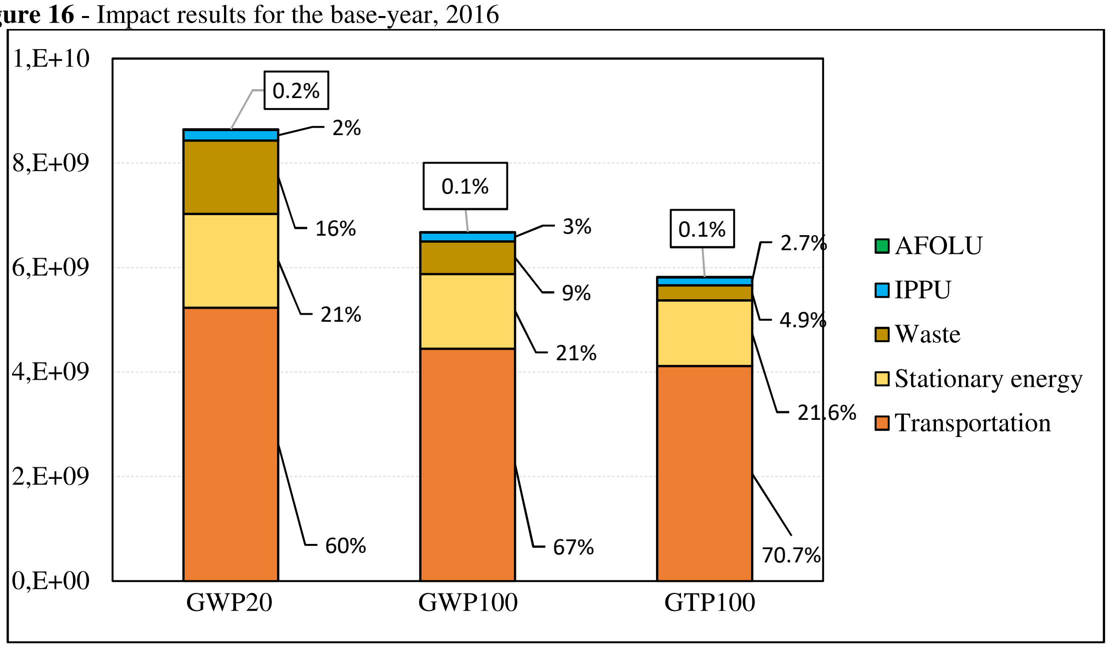
Table 28 – Demand vector in the base-year (continued)

Dataset Name	Unit	Amount
market for wastewater, from residence	m3	-4.09E+08
market for steel, unalloyed	kg	0.00E+00
market for sodium cyanide	kg	4.16E+05
market for solvent, organic	kg	2.12E+04
market for sodium hydroxide, without water, in 50% solution state	kg	1.35E+06
market for wire drawing, steel	kg	1.10E+05
market for hot rolling, steel	kg	5.88E+08
market for extrusion of plastic sheets and thermoforming, inline	kg	0.00E+00
market for steel, unalloyed	kg	1.48E+04
market for synthetic rubber	kg	1.83E+06
market for aluminum, cast alloy	kg	0.00E+00
market for hydrogen peroxide, without water, in 50% solution state	kg	1.46E+03
market for acetic acid, without water, in 98% solution state	kg	3.65E+07
market for solvent, organic	kg	8.40E+02
market for nitric acid, without water, in 50% solution state	kg	8.48E+04
market for sulfuric acid	kg	0.00E+00
market for nitrogen, liquid	kg	3.42E+05
market for sodium hydroxide, without water, in 50% solution state	kg	3.48E+05
market for ammonia, liquid	kg	1.83E+06
market for cement, Portland	kg	9.49E+04
market for gravel, crushed	kg	3.65E+07
market for sand	kg	2.20E+06
market for polymethyl methacrylate, sheet	kg	0.00E+00
market for sulfur	kg	2.15E+04
market for paraffin	kg	4.02E+06
market for zinc oxide	kg	1.00E+06
market for copper	kg	7.30E+02
paper production, newsprint, recycled	kg	1.64E+05
market for injection molding	kg	0.00E+00
market for roundwood, eucalyptus ssp. from sustainable forest management, under bark	m3	1.55E+06
market for sawnwood, board, softwood, raw, dried (u=20%)	m3	0.00E+00
market for medium density fiberboard	m3	1.14E+06
market for swine for slaughtering, live weight	kg	0.00E+00
market for steel, unalloyed	kg	0.00E+00
market for cast iron	kg	1.83E+03
market group for tap water	kg	2.46E+05
market for mastic asphalt	kg	0.00E+00
market for cow milk	kg	4.70E+05
market for maize grain	kg	3.30E+04
cattle for slaughtering, live weight to generic market for red meat, live weight	kg	3.96E+05
swine production	kg	3.60E+03
market for sheep for slaughtering, live weight	kg	1.35E+05

4.1.2 Life Cycle Impact Assessment Of The Base-Year

Through the linear algebra Equations described in Section 3, the potential impacts of climate change in the base-year in Curitiba were obtained, as showed in Figure 16.

Figure 16 - Impact results for the base-year, 2016



Transportation is the most pollutant sector for all impacts analyzed, followed by Stationary Energy and Waste sectors.

Shor-lived compounds, such as methane, commonly classified as near-term climate forcers, play a relevant role in Global Warming Potential for 20 years (GWP20) impact. While for long-term impacts the contribution is modest (FRISCHKNECHT; JOLLIET, 2016). Thus, Waste sector that emits high amount of methane, has a greater impact for GWP20 than for GWP100 or GTP100. Whereas, well-mixed greenhouse gases, such as carbon dioxide, are important for long-term impacts (FRISCHKNECHT; JOLLIET, 2016). Consequently, transportation activities have a greater participation for GTP100 than for other impacts, due to their contribution on CO2 emissions.

Passenger transportation by cars, motorcycle and urban bus represent 71% of the GWP100 impact category in the base-year, as shown in Table 29. Therefore, these activities are the priority and alternative technologies are suggested to minimize the GWP100 impact over the period under analysis.

Table 29 – Contribution of Transportation sector and its activities in the impacts of the base-year

	GWP20 ($Mt\ CO_2$ eq.)		GWP100 ($Mt\ CO_2$ eq.)		GTP100 ($Mt\ CO_2$ eq.)	
Subsector: Aviation						
market for kerosene	0.0011	0.02%	0.0010	0.02%	0.0009	0.02%
market for petrol, unleaded	0.0004	0.01%	0.0004	0.01%	0.0003	0.01%
Subsector: On Road						
market for transport, lorry, unspecified, use phase, BR	1.34	25.58%	1.27	28.46%	1.23	30.00%
transport, motorcycle, use phase	0.21	4.02%	0.15	3.29%	0.12	2.91%
transport, passenger car, ethanol	0.39	7.48%	0.37	8.40%	0.37	8.89%
transport, passenger car, petrol	2.17	41.59%	2.02	45.34%	1.95	47.31%
transport, urban bus, use phase	1.11	21.31%	0.64	14.48%	0.45	10.86%
Total	5.69	100.00%	4.90	100.00%	4.57	100.00%

4.1.3 Alternative Technologies

Focusing on transportation of passengers, the alternative technologies were chosen, classified by Public Transportation (PuT) and Individual Transportation (InT). These technologies are briefly described in sequence:

4.1.3.1 Public Transportation

Options of on-road public transportation were selected following the suggestion reported by "Alternativas tecnológicas para ônibus no Rio de Janeiro: relatório final"(COPPE; FETRANSPOR, 2012), and "Impactos ambientais da substituição dos ônibus urbanos por veículos menos poluentes" (AGENCIA NACIONAL DE TRANSPORTES TERRESTRES; VOLVO, 2016).

4.1.3.1.1 Biodiesel with 20% in composition (B20)

This alternative is highly political accepted (COPPE; FETRANSPOR, 2012, p. 57). In the use phase this technology has 15% less CO2 emission compared to diesel with 5% of biodiesel. It can be unfavorable in cold regions due to the possibilities to clog up the injectors, mainly the biodiesel has made by animal fat (AGENCIA NACIONAL DE TRANSPORTES

TERRESTRES; VOLVO, 2016; MYCLEANDISEL, 2018, p. 16). Microbiology contamination is another evident problem with B20. In São Paulo, 1200 vehicles stopped to operate in 2014, due to these problems (AGENCIA NACIONAL DE TRANSPORTES TERRESTRES; VOLVO, 2016, p. 16).

4.1.3.1.2 Trolleybus

Since 1949, in São Paulo, the trolleybus offers low noise and comfort travels for its passengers. In use phase, the emissions are actually low. In the *ecoinvent* dataset for trolley bus, the emissions concerning the climate change impact are almost zero, in the use phase (WERNET et al., 2016).

4.1.3.1.2.1. Compressed Natural Gas (CNG)

Natural gas reduce the internal and external noises. Market players, such as Volvo, MAN, Scania, Mercedez and Iveco, have vehicles dedicated to methane in Otto cycle engines. Other manufactures have been developing Dual Fuel engines, able to burn diesel and gas together (AGENCIA NACIONAL DE TRANSPORTES TERRESTRES; VOLVO, 2016, p. 22). Moreover, the use of natural gas and biofuels help to reduce the dependence of petroleum based fuels in public transportation, improving the energetic security of the nation (COPPE; FETRANSPOR, 2012, p. 34).

4.1.3.1.3 Biogas

All engines enable to operate with CNG can use biogas. This biogas have to be treated and purified to reach the same quality of the natural gas, with 90-99% of methane (AGENCIA NACIONAL DE TRANSPORTES TERRESTRES, 2016, p. 22).

4.1.3.1.4 Hybrid-electric bus (HBR)

Hybrid buses are already operating in Curitiba. This technology present higher cost of acquisition and maintenance compared to conventional vehicles. However, HBR can have up to 35% fuel economy. The tests in Curitiba obtained by Volvo show significant decrease in greenhouse gas emissions in the use phase (AGENCIA NACIONAL DE TRANSPORTES TERRESTRES; VOLVO, 2016, p. 26). This bus do not need a charging infrastructure as plug-in electric bus, and when considered the whole life cycle, it can reduce 30% of GHG emissions compared to conventional two-axle city bus (DREIER et al., 2018). The international experiences with hybrid bus confirm its better performance in terms of consumption at low and medium speed (COPPE; FETRANSPOR, 2012, p. 38).

4.1.3.1.5 Ethanol bus (E95)

It is a bus with Diesel cycle engine that consumes additivity ethanol. In the project BioEthanol for Sustainable Transport, the use of ethanol has demonstrated a significant reduction in greenhouse gases emissions during the use phase (FENTON et al., 2010, p. 88). Although the engine is prepared to operate with ethanol, it cannot accept diesel neither been converted to diesel.

4.1.3.1.6 Subway

The idea of set the subway as an alternative for public transportation in Curtiba, is based on a real project (CURITIBA, 2014). The project stages with its length of railways, number of trains and capacity is based on the “Projeto linha-azul” (MOBILIZE, 2010). The project data are summarized in Table 30.

Table 30 – Subway project in numbers

Project stage	Railway length (km)	Number of trains	Capacity	Construction lead-time (years)
1	13.16	1	60%	4
2	17.54	1	90%	3
3	21.90	2	100%	3

4.1.3.2 Individual Transportation

4.1.3.2.1 Natural gas

Otto cycle engines operating with natural gas are already in use. However, the emissions of this technology was not addressed to Transportation sector in the base-year. Thus, it is considered as an alternative technology to estimate how this option can contribute to reduce the GHG emissions.

4.1.3.2.2 Hybrid Electric Vehicle powered by petrol (HEVp)

Hybrid passenger cars are also present in the Brazilian fleet, but in small quantity less than 2500 units[2]. They are less pollutant due to lower fuel consumption when compared to conventional cars. The long-term scenarios show that the costs tend to decrease and the technologies to expand, enabling the rapid penetration of these technologies (EPE, 2016, p. 106).

4.1.3.2.3 Battery Electric Vehicle (BEV) plug-in

Battery electric vehicles are often a better option to reduce the GHG emissions. BEV present the lowest potential of climate change impact for Brazilian conditions, when compared to internal combustion engines or hybrid electric vehicles. However, the batteries must to be improved to reduce other impacts, such as human toxicity potential (DE SOUZA et al., 2018, p. 466).

4.1.4 Life Cycle Impact Of Alternative Technologies

Appling the approach mentioned in the Section 3, the following impacts (Table 31) of

[2] Including BEV

GWP100 for each technology were obtained. The impact of these technologies, which are business-as-usual and alternative technologies, were used in the optimization step.

Table 31 – Unitary impact of technologies for individual and public transportation

Alternative	Technology	Life cycle phase	Unit	GWP100 [kg/unit]
BAU	Passenger car, petrol	Operation	person*km	0.24694
	Passenger car, ethanol	Operation	person*km	0.39741
	Passenger car, petrol/natural gas/ethanol[1]	Sale	unit	7120.22
	Urban bus, production	Sale	unit	36340.79
	Urban bus B7	Operation	person*km	0.09669
	Urban bus B8	Operation	person*km	0.09661
	Urban bus B10	Operation	person*km	0.09646
	Urban bus B11	Operation	person*km	0.09639
	Urban bus B12	Operation	person*km	0.09632
	Urban bus B13	Operation	person*km	0.09624
	Urban bus B14	Operation	person*km	0.09617
	Urban bus B15	Operation	person*km	0.09609
NEW	Passenger car, BEV, without battery, production[1]	Sale	unit	8269.46147
	Passenger car, HEVp, without battery, production[1]	Sale	unit	8269.46147
	Passenger car, BEV	Operation	km	0.09331
	Passenger car, CNG	Operation	person*km	0.16572
	Passenger car, HEVp	Operation	person*km	0.12915
	Train, urban use phase	Operation	person*km	0.02022
	Train, passenger, long-distance, production	Sale	unit	3115051.56
	Railway track construction	Sale	m*year	58.40112
	Trolleybus	Operation	person*km	0.04030
	Urban bus, GNV	Operation	person*km	0.03326
	Urban bus, biogas	Operation	person*km	0.02385
	Urban bus, HBR	Operation	person*km	0.02780
	Urban bus, E95	Operation	person*km	0.03803
	Urban bus B20	Operation	person*km	0.09572

Notes: [1]Assuming that all cars weight 1000 kg.

The impacts of electric batteries are considered in the use phase of each vehicles. The reason is that the consumption of batteries is expressed in units per kilometer of transportation by these vehicles. In addition, the impacts of BEV and HEV vehicles are the same because it was considered the same weight for both types of vehicles.

4.2 Statistics of the MILP solution

During the execution of optimization models in CPLEX some parameters were set and conditions were observed, as illustrated in Table 32.

Table 32 – Statistics of MILP solutions

Description	Scenario 1	Scenario 2
Constraints	2419	2419
Variables		
Binary	144	144
Integer	288	288
Other	312	312
MILP solution		
Objective value	7.17E10	6.74E10
Nodes	909	1302
Iterations	3430	3449
Relative MIP gat tolerance	0.001	0.001
Other parameters	Default	Default
Time to solution	2.05 s	3.44 s

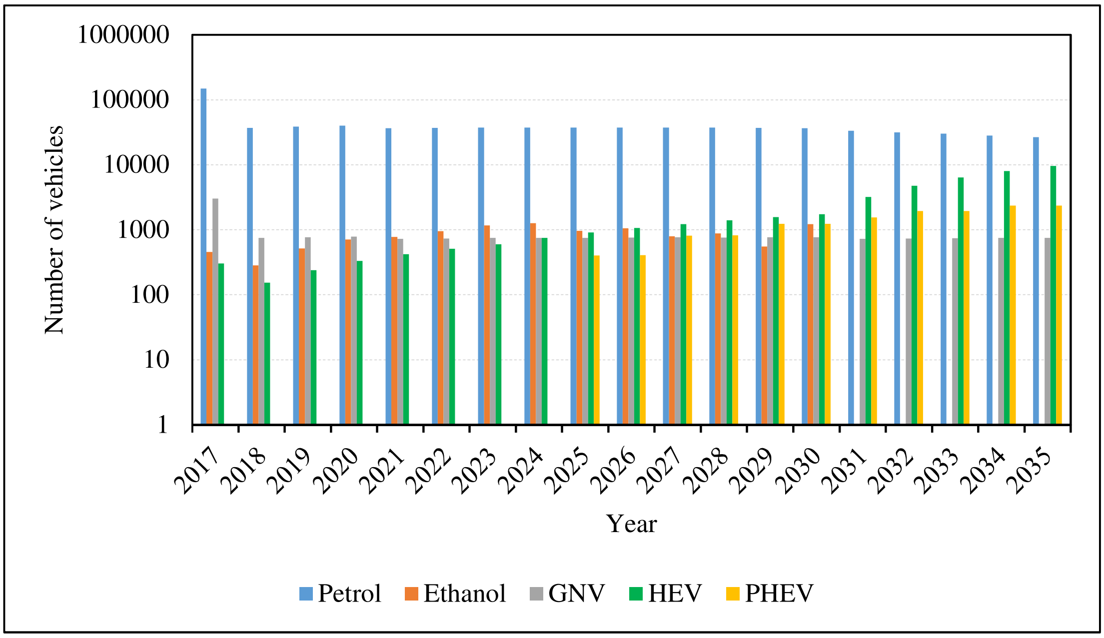
4.3 THE ROADMAPS

4.3.1 Scenario 1

In 2017, the number of petrol-based cars sold was high, reaching 147 thousand cars, meanwhile for the same year the sum of other alternatives were 3.7 thousand, as shown in. Figure 17.

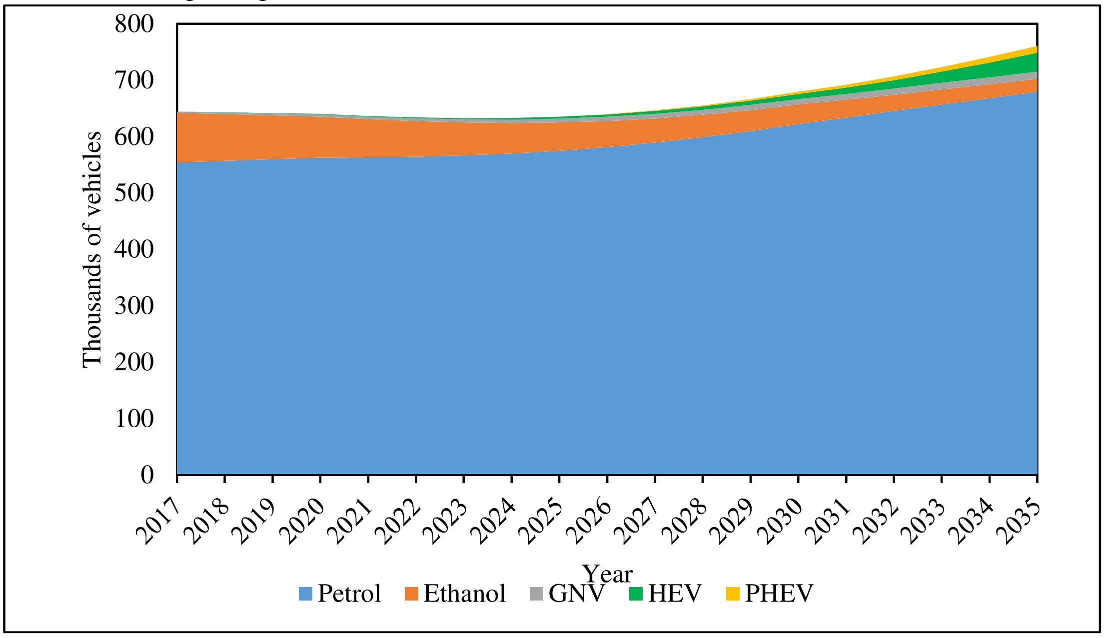
Following the trends of market share, implied by the constraints, Plug-in Battery Electric Vehicles (BEV) started the sales in 2026, reaching 2.3 thousand units sold in 2035. The number of vehicles for each year are presented in Table 52 , in Appendix.

Figure 17 – Sales of passenger cars in Scenario 1



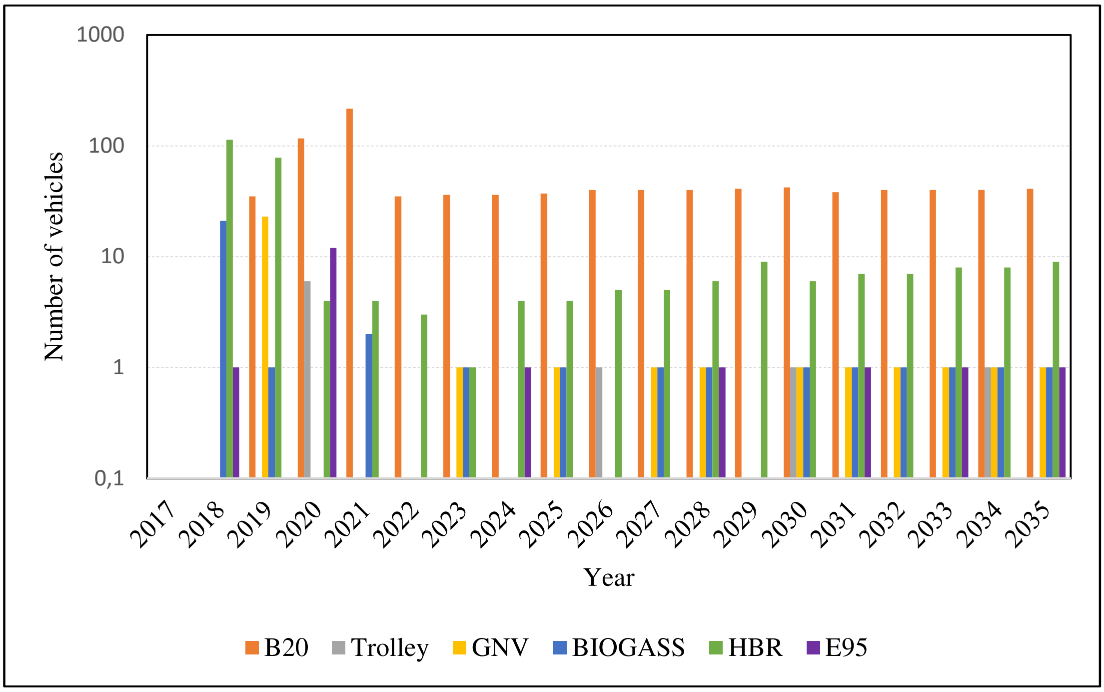
The increment of new alternative technologies decreases the dependence for petrol and ethanol fuels; hence, the fleet in 2035 is cleaner than in the base-year, as illustrated in Figure 18. From 2017 to 2023, the number of vehicles in operation decrease by the rate of 0.31% per year in average, then it start growing, and in 2035, there are more 116 thousand cars than in 2017. The share of cars using ethanol decreases along the years. On the other hand, the fleet of CNG, HEVp and BEV increases. In 2035, the fleet is 89% of petrol, 3% of ethanol, 2% of CNG, 2% of BEV, and 4% of HEV.

Figure 18 – Fleet of passenger cars for Scenario 1



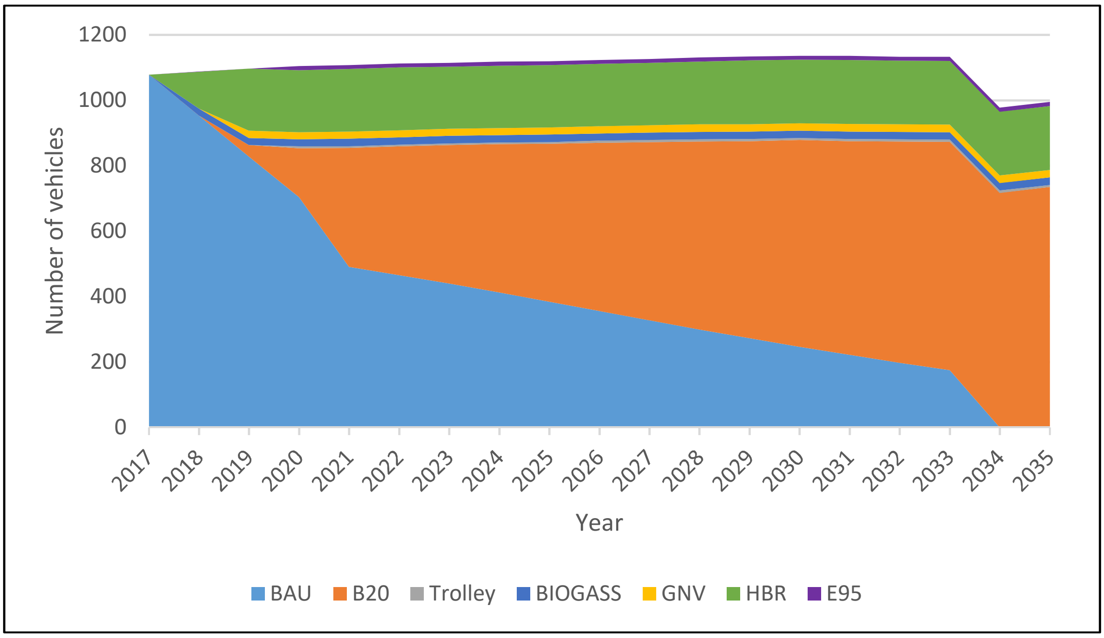
For public transportation, the results show that subway is not built during the period under analysis, due to its GWP100 impacts. This imply that urban buses must supply the public transportation demand. Business-as-usual fleet in operation, in 2017, is enough to support this demand, and the city does not need to purchase any additional vehicles, as observed in Figure 19. Conventional buses operating with 20% of biodiesel in the diesel mixture (B20) are 70% of all buses sold in the period. Only in 2018, new vehicles start to compose the fleet. The sales from 2018 to 2021 reflect the replacement of old vehicles, which is imposed by the constraint (22), where the renovation rate is 125 vehicles per year.

Figure 19 – Sales of buses in Scenario 1



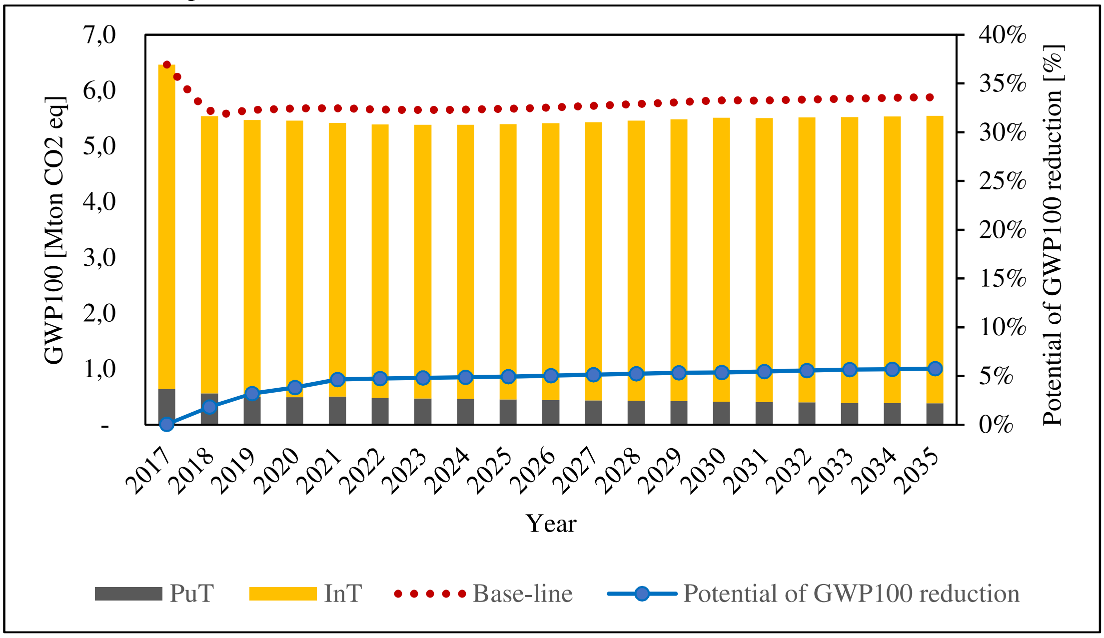
In 2034 the BAU technology is removed, due to its age. The cut-off age is 26 years old, i.e., the urban bus stops to operate. The number of vehicles in operation in the period is illustrated by Figure 20. The percentage of vehicles in operation in 2035 is 74% of B20, 1% of Trolleybus, 2% of CNG and BIOGAS, 20% of HBR, and 1% of E95.

Figure 20 – Fleet of buses in Scenario 1



Summing the impacts of sales and operation for Individual Transportation (InT) and Public Transportation (PuT), for vehicles and for subway (that is zero), the total impact arise. For Scenario 1, the maximum potential of impact reduction is 5% when compared to the base-line scenario, as shown in Figure 21.

Figure 21 – Total impact, Scenario 1

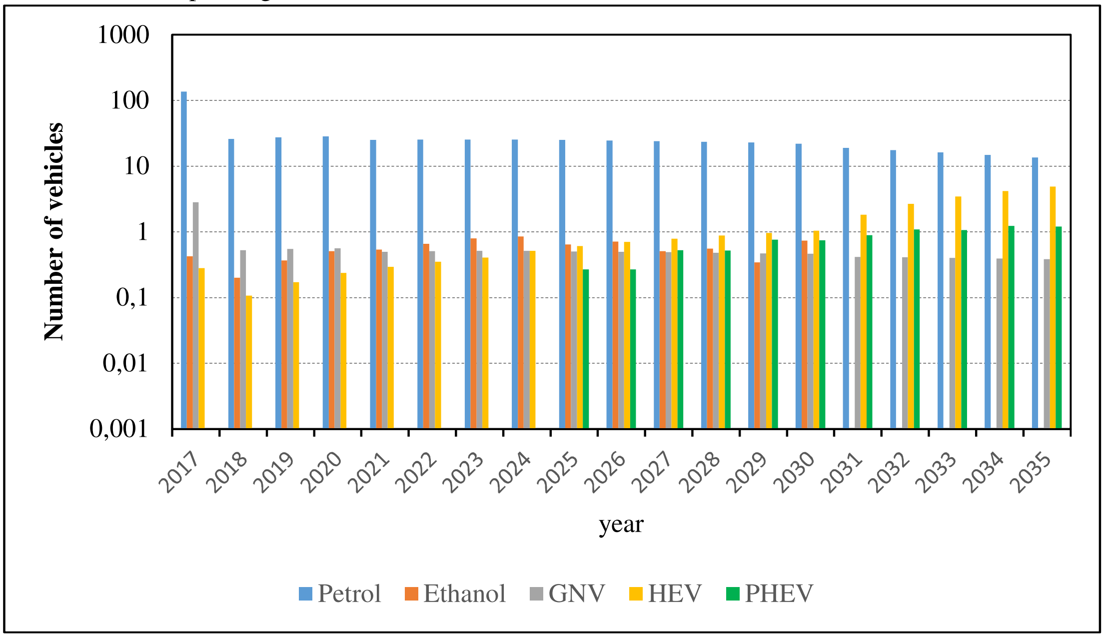


The baseline express the total impacts whether the city would keep the same technologies (petrol and ethanol for InT, and BAU for PuT) to supply the transportation demand. The dot line evidences the potential impact reduction over the years. i.e., the difference between optimized total impact and baseline impact.

4.3.2 Scenario 2

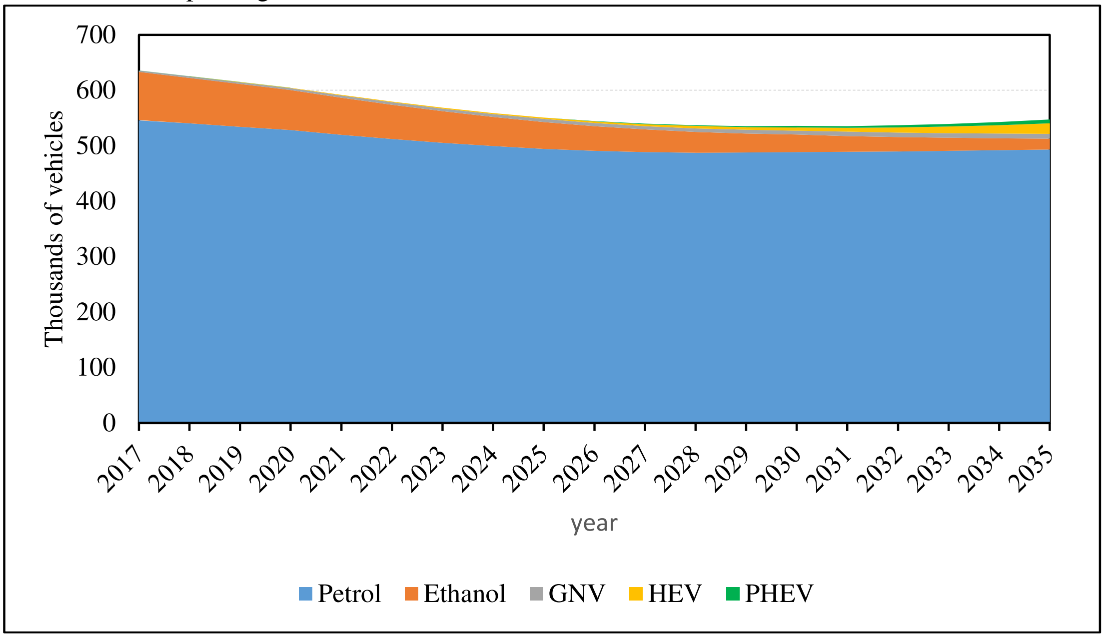
Scenario 2 takes into account an improvement in percentage of people using public transportation, which increase from 25% in 2017 to 40.5% in 2040, meanwhile the individual transportation decrease from 50% to 34.5% for the same period. These conditions imply in lower number of passenger cars sold, as described in Figure 22. For this scenario, 30% less vehicles are sold for the same period.

Figure 22 – Sales of passenger cars in Scenario 2



The fleet of passenger cars behaves differently from the scenario 1, as shown by Figure 23. The number of cars decreases along the period, totalizing 547,260 vehicles in 2035, 28% lower than in scenario 1.

Figure 23 – Fleet of passenger cars in Scenario 2



For public transportation, the sales (Figure 24) and consequently the fleet of buses (Figure 25) increase along the period. Scenario 2, present 814 more vehicles sold in the period compared to Scenario 1, which is 63% more vehicles. Consequently, in 2035, there is 1673 vehicles, 68% more than in Scenario 1.

Figure 24 – Sales of urban buses in Scenario 2

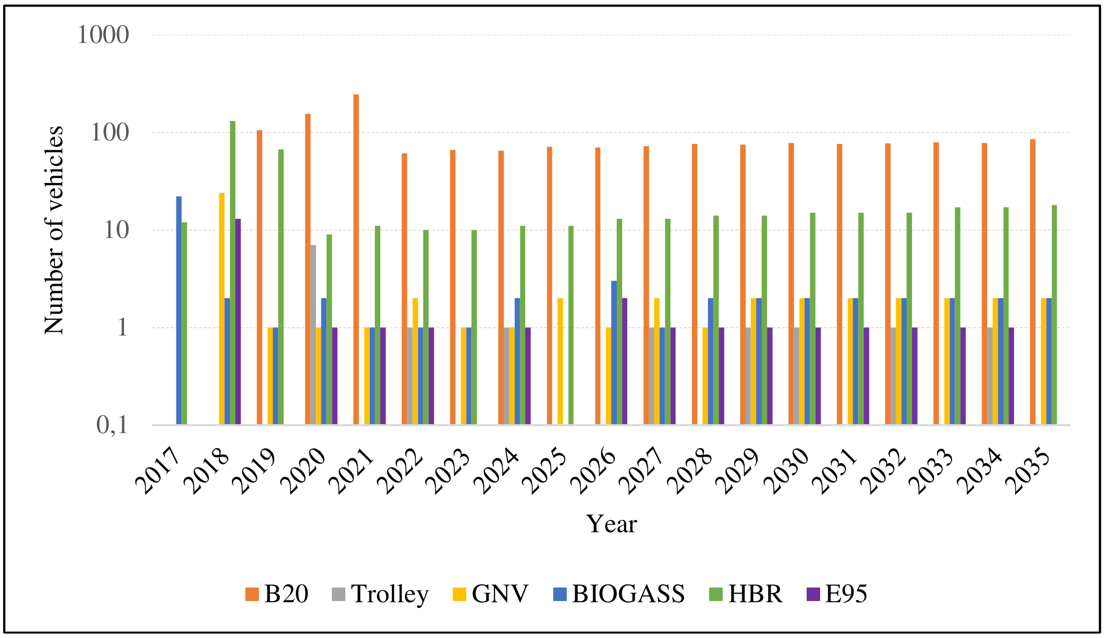
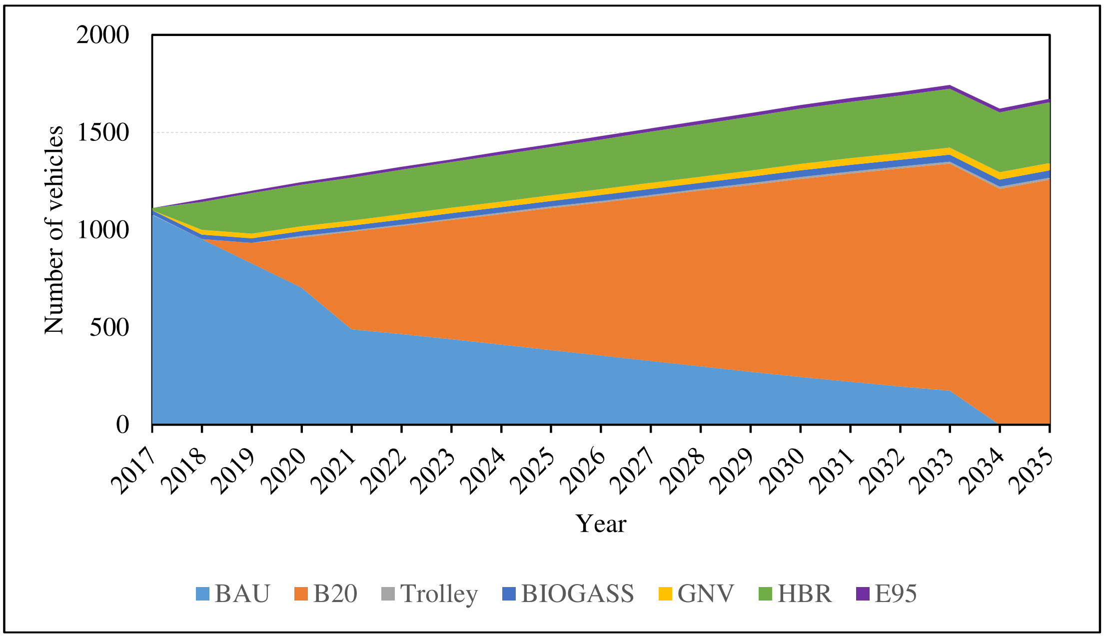
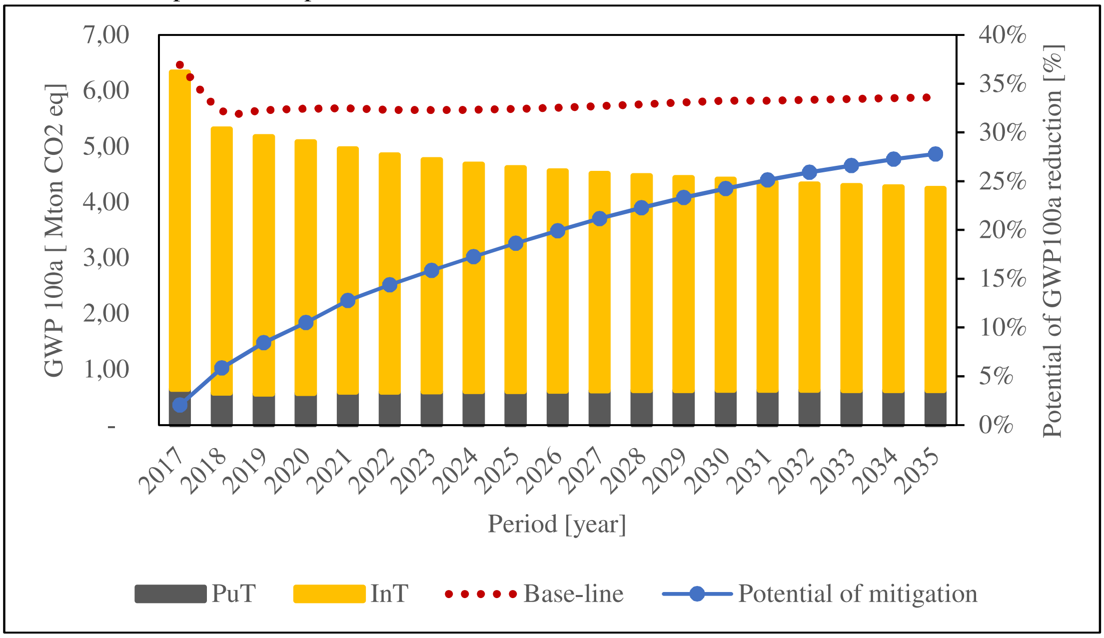


Figure 25 – Fleet of urban buses in Scenario 2



The improvement in public transportation implies in a better potential of impact reduction, as observed in Figure 26. Differently of scenario 1, in this scenario, the potential of GWP100 reduction reaches 28% in 2035, compared to the baseline scenario. That is, better conditions of public transportation could imply in greater share of population using this option and hence the global warming impacts would be lower.

Figure 26 – The impact roadmap in Scenario 2



4.3.3 Discussion And Recommendations

The improvements in public transportation, decreasing the demand of passenger cars (Scenario 2), is the best alternative for Curitiba in the period analyzed. Following this backcasting scenario, the city can prevent the emissions of 20 Mega tons of CO2 equivalent until 2035, just in the passenger transportation sector.

The potential of GWP100 reduction for both scenarios could be better whether the age of the business-as-usual fleet would be represented as a distribution instead of an average age, both for cars or buses.

Ethanol-based technology is the worst alternative available at the moment, due to the sugar-cane cultivation impact. This result reflect the use of *ecoinvent* dataset for ethanol production by Brazilian cultivation process. However, novel researches have been demonstrated improvements to produce ethanol from different feedstock, such as the third generation ethanol. Therefore, implement these alternatives in the problem addressed here could improve the results.

Concerning the trends of individual transportation, this research based on a conservative scenario for Brazil (EPE, 2016), but better scenarios for BEV and HEVp can arise soon. In addition, other optimist scenarios could be tested.

5 FINAL REMARKS

5.1 CONCLUSIONS

In order to solve the problem of how to decrease the emissions of greenhouse gases in cities, quantitative roadmaps for passenger transportation were developed by means of Life Cycle Assessment and mathematical optimization. These roadmaps provide a possible vision for the city of Curitiba, Brazil in the period of 2017-2035.

An integrated framework was suggested to estimate the potential climate change impacts of the city in the base-year (2016), and based on contribution analysis, define the priority sector to be tackled. LCA was used to estimate these impacts, which were GWP20, GWP20 and GTP100. Then, the problem of passenger transportation was modeled as a Mixed-Integer Linear Programing (MILP). This modelling approach was defined based on a literature review presented in Section 2.

To make the problem solvable, many decisions were taken, such as the activities considered, trends of exogenous variables and other factors. The emissions due to food consumption and transportation of goods were unconsidered. Indeed, these emissions could influence the final results; however, other studied have showed that energy and passenger transportation usually have higher impacts. In addition, eighteen datasets for transportation were created to accomplish the study. These datasets took into account information from public and private business reports. Other considerations concerned the choices to build the scenarios under analysis. Trends of population growth, demand of public and individual transportation, trends for electric and hybrid vehicles and options of alternative technologies are some examples assumed in this research.

Through the considerations, the following results were found. In the base-year, transportation alone has 70% of total impacts analyzed, followed by stationary energy and waste sectors. Therefore, transportation sector is the priority and options to improve the current profile were suggested and simulated. Two distinct scenarios were analyzed. One analyzed the optimum roadmap whether the share of passengers using public and individual transportation remained constant along the years. The second scenario identifies the optimum roadmap if an improvement occurs in public transportation. The second scenario is the best case. That is, the improvement in public transportation implies in a better potential of impact reduction reaching 28% the GWP100 reduction, when compared to the base-line scenario.

The methodology defined and used in this research can be applied in other cities. Adaptations of data may be necessary mainly for industrial processes and individual transportation. The optimization model needs to be adapted only for railway transportation, because the model considered the stages of Curitiba's subway project.

The results showed here are not a unique solution to mitigate the climate change in Curitiba over the period. But certainly, the methodology proposed and its outcome provide a good opportunity to decision takers and scientific community toward a greener future.

5.2 FUTURE WORKS

This research has presented a robust integrated methodology to estimate the city's impact and identify the optimum roadmaps. However, some improvements are welcome as suggested in sequence.

The approach applied to identify the global warming potential did not consider the food consumption emissions neither the transportation of goods. In addition, the electricity grid dataset used was the market for Brazilian electricity, which could be improved to take into account the grid of the state of Paraná.

For transportation sector, some technologies both for individual transportation and public transportation were analyzed, but other alternatives should be tested. In this research, passenger cars consuming ethanol presented as the worst alternative; nonetheless, third generation of ethanol would likely to have better results.

Finally, assuming that many data were naturally approximated, or sometimes inexistent, a sensibility analysis is recommended. This analysis can answer the question: how does stable is the outcomes if the data very?

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APPENDIX

A.1 DATASETS

Table 33 – Dataset: transport, passenger car, petrol, use phase

Activity Name: transport, passenger car, petrol, use phase
Unit Name: Km
Based on the *ecoinvent* dataset: transport, passenger car, small size, petrol, EURO 5, RoW

Considerations: The environmental emissions are considered the same as the original dataset.

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
transport, passenger car, petrol, use phase	BR	km	1.00E+00
market for petrol, 15% ETBE additive by volume, with ethanol from biomass	GLO	kg	-6.58E-02
market for road	RoW	m*year	-6.97E-04
market for brake wear emissions, passenger car	GLO	kg	5.77E-06
market for passenger car maintenance	GLO	unit	-6.45E-06
market for road wear emissions, passenger car	GLO	kg	1.27E-05
market for tyre wear emissions, passenger car	GLO	kg	7.43E-05

Table 34 – Dataset: transport, passenger car, ethanol, use phase

Activity Name: transport, passenger car, ethanol, use phase
Unit Name: Km
Based on the *ecoinvent* dataset: transport, passenger car, small size, petrol, EURO 5, RoW

Considerations: The environmental exchanges are based on 2007 values for passenger car, flex fuel technology (CETESB, 2016, p. 180).

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
transport, passenger car, ethanol, use phase	BR	km	1.00E+00
ethanol production from sugarcane	BR	kg	-1.01E-01
market for road	RoW	m*year	-6.97E-04
market for brake wear emissions, passenger car	GLO	kg	5.77E-06
market for passenger car maintenance	GLO	unit	-6.45E-06
market for road wear emissions, passenger car	GLO	kg	1.27E-05
market for tire wear emissions, passenger car	GLO	kg	7.43E-05

Environmental exchange

Elementary Flow Name	**Comp**	**Sub compartment**	**Unit Name**	**Amount**
Carbon monoxide, non-fossil	air	urban air close to ground	kg	4.92E-04
NMVOC, non-methane volatile organic compounds, unspecified origin	air	urban air close to ground	kg	8.70E-05
Methane, non-fossil	air	urban air close to ground	kg	3.90E-05
Nitrogen oxides	air	urban air close to ground	kg	6.10E-05
Aldehydes, unspecified	air	urban air close to ground	kg	2.12E-05
Carbon dioxide, non-fossil	air	urban air close to ground	kg	0.195
Dinitrogen monoxide	air	urban air close to ground	kg	1.70E-05

Table 35 – Dataset: transport, motorcycle, use phase

Activity Name: transport, motorcycle, use phase
Unit Name: Km
Based on the *ecoinvent* dataset: transport, passenger, motor scooter, RoW

Considerations: Consumption of petrol, is based on (BRASIL, 2013, n. Table 25)
Environmental exchanges are the same for activity original dataset

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
market for petrol, 15% ETBE additive by volume, with ethanol from biomass	GLO	kg	-2.08E-02
market for road	RoW	m*year	-8.38E-05
transport, motorcycle, use phase	RoW	person*km	1.00E+00
market for maintenance, motor scooter	GLO	unit	-1.82E-05

Table 36 – Dataset: transport, urban bus, B7, use phase

Activity Name: transport, urban bus, B7, use phase
Unit Name: Person*km
Based on the *ecoinvent* dataset: transport, regular bus, RoW

Considerations: The consumption of diesel is the sum of market for diesel, low sulfur from 'Europe without Switzerland' and 'RoW' from the original dataset. For diesel and biodiesel was considered the amount in 2016, which was 7% of biodiesel (LEI Nº 13.263).
The consumption is based on the information given by URBS (2016), considering the average consumption (L/km), total distance traveled in a year (km), the number of person transported (p) and the trip distance (km). Below, only the environmental exchanges modified from the original dataset are listed.

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
market for diesel, low-sulfur	RoW	kg	-9.56E-03
market for road	RoW	m*year	-4.57E-04
transport, urban bus, B7, use phase	BR	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-7.14E-08
esterification of soybean oil	BR	kg	-7.20E-04

Environmental exchange

Elementary Flow Name	**Comp**	**Sub compartment**	**Unit Name**	**Amount**
Carbon dioxide, fossil	air	unspecified	kg	0.073
Carbon dioxide, non-fossil	air	unspecified	kg	0.006
Carbon monoxide, fossil	air	unspecified	kg	0.0002135
Carbon monoxide, non-fossil	air	unspecified	kg	1.61E-05
Methane, fossil	air	unspecified	kg	1.497E-06
Methane, non-fossil	air	unspecified	kg	1.127E-07

Table 37 – Dataset: market for transport, freight, lorry - use phase, BR

Activity Name: transport, urban bus, B7, use phase
Unit Name: metric ton*km
Based on the *ecoinvent* dataset:

Considerations: The value of lorry 7.5-16 is the sum of 'leves' and 'medios'

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
transport, freight, lorry 3.5-7.5 metric ton, EURO3	RoW	metric ton*km	-0.06950296
transport, freight, lorry 7.5-16 metric ton, EURO3	RoW	metric ton*km	-0.34377658
transport, freight, lorry 16-32 metric ton, EURO3	RoW	metric ton*km	-0.28635851
transport, freight, lorry >32 metric ton, EURO3	RoW	metric ton*km	-0.30036195
market for transport, lorry, unspecified, use phase, BR	BR	metric ton*km	1

Table 38 – Dataset: transport, freight, lorry 3.5-7.5 metric ton, EURO3 - use phase

Activity Name: transport, freight, lorry 3.5-7.5 metric ton, EURO3, use phase
Unit Name: metric ton*km
Based on the *ecoinvent* dataset: transport, freight, lorry 3.5-7.5 metric ton, EURO3, RoW

Considerations: For diesel and biodiesel was considered the amount in 2016, which was 7% of biodiesel.

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
transport, freight, lorry 3.5-7.5 metric ton, EURO3 - use phase	RoW	metric ton*km	1
market for diesel, low-sulfur	RoW	kg	-1.03E-01
market for road	RoW	m*year	-1.95E-03
esterification of soybean oil	BR	kg	-7.78E-03
market for brake wear emissions, lorry	GLO	kg	4.13E-05
market for maintenance, lorry 16 metric ton	GLO	unit	-1.88E-06
market for road wear emissions, lorry	GLO	kg	3.56E-05

Environmental exchange

Elementary Flow Name	**Comp**	**Sub compartment**	**Unit Name**	**Amount**
Carbon dioxide, fossil	air	unspecified	kg	3.28E-01
Carbon dioxide, non-fossil	air	unspecified	kg	2.47E-02
Carbon monoxide, fossil	air	unspecified	kg	4.75E-04
Carbon monoxide, non-fossil	air	unspecified	kg	3.58E-05
Methane, fossil	air	unspecified	kg	2.13E-06
Methane, non-fossil	air	unspecified	kg	1.603E-07

Table 39 – Dataset: transport, freight, lorry 7.5-16 metric ton, EURO3 - use phase

Activity Name: transport, freight, lorry 3.5-7.5 metric ton, EURO3, use phase
Unit Name: metric ton*km
Based on the *ecoinvent* dataset: transport, freight, lorry 7.5-16 metric ton, EURO3 - RoW

Considerations: For diesel and biodiesel was considered the amount in 2016, which was 7% of biodiesel.

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
transport, freight, lorry 7.5-16 metric ton, EURO3 - use phase	RoW	metric ton*km	1.00E+00
market for diesel, low-sulfur	RoW	kg	-4.47E-02
esterification of soybean oil	BR	kg	-3.37E-03
market for road	RoW	m*year	-1.09E-03
market for brake wear emissions, lorry	GLO	kg	2.29E-05
market for maintenance, lorry 16 metric ton	GLO	unit	-5.63E-07
market for road wear emissions, lorry	GLO	kg	1.98E-05

Environmental exchange

Elementary Flow Name	**Comp.**	**Sub compartment**	**Unit Name**	**Amount**
Carbon dioxide, fossil	air	unspecified	kg	1.41E-01
Carbon dioxide, non-fossil	air	unspecified	kg	1.06E-02
Carbon monoxide, fossil	air	unspecified	kg	2.16E-04
Carbon monoxide, non-fossil	air	unspecified	kg	1.62E-05
Methane, fossil	air	unspecified	kg	9.96E-07
Methane, non-fossil	air	unspecified	kg	7.49E-08

Table 40 – Dataset: transport, freight, lorry 16-32 metric ton, EURO3 - use phase

Activity Name: transport, freight, lorry 16-32 metric ton, EURO3 - use phase
Unit Name: metric ton*km
Based on the *ecoinvent* dataset: transport, freight, lorry 16-32 metric ton, EURO3, RoW

Considerations: The value of lorry 7.5-16 is the sum of 'leves' and 'médios'.
For diesel and biodiesel was considered the amount in 2016, which was 7% of biodiesel

Economic exchanges

Product Name	**Geo**	**Unit Name**	**Amount**
transport, freight, lorry 16-32 metric ton, EURO3 - use phase	RoW	metric ton*km	1.00E+00
market for diesel, low-sulfur	RoW	kg	-3.52E-02
esterification of soybean oil	BR	kg	-2.65E-03
market for road	RoW	m*year	-1.05E-03
market for brake wear emissions, lorry	GLO	kg	2.22E-05
market for maintenance, lorry 16 metric ton	GLO	unit	-3.20E-07
market for road wear emissions, lorry	GLO	kg	1.91E-05

Environmental exchange

Elementary Flow Name	**Comp.**	**Sub compartment**	**Unit Name**	**Amount**
Carbon dioxide, fossil	air	unspecified	kg	1.10E-01
Carbon dioxide, non-fossil	air	unspecified	kg	8.31E-03
Carbon monoxide, fossil	air	unspecified	kg	1.79E-04
Carbon monoxide, non-fossil	air	unspecified	kg	1.34E-05
Methane, fossil	air	unspecified	kg	9.20E-07
Methane, non-fossil	air	unspecified	kg	6.92E-08

Table 41 – Dataset: transport, freight, lorry >32 metric ton, EURO3 - use phase

Activity Name: transport, freight, lorry 3.5-7.5 metric ton, EURO3, use phase
Unit Name: metric ton*km
Based on the *ecoinvent* dataset: transport, freight, lorry >32 metric ton, EURO3

Considerations: For diesel and biodiesel was considered the amount in 2016, which was 7% of biodiesel.

Economic exchanges

Product Name	Geo	Unit Name	Amount
transport, freight, lorry >32 metric ton, EURO3 - use phase	RoW	metric ton*km	1.00E+00
market for diesel, low-sulfur	RoW	kg	-1.82E-02
esterification of soybean oil	BR	kg	-1.37E-03
market for road	RoW	m*year	-1.09E-03
market for brake wear emissions, lorry	GLO	kg	1.69E-05
market for maintenance, lorry 16 metric ton	GLO	unit	-9.65E-08
market for road wear emissions, lorry	GLO	kg	1.46E-05

Environmental exchange

Elementary Flow Name	Comp.	Sub compartment	Unit Name	Amount
Carbon dioxide, fossil	air	unspecified	kg	5.81E-02
Carbon dioxide, non-fossil	air	unspecified	kg	4.37E-03
Carbon monoxide, fossil	air	unspecified	kg	8.95E-05
Carbon monoxide, non-fossil	air	unspecified	kg	6.74E-06
Methane, fossil	air	unspecified	kg	4.28E-07
Methane, non-fossil	air	unspecified	kg	3.22E-08

Table 42 – Dataset: transport, urban bus, B20 use phase

Activity Name: transport, urban bus,B20 use phase
Unit Name: metric ton*km
Based on the *ecoinvent* dataset: transport, regular bus, RoW

Considerations: Emission factors of P7 (Euro 5) with diesel mixture of 20% of biodiesel (ANTP; VOLVO, 2016)

Economic exchanges

Product Name	Geo	Unit Name	Amount
market for diesel, low-sulfur	RoW	kg	-8.23E-03
market for road	RoW	m*year	-4.57E-04
transport, urban bus,B20 use phase	BR	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-7.14E-08
esterification of soybean oil	BR	kg	-2.06E-03

Environmental exchange

Elementary Flow Name	Comp	Sub compartment	Unit Name	Amount
Carbon monoxide, fossil	air	urban air close to ground	kg	5.00E-06
Hydrocarbons, aliphatic, alkanes, unspecified	air		kg	1.88E-07
Particulates, > 2.5 um, and < 10um	air		kg	2.13E-06
Nitrogen oxides	air		kg	3.36E-05
Carbon dioxide, fossil	air		kg	1.95E-02
Carbon dioxide, non-fossil	air		kg	4.87E-03

43 – Dataset: Transport, regular bus, E95, use phase

Activity Name: Transport, regular bus, E95, use phase
Unit Name: person*km
Based on the *ecoinvent* dataset: transport, regular bus, RoW

Considerations:

Economic exchanges

Product Name	Geo	Unit Name	Amount
ethanol production from sugarcane	BR	kg	-7.37E-03
market for road	RoW	m*year	-4.57E-04
Transport, regular bus, E95, use phase	BR	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-7.14E-08

Environmental exchange

Elementary Flow Name	Comp.	Sub compartment	Unit Name	Amount
Carbon monoxide, non-fossil	air		kg	4.00E-07
Hydrocarbons, aliphatic, alkanes, unspecified	air	urban air close to ground	kg	2.00E-08
Nitrogen oxides	air		kg	2.29E-05
Particulates, > 2.5 um, and < 10um	air	unspecified	kg	1.05E-07

Table 44 – Dataset: Transport, regular bus, CNG, use phase

Activity Name: Transport, regular bus, CNG, use phase
Unit Name: person*km
Based on the *ecoinvent* dataset: transport, regular bus

Considerations:

Economic exchanges

Product Name	Geo	Unit Name	Amount
market for natural gas, high pressure	RoW	m3	-7.35E-03
market for road	RoW	m*year	-4.57E-04
Transport, regular bus, CNG, use phase	BR	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-7.14E-08
market for natural gas, high pressure	RoW	m3	-7.35E-03

Environmental exchange

Elementary Flow Name	Comp	Sub compartment	Unit Name	Amount
Carbon monoxide, fossil	air		kg	1.25E-07
Hydrocarbons, aliphatic, alkanes, unspecified	air		kg	1.31E-07
Particulates, > 2.5 um, and < 10um	air	urban air close to ground	kg	1.60E-07
Nitrogen oxides	air		kg	3.36E-05
Carbon dioxide, fossil	air		kg	2.03E-02

Table 45 – Dataset: Transport, regular bus, HBR, use phase

Activity Name: Transport, regular bus, HBR, use phase
Unit Name: person*km
Based on the *ecoinvent* dataset: transport, regular bus
Considerations:

Economic exchanges

Product Name	Geo	Unit Name	Amount
market for diesel, low-sulfur	RoW	kg	-2.70E-03
market for road	RoW	m*year	-4.57E-04
Transport, regular bus, HBR, use phase	BR	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-7.14E-08
esterification of soybean oil	BR	kg	-3.00E-04

Environmental exchange

Elementary Flow Name	Comp	Sub compartment	Unit Name	Amount
Hydrocarbons, aliphatic, alkanes, unspecified	air	urban air close to ground	kg	1.23E-07
Nitrogen oxides	air		kg	1.58E-05
Carbon dioxide, fossil	air	unspecified	kg	1.31E-02
Carbon dioxide, non-fossil	air	unspecified	kg	1.45E-03
Carbon monoxide, non-fossil	air	unspecified	kg	6.35E-07
Particulates, > 2.5 um, and < 10um	air	unspecified	kg	1.76E-07
Carbon monoxide, fossil	air	unspecified	kg	5.72E-06

Table 46 – Dataset: Transport, regular bus, biogas, use phase

Activity Name: Transport, regular bus, HBR, use phase
Unit Name: person*km
Based on the *ecoinvent* dataset: transport, regular bus

Considerations:

Economic exchanges

Product Name	Geo	Unit Name	Amount
biogas purification to methane 96 vol-%	RoW	m3	-7.35E-03
market for road	RoW	m*year	-4.57E-04
Transport, regular bus, biogas, use phase	BR	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-7.14E-08

Environmental exchange

Elementary Flow Name	Comp.	Sub compartment	Unit Name	Amount
Carbon monoxide, non-fossil	air	urban air close to ground	kg	1.25E-07
Hydrocarbons, aliphatic, alkanes, unspecified	air		kg	1.31E-07
Nitrogen oxides	air		kg	3.36E-05
Carbon dioxide, non-fossil	air		kg	2.03E-02
Particulates, > 2.5 um, and < 10um	air	Unspecified	kg	1.60E-07

Table 47 – Dataset: Transport, trolleybus, use phase

Activity Name:	Transport, regular bus, HBR, use phase		
Unit Name:	person*km		
Based on the *ecoinvent* dataset:	Transport, trolleybus		
Considerations:	As a use phase dataset, the construction of trolley bus is not considered. The emissions of use were maintained as the same of the original dataset. The electricity was changed to BR geography.		
Economic exchanges			
Product Name	**Geo**	**Unit Name**	**Amount**
market for road	RoW	m*year	-5.30E-04
Transport, trolleybus, use phase	RoW	person*km	1.00E+00
market for maintenance, bus	GLO	unit	-5.03E-08
market for electricity, medium voltage	BR	kWh	-1.17E-01

Table 48 – Dataset: transport, subway, use phase

Activity Name:	***Transport, subway,*** **use phase**		
Unit Name:	person*km		
Based on the *ecoinvent* dataset:	Transportation, train		
Considerations:	As a use phase dataset, the construction of train is not considered. The emissions of use were maintained as the same of the original dataset. The electricity geography was changed to BR.		
Economic exchanges			
Product Name	**Geo**	**Unit Name**	**Amount**
electricity, high voltage, production mix	BR	kWh	-0.082664
market for maintenance, train, passenger, l distance	GLO	unit	-1.08E-09
transport, train, urban use phase	BR	person*km	1.00E+00

Table 49 – Dataset: transport, passenger car, small size, natural gas, EURO 5, use phase

Activity Name:	transport, passenger car, small size, natural gas, EURO 5, use phase		
Unit Name:	km		
Based on the *ecoinvent* dataset:	transport, passenger car, small size, natural gas, EURO 5		
Considerations:	The emissions are considered the same as the original dataset		
Economic exchanges			
Product Name	**Geo**	**Unit Name**	**Amount**
market for natural gas, high pressure	RoW	m3	-6.23E-02
market for road	RoW	m*year	-6.97E-04
transport, passenger car, small size, natural gas, EURO 5, use phase	RoW	km	1.00E+00
market for brake wear emissions, passenger car	GLO	kg	5.77E-06
market for passenger car maintenance	GLO	unit	-6.45E-06
market for road wear emissions, passenger car	GLO	kg	1.27E-05
market for tyre wear emissions, passenger car	GLO	kg	7.43E-05

Table 50 – Dataset: transport, passenger car, HEVp, use phase

Activity Name:	transport, passenger car, HEVp, use phase
Unit Name:	km
Based on the *ecoinvent* dataset:	transport, passenger car, small size, petrol, EURO 5, RoW
Considerations:	Emission and consumption were based on Toyota Prius NGA 1.8 16v 2018 (PETROBRAS, 2018)

Economic exchanges

Product Name	**Geography**	**Unit Name**	**Amount**
transport, passenger car, HEVp, use phase	GLO	km	1.00E+00
market for petrol, 15% ETBE additive by volume, with ethanol from biomass	GLO	kg	-4.07E-02
market for road	RoW	m*year	-6.97E-04
market for brake wear emissions, passenger car	GLO	kg	5.77E-06
market for passenger car maintenance	GLO	unit	-6.45E-06
market for road wear emissions, passenger car	GLO	kg	1.27E-05
market for tyre wear emissions, passenger car	GLO	kg	7.43E-05

Environmental exchange

Elementary Flow Name	**Comp**	**Sub compartment**	**Unit Name**	**Amount**
Carbon monoxide, fossil	air	urban air close to ground	kg	3.80E-05
NMVOC, non-methane volatile organic compounds, unspecified origin	air	urban air close to ground	kg	6.00E-06
Nitrogen oxides	air	urban air close to ground	kg	6.00E-06
Carbon dioxide, fossil	air	urban air close to ground	kg	7.10E-02

Table 51 – Dataset: transport, passenger car, BEV, use phase

Activity Name:	transport, passenger car, BEV, use phase
Unit Name:	km
Based on the *ecoinvent* dataset:	Transport, passenger car, electric [GLO]
Considerations:	The battery consumption is included in this dataset

Economic exchanges

Product Name	**Geography**	**Unit Name**	**Amount**
market for road	RoW	m*year	-4.83E-04
market for brake wear emissions, passenger car	GLO	kg	1.05E-06
market for maintenance, passenger car, electric, without battery	GLO	unit	-6.67E-06
market for road wear emissions, passenger car	GLO	kg	1.16E-05
market for tyre wear emissions, passenger car	GLO	kg	6.76E-05
market for electricity, low voltage	BR	kWh	-1.99E-01
transport, passenger car, electric, use phase	GLO	km	1.00E+00
market for battery, Li-ion, rechargeable, prismatic	GLO	kg	-2.62E-03

A.2 Sales Of Vehicles

Table 52 - Sales for Individual Transportation in Scenario 1

	Petrol	Ethanol	CNG	BEV	HEVp
2017	147275	454	3021	0	302
2018	36836	282	745	0	152
2019	38432	513	767	0	239
2020	39565	708	782	0	331
2021	36351	775	719	0	420
2022	36798	945	732	0	506
2023	36998	1154	742	0	592
2024	37101	1252	749	0	749
2025	37145	958	750	401	903
2026	37089	1051	754	403	1061
2027	37053	787	759	812	1218
2028	36940	874	758	815	1386
2029	36884	551	762	1229	1557
2030	36212	1211	765	1234	1728
2031	33107	0	720	1541	3176
2032	31273	0	731	1934	4751
2033	29803	0	737	1940	6334
2034	27922	0	743	2335	7925
2035	26402	0	748	2340	9517

Table 53 - Sales for Public Transportation in Scenario 1

	BAU	B20	Trolley	GNV	BIOGASS	HBR	E95
2017	0	0	0	0	0	0	0
2018	0	0	0	0	21	113	1
2019	0	35	0	23	1	78	0
2020	0	116	6	0	0	4	12
2021	0	216	0	0	2	4	0
2022	0	35	0	0	0	3	0
2023	0	36	0	1	1	1	0
2024	0	36	0	0	0	4	1
2025	0	37	0	1	1	4	0
2026	0	40	1	0	0	5	0
2027	0	40	0	1	1	5	0
2028	0	40	0	1	1	6	1
2029	0	41	0	0	0	9	0
2030	0	42	1	1	1	6	0
2031	0	38	0	1	1	7	1
2032	0	40	0	1	1	7	0
2033	0	40	0	1	1	8	1
2034	0	40	1	1	1	8	0
2035	0	41	0	1	1	9	1

Table 54 - Sales for Individual Transportation in Scenario 2

	Petrol	Ethanol	CNG	BEV	HEVp
2017	136530	421	2800	0	280
2018	25934	199	524	0	107
2019	27362	365	546	0	170
2020	28286	507	559	0	236
2021	25142	536	497	0	291
2022	25417	652	506	0	350
2023	25388	792	509	0	406
2024	25206	851	509	0	509
2025	24873	642	502	268	605
2026	24455	706	497	266	700
2027	23908	507	490	524	786
2028	23374	554	479	516	877
2029	22781	342	470	759	961
2030	21811	730	461	743	1041
2031	18993	0	413	884	1822
2032	17469	0	408	1080	2653
2033	16186	0	400	1054	3440
2034	14725	0	392	1231	4179
2035	13508	0	383	1197	4869

Table 55 - Sales for Public Transportation in Scenario 2

	BAU	B20	Trolley	GNV	BIOGASS	HBR	E95
2017	0	0	0	0	22	12	0
2018	0	0	0	24	2	131	13
2019	0	105	0	1	1	67	0
2020	0	155	7	1	2	9	1
2021	0	246	0	1	1	11	1
2022	0	61	1	2	1	10	1
2023	0	66	0	1	1	10	0
2024	0	65	1	1	2	11	1
2025	0	71	0	2	0	11	0
2026	0	70	0	1	3	13	2
2027	0	72	1	2	1	13	1
2028	0	76	0	1	2	14	1
2029	0	75	1	2	2	14	1
2030	0	78	1	2	2	15	1
2031	0	76	0	2	2	15	1
2032	0	77	1	2	2	15	1
2033	0	79	0	2	2	17	1
2034	0	78	1	2	2	17	1
2035	0	85	0	2	2	18	0

ATTACHEMENTS

Table 56 – Intensity of use

Age [years]	Passenger cars, Otto cycle [km/year]	Motorcycle [km/year]	Urban bus [km/year]
0	10000	6000	45997
1	19400	11600	88443
2	18800	11200	84892
3	18200	10800	81341
4	17600	10400	77790
5	17000	10000	74240
6	16400	9600	70689
7	15800	9200	67138
8	15200	8800	63587
9	14600	8400	60036
10	14000	8000	56485
11	13400	7600	52935
12	12800	7200	49384
13	12200	6800	45833
14	11600	6400	42282
15	11000	6000	38731
16	10400	5600	35180
17	9800	5200	31630
18	9200	4800	28079
19	8600	4400	24528
20	8000	4000	20977
21	7400	3600	17426
22	6800	3200	13875
23	6200	2800	10324
24	5600	2400	6774
25	5000	2000	3223
26	4400	2000	0
27	3800	2000	0
28	3200	2000	0
29	2600	2000	0
30	2000	2000	0
31	2000	2000	0
32	2000	2000	0
33	2000	2000	0
34	2000	2000	0
35	2000	2000	0
36	2000	2000	0
37	2000	2000	0
38	2000	2000	0
39	2000	2000	0

Table 56 – Intensity of use (continued)

Age [years]	Passenger cars, Otto cycle [km/year]	Motorcycle [km/year]	Urban bus [km/year]
40	2000	2000	0
41	2000	2000	0
42	2000	2000	0
43	2000	2000	0
44	2000	2000	0
45	2000	2000	0
46	2000	2000	0
47	2000	2000	0
48	2000	2000	0
49	2000	2000	0
50	2000	2000	0

Source: (BRASIL, 2013, n. Table 34)

Table 57 – Fuel consumption for cars in km/L

Model-year	**Category**	**Petrol**	**Ethanol**	**Flex Fuel**	
				Petrol	**Ethanol**
1957 a 1982	Cars and light commercial vehicles	8.9	7.1	-	-
1983	Cars and light commercial vehicles	9.65	7.9	-	-
1984	Cars and light commercial vehicles	10.19	8.25	-	-
1985	Cars and light commercial vehicles	10.39	8.54	-	-
1986	Cars and light commercial vehicles	10.42	8.46	-	-
1987	Cars and light commercial vehicles	10.64	8.52	-	-
1988	Cars and light commercial vehicles	10.86	8.58	-	-
1989	Cars and light commercial vehicles	11.07	8.65	-	-
1990	Cars and light commercial vehicles	11.82	8.65	-	-
1991	Cars and light commercial vehicles	11.82	8.65	-	-
1992	Cars and light commercial vehicles	10.98	8.01	-	-
1993	Cars and light commercial vehicles	10.98	8.54	-	-
1994	Cars and light commercial vehicles	10.04	7.54	-	-
1995	Cars and light commercial vehicles	10.04	7.54	-	-
1996	Cars and light commercial vehicles	11.04	7.17	-	-
1997	Cars and light commercial vehicles	11.04	7.17	-	-
1998	Cars and light commercial vehicles	11.82	7.41	-	-
1999	Cars and light commercial vehicles	11.82	8.01	-	-
2000	Cars and light commercial vehicles	11.89	6.96	-	-
2001	Cars and light commercial vehicles	11.97	6.96	-	-
2002	Cars and light commercial vehicles	10.9	7.2	-	-
2003	Cars and light commercial vehicles	11.2	7.5	10.3	6.9
2004	Cars and light commercial vehicles	11.4	8.6	10.8	7.3
2005	Cars and light commercial vehicles	11.3	8.6	11.5	7.7
2006	Cars and light commercial vehicles	11.3	6.9	11.7	7.8
2007	Cars and light commercial vehicles	11.3	6.9	11.7	7.8

Table 57 – Fuel consumption for cars in km/L (continued)

Model-year	Category	Petrol	Ethanol	Flex Fuel	
				Petrol	Ethanol
2008	Cars and light commercial vehicles	9.74	6.9	11.7	7.38
2009	Cars	9.9	-	11.5	7.8
	Light commercial vehicles	8.3	-	8.3	6.9
2010	Cars	10.4	-	12.2	8.3
	Light commercial vehicles	8.8	-	8.2	6.8
2011	Cars	11.2	-	12.2	8.6
	Light commercial vehicles	9.9	-	9	6.3
2012	Cars	11.3	-	12.2	8.5
	Light commercial vehicles	9.9	-	9.1	6.2

Source: (BRASIL, 2013, n. Table 24)

Table 58 – Fuel consumption for motorcycles

Model-year	Petrol (km/L)
Until 2003	37.38
2004	37.45
2005	37.45
2006	37.2
2007	37.09
2008	37.2
2009	37.27
2010	37.04
2011	36.14
2012	37.19

Source: (BRASIL, 2013, n. Table 25)