Doctoral Program in Transportation Systems

A decision support system for policy design and assessment of sustainable mobility in emerging cities

Juan Camilo Medina Arguello

Submitted in partial fulfilment of the requirements for the degree of Doctor in Transportation Systems

Supervisors:
Professor Jorge Pinho de Sousa
Faculty of Engineering, University of Porto
Professor Edgar Ramiro Jimenez Pérez
School of Aerospace, Transport and Manufacturing, Cranfield University

Faculty of Engineering, University of Porto
October 2020

This research was supported by the Ph.D. Grant funded by the NORTE-08-5369-FSE-000038, supported by the Northern Portugal Regional Operational Program (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Social Fund (ESF).

To God

For giving me the opportunity to live and for being with me at every step I take, for strengthen my heart and illuminate my mind and for have put in my way those people who have been my support and company during this study period.

Acknowledgements

The road was long but fruitful. There are many people who have contributed to the process and conclusion of my doctoral project. Without their support, the development of this research would not have been possible. I would like, therefore, to express them my sincere thanks.

First, to the director of the doctoral program and my supervisor, Professor Jorge Pinho de Sousa, for his friendship, confidence and support. His guidance was fundamental to the maturation of my research ideas, which are now consolidated in this thesis.

I would also like to thank Professor Edgar Ramiro Jiménez, who co-supervised my research with Professor Jorge, for his guidance during the development of this thesis, for everything he taught me, for trusting me, for his time, patience, advice, and for the encouragement he has always given me during this important stage of my life.

My deep thanks to CCDR-N for having funded my studies at FEUP (through a scholarship of the NORTE 2020 program).

To Professor Andrés Felipe Valderrama and Aalborg University in Copenhagen, for their collaboration and for having given me the opportunity to acquire invaluable knowledge and experiences for my research and for my life. In Copenhagen, I also met Professor Henrik Gudmunsson, whose work was an extremely important contribution for the development and fulfilment of the objectives of this research.

To the 19 sustainability experts from various countries who answered the questionnaire and attended the semi-structured interviews, and also to the 105 people with interest in sustainability topics who answered the survey and gave me relevant feedback that was taken into account in the development of the thesis.

To all my classmates and professors of the Doctoral Program in Transportation Systems, with whom I have shared good times, for their contributions both in my professional and personal development.

Finally, but most importantly, I wish to express my sincere thanks to my family, who are my greatest motivation in life, at work and in these academic processes. To my parents, Fabiola

Arguello and Arturo Medina, and to my brother, José Arturo Medina, for their unconditional support.

A decision support system for policy design and assessment of sustainable mobility in emerging cities

Abstract

The significant economic and social changes in emerging cities, as well as the urgency of environmental protection, make sustainable urban mobility planning a very critical issue. In such context, enhancing the sustainability of mobility systems is increasingly important, and, though sustainability is quite difficult to be measured directly, it can be assessed through a series of parameters reflecting its multiples aspects.

These concerns require a shift in paradigm to understand mobility requirements. We must guarantee a constant monitoring and evaluation of the actions implemented to improve sustainability, through acceptable methodological tools. The definition of adequate *indicators* constitutes an essential part of this process. This research, therefore, proposes a set of indicators, grouped in five different dimensions, as a tool for the assessment of sustainability in mobility system, for the specific context of *emerging cities*.

These dimensions and indicators are based on a comprehensive literature review on the evaluation of sustainability in urban mobility systems; and are subsequently validated with experts, through surveys, semi-structured interviews and statistical analysis, to identify the significance of the indicators and their priority within the selected dimensions. Since the validity of these dimensions is heavily dependent on how their components are weighted, it was necessary to design a sound framework of prioritized sustainability measures to support transportation managers in their policy making processes. Consequently, a specific *conceptual framework* to assess sustainability in mobility systems was developed using multi-criteria decision analysis methods.

Since transportation systems are largely complex systems, the assessment and measurability of their performance, regarding sustainability, are crucial for implementing more effective decisions. In such context, this research develops a *decision support system* (*DSS*) for the design of sustainability mobility policies in the case of emerging cities. The approach is based on a *system dynamics* model to represent the relationships between stated and flow variables, organized as feedback loops.

For that purpose, we have developed a model intended to analyze the *cause-and-effect* relationships in a system that integrates high-level policies, specific strategies and actions, and a sub-system to measure the impact of those policies and actions, in terms of sustainability. This multi-layered model analyzes how the different factors change over time, and visualizes the impact of those factors on "*a more sustainable mobility system*". Analyzed policies were designed around the ideas of: green mobility; mobility for health and wellbeing; mobility for competitiveness and quality of life; integrating mobility and land use; and modern governance for efficient and safe mobility.

Keywords: sustainability; sustainable urban mobility; mobility planning; indicators; policy design; multi-criteria decision analysis; system dynamics; emerging cities.

Um sistema de apoio à decisão para o desenho de políticas e avaliação da mobilidade sustentável em cidades emergentes

Resumo

As constantes mudanças económicas e sociais nas cidades emergentes, bem como a urgência da proteção ambiental, fazem do planeamento da mobilidade urbana, uma questão muito crítica. Neste contexto, melhorar os sistemas de mobilidade em termos ambientais é cada vez mais importante e, embora seja bastante difícil de ser medida diretamente, a sustentabilidade desses sistemas poderá antes ser avaliada através de uma série de parâmetros que reflitam adequadamente os seus múltiplos aspetos.

Estas preocupações exigem uma mudança de paradigma no que se refere aos requisitos da mobilidade. É necessário garantir uma constante monitorização e avaliação das ações implementadas para melhorar a sustentabilidade, através de ferramentas metodológicas adequadas. A definição de indicadores constitui parte essencial deste processo. Nesse sentido, esta investigação propõe um conjunto de indicadores, agrupados em cinco dimensões diferentes, como ferramenta de avaliação da sustentabilidade de um sistema de mobilidade, para o contexto específico das cidades emergentes.

Essas dimensões e indicadores são baseados numa revisão abrangente da literatura sobre a avaliação da sustentabilidade em sistemas de mobilidade urbana; e foram validados com especialistas, por meio de inquéritos, entrevistas semiestruturadas e análise estatística, procurando-se assim identificar a significância dos indicadores e a sua prioridade nas dimensões selecionadas. Como a validade dessas dimensões depende fortemente dos "pesos" atribuídos aos seus componentes, foi necessário desenvolver um sistema de medidas de sustentabilidade priorizadas, para apoiar os gestores da mobilidade na elaboração de políticas. Na sequência, foi desenvolvido um quadro conceptual específico ("framework") para avaliar a sustentabilidade em sistemas de mobilidade usando métodos de análise multi-critério.

Como os sistemas de transporte são de grande complexidade, a avaliação e medição do seu desempenho, em termos de sustentabilidade, são cruciais para a implementação de decisões mais eficazes. Neste contexto, esta investigação desenvolveu um sistema de apoio à decisão

(SAD) para o desenho de políticas de mobilidade sustentável, no caso de cidades emergentes. A abordagem é baseada num modelo de "system dynamics" para representar as relações entre variáveis declaradas e variáveis de fluxo, organizadas em "feedback loops".

Com este objetivo, desenvolvemos um modelo destinado a analisar as relações de causa/efeito num sistema que integra políticas de alto nível, estratégias e ações específicas, e num subsistema para medir o impacto dessas políticas e ações, em termos de sustentabilidade. Este modelo multicamadas serve para analisar como os diferentes fatores mudam ao longo do tempo e para visualizar o impacto desses fatores num "sistema de mobilidade mais sustentável". As políticas analisadas foram projetadas em torno das ideias de: mobilidade verde; mobilidade para a saúde e o bem-estar; mobilidade para a competitividade e qualidade de vida; integração da mobilidade e uso do solo; e governança inovadora para uma mobilidade eficiente e segura.

Palavras-chave: sustentabilidade; mobilidade urbana sustentável; planeamento da mobilidade; indicadores; desenho de políticas; análise de decisão multicritério; dinâmica de sistemas; cidades emergentes.

Un sistema de apoyo a la toma de decisiones para el diseño de políticas y la evaluación de la movilidad sostenible en ciudades emergentes

Resumen

Los constantes cambios económicos y sociales en las ciudades emergentes, así como la urgencia de la protección del medio ambiente, hacen que la planificación de la movilidad urbana sea un tema muy crítico. En ese contexto, planificar sistemas de movilidad hacia la sostenibilidad es cada vez más importante y, aunque no es fácil de medir directamente, se puede evaluar a través de una serie de parámetros que reflejen sus múltiples aspectos.

Estas preocupaciones requieren un cambio de paradigma para comprender las necesidades de los sistemas de movilidad a partir de una visión de sostenibilidad. Por lo tanto, es necesario realizar seguimiento y evaluaciones constantes de las acciones implementadas para mejorar la sostenibilidad, a través de herramientas metodológicas apropiadas. La definición de indicadores es una parte esencial de este proceso. En este sentido, esta investigación propone un conjunto de indicadores, agrupados en cinco dimensiones diferentes de sostenibilidad, como una herramienta para evaluar la sostenibilidad de los sistemas de movilidad, para el contexto específico de las ciudades emergentes.

Estas dimensiones e indicadores se basan en una revisión exhaustiva de la literatura sobre la evaluación de la sostenibilidad en los sistemas de movilidad urbana; que posteriormente fueron validados por expertos, a través de encuestas, entrevistas semiestructuradas y análisis estadístico de la información obtenida, buscando así identificar la importancia de los indicadores y su prioridad en las dimensiones seleccionadas. Puesto que la validez de estas dimensiones depende en gran medida de los "pesos" atribuidos a sus componentes, fue necesario desarrollar un marco estructurado de medidas de sostenibilidad priorizadas, para apoyar a las autoridades de movilidad en la elaboración de políticas de movilidad sostenible. En consecuencia, se desarrolló un marco conceptual específico para evaluar la sostenibilidad en los sistemas de movilidad utilizando métodos de análisis de decisión multicriterio.

Dado que los sistemas de transporte son en gran medida sistema complejos, la evaluación y medición de su desempeño, en términos de sostenibilidad, son cruciales para la implementación de decisiones más efectivas. En este contexto, esta investigación ha desarrollado un sistema de apoyo a la toma de decisiones (SAD) para el diseño de políticas de movilidad sostenible, en el contexto de las ciudades emergentes. El enfoque se basa en un modelo de dinámica de sistemas para representar las relaciones entre las variables fijas y las variables de flujo, organizadas en diagramas de ciclos causales.

Para este propósito, hemos desarrollado un modelo para analizar las relaciones de causa y efecto en un sistema que integra políticas de alto nivel, estrategias y acciones específicas, y en un subsistema para medir el impacto de estas políticas y acciones, en términos de sostenibilidad. Este modelo de capas múltiples sirve para analizar cómo cambian los diferentes factores con el tiempo y para visualizar el impacto de estos factores en un sistema de movilidad más sostenible. Las políticas analizadas se diseñaron en torno a las ideas de: movilidad verde; movilidad para la salud y el bienestar; movilidad para la competitividad y calidad de vida; integración de movilidad y uso del suelo; y gobernanza innovadora para una movilidad eficiente y segura.

Palabras clave: sostenibilidad; movilidad urbana sostenible; planificación de la movilidad; indicadores; diseño de políticas; análisis de decisión multicriterio; sistemas dinámicos; ciudades emergentes.

Table of contents

1 Assessing sustainability in mobility systems of emerging cities

1.1 Introduction

There is a generalized and increasing interest in the concepts of sustainability, sustainable development and sustainable transportation [1], as transportation systems have a significant impact on environmental, social and economic sustainability [2]. Sustainability refers to a balance of economic, social and environmental goals, and reflects the essential human desire to improve and protect our world [3]. The concept emphasizes the integrated nature of human activities and the need for coordinated decisions between different jurisdictions, sectors and groups [4].

According to [5], "*sustainable development reflects a more sophisticated understanding of the impacts of our activity: it recognizes that our future will result, in part, from our current decisions*". Sustainability and sustainable development are generally considered desirable. A sustainable transport system should be accessible, safe, environmentally-friendly, and affordable [6]. It should deliver facilities to connect all people and should consider economic, social and environmental aspects of society [1], and recognize that transport decisions affect people in many ways, so that a variety of objectives and impacts should be taken into account in the planning process [5].

Transport is widely considered as a sector with significant positive and negative externalities, not always taken into account, affecting society, the environment and the economy, hence it is directly connected to the sustainable development of cities [7]. Therefore, one of the priorities of transport policy should be the creation of sustainable transport systems that improve the overall quality of mobility, including aspects related to accidents and health hazards, accessibility and affordability, personal safety and protection of passenger rights [1].

Consequently, according to [1], the Declaration of Principle of Charter of Aalborg asks for a commitment from cities to achieve a sustainable urban model. The issues related to mobility on which cities should be particularly active include improving accessibility and supporting social welfare and urban lifestyle, while reducing the mobility. "*A sustainable city has now the imperative requirement to reduce forced mobility and should not promote and support the unnecessary use of motor vehicles. The environmentally friendly means of transport (particularly walking, cycling and using public transport) should be preferred and planning efforts must converge in the realization of a combination of these means, The individual means* *of transport should have only an auxiliary function in the cities, to facilitate access to local services and maintain urban economic activities*” [1].

Hence, the sustainability of mobility systems is increasingly crucial for cities. This requires a shift in paradigm, to understand mobility needs, as well as a constant monitoring and evaluation of the actions implemented through acceptable methodological tools. Therefore, the question of transport cannot be reduced to technical matters of adjustment between the supply of infrastructure and services, with the demand for mobility. It must also include other aspects related to the daily movement of citizens and goods [1].

Furthermore, as urban growth patterns change, attention has shifted to the so-called *emerging cities*, i.e. cities with less than two million inhabitants but with high growth rates, and where the major transformations of urban space are occurring. This new pattern of settlement is creating great opportunities, but also new challenges [8]. Hence, emerging cities must achieve sustainable development by promoting new strategies to improve their resilience and to adapt to climate change [8]. Until now, public policies in emerging cities have promoted the use of cars, increasing congestion and causing a number of negative consequences, including inefficient economy, productivity loss, pollution and traffic fatalities and injuries [9], [10].

The increasing interest in making transportation environmentally, economically and socially sustainable, has created the need for the design of *sustainable transportation indicators* to be used for planning purposes [3]. In the transportation context, indicators have been applied extensively to the assessment of sustainability [11]–[13].

In this line, [1] stated that a set of indicators could be a good instrument to evaluate the aspects related to sustainability in mobility systems. Moreover, if these metrics are integrated into simulation models, they can provide important tools to support the decision-making processes of stakeholders, taking into account sustainable alternatives for the development of urban transport [1]. This leads to establishing the requirement for sustainable transportation indicators as a suitable planning tool.

Traditional transportation performance metrics tend to focus on vehicle mobility and congestion and, in practice, fail to assess the degree to which transportation planning leads to sustainable outcomes. Without appropriate metrics, transportation managers and policy-makers seldom have sufficient information to make decisions, explicitly taking into account sustainability concerns [2]. A promising approach to design mobility systems is planning through indicators. Indicators are capable of generating information for decision-making processes, and enable tracking and monitoring goals, benefits, effectiveness and efficiency of the proposed actions [14].

Indeed, it is important to analyze all the aspects involved in the definition of "sustainable transport", possibly by characterizing a set of indicators that simultaneously take into account the dimensions of sustainability broadly defined and accepted by different authors [1], [2], [5], [15]–[17]. Such set of indicators may aid policy making and planning of urban transport systems.

Nevertheless, a broad set of indicators can provide a higher level of completeness, but it implies high data collection costs and serious difficulties of interpretation [1]. On the other hand, a limited and easily available set of indicators can be more convenient, but it may overlook important impacts, thus distorting planning decisions [1].

Therefore, due to the inherent complexity in determining the factors that affect the sustainability of mobility systems, and considering uncertainty about future developments in the area, it is necessary to consolidate a consistent set of indicators to be articulated with the formulation of sustainable transport policies.

In such context, despite the great usage of different indicator sets, there are still issues to be addressed regarding their implementation in specific cases, since there is no single strategy to correctly use these tools to measure sustainability in urban mobility systems. Therefore, given the high levels of involved uncertainty, along with a variety of relevant practical aspects, a successful assessment of sustainability will strongly depend on a careful and sound selection of indicators [3].

Thus, as a response to the abundance of existing metrics, this research uses two multi-criteria decision analysis (MCDA) approaches to validate and to prioritize indicators in the proposed sustainability assessment *analysis structure*. The resulting prioritized framework is applied in a selection of representative cities: Lund (Sweden), Copenhagen (Denmark), Porto (Portugal) and Ibague (Colombia).

This research aims at providing guidance on which measuring tools can improve the design of sustainable transportation, and how they can articulate with the decision-making processes, by proposing a framework intended to aid in the development and improvement of innovative mobility strategies.

Given that policies to promote sustainable mobility require the implementation of specific actions, often demanding considerable investments, their rational use is expected to result in a significant benefit to the public [18]. Consequently, different policies, and associated strategies and actions can be adopted, but a large set of factors can influence their results, particularly because the interactions between such actions is not straightforward to measure [19]. Beyond the development of a measurement *framework*, there is the need to further develop a methodology to evaluate the relationships between the variables, as well as their response to implemented actions.

Hence, this research incorporates a *system dynamics* model that is based on relationships between *state and flow variables*, organized in *feedback loops*. This model assumes that the mobility system will evolve according to a set of identified relationships between the levels considered in the proposed framework, these levels being integrated through vertical and horizontal "links".

The model uses qualitative and quantitative variables, by allocating weights to each connection between variables and by comparing the influences the factors have on the expected outcome "*a more sustainable mobility system*", during a specific period. It also shows the influence of changes in the variables, over time, due to feedback loops or delays. Moreover, the model visualizes and analyzes how variables are interconnected using an *insight matrix*, thus allowing for better planning, decision-making and communication.

This constitutes the *decision support system (DSS)* proposed by this research for policy design and assessment of sustainable mobility, in the specific context of emerging cities.

1.2 Motivation

Sustainability is a concept that can be difficult to operationalize because it involves goals that are often in conflict, such as environmental conservation, social responsibility, and economic viability [4], [20]. Sustainability in the context of transportation does not simply refer to the act of “sustaining” a transportation system; but rather to understanding its broader impacts [2]. Transportation is widely recognized as a major component of sustainability [4].

Hence, achieving sustainability goals through transportation systems has become an important objective of policy makers and public initiatives [2]. In line with these concerns, developing metrics for sustainable transportation is the subject of numerous publications [2], [3], [5], [16], [17], [21], [22]. Metrics are critical in the decision-making process, but the relationships between sustainability goals and policy/decisions can be very complex [23].

Thus, if transportation sustainability is not measured, transport systems often develop in a way that poses serious challenges for sustainability [2]. [24] stated that “*just as people rely on their senses such as sight, hearing and touch; transportation planning should rely on standardized information suitable for analysis and guidance of the transportation systems*”. In other words, the classic saying “what gets measured gets managed” applies [2].

On the other hand, even though larger metropolises continue to have an important specific weight in the world, these mega-cities are no longer those with the highest growth rates. Nowadays, the urban population and economic growth are increasingly taking place in intermediate-sized cities, which are expanding exponentially. This new pattern of urbanization is creating enormous challenges for such emerging cities [8]. Those cities are urban areas that are classified as intermediate, according to the population of each country, and which also have sustained population and economic growth, in an environment of social stability and governance [8].

Accordingly, this research focuses on the development of a *measurement framework* for the particular context of emerging cities, thus responding to the need for a tool that could be systematically applied for assessing the sustainability in mobility systems of emerging cities. Indeed, the definition of adequate indicators constitutes an essential part of this process, even if the literature is abundant in available metrics. The fundamental concepts of sustainability are often illustrated through the three dimensions of sustainability, which refers to the integrated nature of environmental, social and economic sustainability [2].

In fact, existing sustainability frameworks typically do not take into account other aspects related to the transport activity affecting the sustainability of the system, such as technical attributes to evaluate the operation, assessing the way public spending is managed, transport-related initiatives and other aspects that support the transport policies formulation processes.

Thus, one goal of this research was to develop a model relating the impact of public policies with the performance of sustainability indicators, thus providing a decision support tool to guide policy, planning and management across multiple sectors and stakeholders. This model was designed and validated by applying system dynamics techniques.

1.3 Research design

1.3.1 Research questions

Sustainable urban mobility is one of the toughest challenges that cities face today, as existing mobility systems are close to breakdown. A *decision support system* for policy design and assessment of sustainable mobility in emerging cities may undoubtedly contribute to face this critical challenge. In order to address this challenge, the following main *research question* has guided this doctoral project:

- How to assess, in an integrated manner, the performance of the mobility systems of emerging cities, in terms of sustainability?

To approach this question, we have considered the following subordinate *research questions*:

- What are the most suitable factors to measure sustainability in the mobility systems of emerging cities?
- How do the measuring tools impact policy design to improve the sustainability of the mobility systems of emerging cities?

1.3.2 Objectives

The following general objective is proposed in order to frame and guide the development of this research:

Develop a conceptual model as a support tool for the definition of strategies and interventions to improve the sustainability of urban mobility systems in emerging cities, thus enhancing a pre-defined set of measurement indicators.

With this general objective, the aim is to generate a reference framework on how to achieve sustainable mobility systems for emerging cities, designed around a consolidated measurement *framework* to evaluate sustainability.

In this context, we have the following specific objectives:

1. *Identify the relevant aspects to take into account for the assessment of sustainability in the mobility systems of emerging cities.*
2. *Define a methodology for the selection of sustainability measurement indicators.*
3. *Develop an analysis structure supported in dimensions and indicators to measure the sustainability of mobility systems.*
4. *Develop a prioritized framework to measure the sustainability of mobility systems, following a multi-criteria decision analysis approach.*
5. *Define how the prioritized measurement framework relates to policy design processes.*
6. *Develop a decision support model through a system dynamics approach that incorporates the relationships between the measurement framework and the impacts of adopting innovative policies.*

1.4 Thesis structure

This thesis is organized in eight chapters, with each chapter including its own supporting literature review. Therefore, unlike more classical thesis structures, a global review or state-of-the-art is not presented in a single, stand-alone chapter.

Chapter 1 introduces the subject of the dissertation and describes the research design.

Chapter 2 summarizes the current context of the research problem, identifies the geo-spatial unit of analysis, and describes the methodological approach for this dissertation.

Chapter 3 identifies sustainability dimensions in the context of mobility systems.

Chapter 4 describes the *analysis structur*e to assess the sustainability of mobility systems, and presents a definition of each element of that structure.

Chapter 5 presents the final *prioritized framework* for the measurement *analysis structure* defined in the previous chapter, based on a set of prioritization techniques.

Chapter 6 presents the application of the developed framework in the case studies, introducing the current context of the different cities, as well as reflecting on the results, needs and public policies, to improve sustainability in their mobility systems.

Chapter 7 presents a *system dynamics* model as a decision support tool for policy design and assessment of sustainable mobility in emerging cities.

Finally, chapter 8 summarizes the research results, the main contributions of the dissertation, the key findings of the entire analysis, and some ideas for future developments.

1.5 Publications

During the development of this research, two working papers were submitted in peer-reviewed conference proceedings. Chapters 4 and 5 extend a working paper presented and published in the *"5th Conference on sustainable urban mobility CSUM 2020"*. The final paper is based on the contents of these chapters and describes the methodology used in the definition of the sustainability measurement framework. The paper presents the final weighting of dimensions and indicators, based on a set of prioritization techniques developed in this work, along with the main findings and conclusions of this part of the thesis.

The second working paper was presented in the *"23rd Euro Working Group on Transportation EWGT 2020"* and formed a large part of chapter 7 in this dissertation. The paper is based on the conceptual framework that supports the model for policy design and assessment of sustainable mobility in emerging cities. This working paper also shows how variables are interconnected in the model, and how the influence of those variables changes over time, because of feedback loops or delays.

The contents of chapter 6 (measuring sustainable mobility in emerging cities – case studies), is now being rewritten as a paper. This working paper will present a comparative analysis of the application of the sustainability measurement framework in four case studies.

2 Methodological approach

2.1 Sustainability in the transportation context

According to [16], transport systems are key elements of urban areas; therefore, their sustainability has a pivotal role in achieving complex urban sustainability. Nowadays, the evaluation of urban sustainability is a hot topic in different scientific fields, with a growing interest for sustainable transportation and transport planning [25].

However, there are no universally accepted definitions of sustainability, sustainable development or sustainable transport [26]. [27] cited in [5] argues that "*Sustainability is not about threat analysis; sustainability is about systems analysis. Specifically, it is about how environmental, economic, and social systems interact to their mutual advantage or disadvantage at various space-based scales of operation*".

Moreover, sustainability is sometimes narrowly defined, focusing on a few specific problems such as resource depletion and pollution, but it is increasingly viewed in a broader way, to include other economic, social and environmental issues [5]. Sustainability is a simple concept with complex implications [25], so according to [24], sustainability reflects a paradigm shift, a fundamental change in the way problems and solutions are defined.

Most current definitions recognize three main dimensions of sustainable development issues: economic, social and environmental (or ecological), and some incorporate issues such as governance and fiscal sustainability [5], [28]. Sustainability balances these three dimensions, also known as the triple bottom line [5], [29].

Sustainability emphasizes the integrated nature of human activities and therefore the need for coordinated planning among different sectors, groups and jurisdictions, expanding the objectives, impacts and options considered in a planning process. This helps ensure that individual, short-term decisions are consistent with strategic, long-terms goals [5]. Along these lines, sustainable development can be defined as meeting the needs of the present, without compromising the ability of future generations to meet their own needs [21].

According to [29], the terms *sustainable transport* and *sustainable mobility* have been coined to reflect the concerns over potential impacts of all transport systems and mobility on sustainable development, including economic, social and environmental impacts. Despite the wide use of these terms, there is no clear agreement on a global definition of *sustainable* *transport* or what it means in detail. This is because the contribution of transport to sustainable development is diverse, complex, dynamic, and context-dependent.

In such context, a *sustainable transportation system* according to [28] is one that:

- allows access to the basic needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations;
- is affordable, operates efficiently, offers a choice of transport modes, and supports a vibrant economy;
- limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.

In the same way, a *sustainable transport system* should reflect the need to govern transport according to sustainability principles [15], [30], [31]. The sustainability of transport in terms of accessibility, pollution, and safety can be pursued via a broad set of strategies [32], with strategies including to avoid unnecessary transport, to shift transport from individual motorized transport to active modes and public transport, and to improve the use of efficient, clean vehicles and fuels [21].

A broader concept of sustainable transportation may be to satisfy current transportation and mobility needs without compromising the ability of future generations to meet their own needs [17]. This concept is a small transformation of the general sustainable development definition provided by [33].

According to [24], transportation has significant economic, social and environmental impacts, and so is an important factor in sustainability. Sustainability supports a paradigm shift occurring in transport planning. Previously, transport was evaluated primarily in terms of mobility (physical movement), but it is increasingly evaluated in terms of accessibility (people's ability to obtain desired goods and services). Accessibility-based planning expands the range of solutions that can be applied to transport problems.

[34] states the main requirements for achieving sustainable urban transport. However, some linkages between transportation activities and environmental degradation still remain unclear [16]. Moreover, analyses of the transportation sector in terms of sustainability show the importance and relevance of the topic at an international scale [35], [36].

The *sustainable mobility paradigm* promotes a broad range of strategies and should focus on the efficiency of the transport system in delivering access and mobility for humans, with quality, diversity and minimal impact, instead of high quantity and speed [29], [32], [37].

Although there are many possible definitions of *sustainability, sustainable development and sustainable transport*, experts increasingly agree that these refer to balancing economic, social and environmental goals [5]. Comprehensive and sustainable transport planning must therefore be evaluated through an *analysis structure* with an equally comprehensive *framework*, that reflects appropriate economic, social and environmental goals and impacts.

Narrowly defined, sustainability can overlook connections between issues and opportunities for integrated solutions. A comprehensive and integrated analysis helps identify strategies that achieve multiple planning objectives, and lead to more sustainable solutions [5].

A comprehensive literature review is therefore a key part for determining which aspects and approaches related to transport activities can affect the development of mobility systems, in terms of sustainability. In such context, the definition of *transport sustainability* provided by the European Council of Ministers of Transport covers the following features ([38] cited in [16]):

- from a social perspective, a sustainable transport system provides basic accessibility of individuals, companies and society, and makes the connection between the present and the future generations;
- from an economic perspective, it enhances competitiveness and regional development trough affordable and efficient operation;
- finally, from an environmental perspective, it promotes the use of renewable resources and considers the limit of emissions and waste in terms of the planet's absorption ability, so that future negative impacts can be prevented.

Since cities are largely complex systems, the assessment and measurability of their subsystems are crucial for implementing efficient decisions. That is the case of *urban transport systems*, a key element in moving goods and people within and between cities. and a major driver of sustainable cities [16], [39]. According to [5], sustainable transport planning recognizes that transport decisions affect people in many ways, requiring the consideration of a variety of objectives and impacts.

Concerns about sustainability in mobility systems can be considered a natural reaction to the lack of tools and comprehensive assessment methodologies (with a clear conceptualization and definition of elements). Yet, mobility systems have generally been evaluated as technical matters concerning the adjustment between the supply of infrastructure and services with the demand for mobility, while ignoring those elements that are more difficult to measure, such as sustainability.

In summary "*the goal of sustainable transportation is to ensure that environment, social and economic considerations are factored into decisions affecting the transportation activity*" [40]. Sustainable transportation should offer citizens an adequate quality of life, minimizing its impacts on the natural environment, preserving the environmental and physical assets of the city for future generations, and promoting economic development and competitiveness, as well as having a government with fiscal and administrative capacity to carry out urban functions with the active participation of citizens [8].

2.2 Geo-spatial scope of the research

Taking into account that sustainable transport is a major concern in urban development worldwide [21], the growing demand for passenger and freight transport in *emerging cities* has led to increasing problems with congestion, environmental pollution and, as a consequence, to a decrease in quality of life [41].

In this context, the demand for urban mobility and the travel needs are evolving very fast. Changes in travel habits show that there is a significant difference between developed cities, where the majority of daily urban trips are made through private motorized modes, and developing cities, where the majority of trips are made in non-motorized modes [42] (see Figure 2.1).

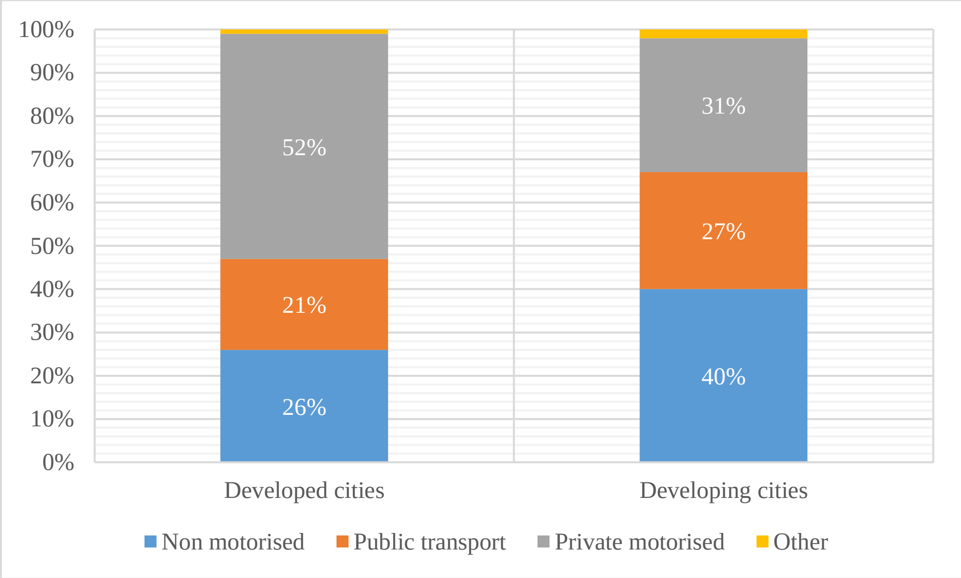


Figure 2.1 Average modal split in developed and developing cities [43]

However, in developed cities the fleet of motor vehicles has largely remained stable during the last decade, but, in emerging cities motorization rates have grown significantly since 1995 [42] (see Figure 2.2). This rapid growth and increased urbanization will continue to stress urban transport systems and infrastructure, leading to externalities, such as congestion and accidents. Therefore, quality of life and health also suffer, and sustainable public policies will need to be put in place to reverse this trend.

Figure 2.2 Evolution of average level of motorization in developed and developing cities [43]

Since most of the urban growth expected for the coming decades will take place in emerging cities [44], tracking the performance of mobility systems in terms of sustainability in these cities will be necessary. Thus, tools will be required to evaluate sustainability in their mobility systems.

Emerging cities must, therefore, achieve sustainable development by promoting growth, in addition to improving their resilience and to adapt to climate change [8], without repeating the mistakes that have taken place in large cities [45].

2.3 Methodology

This research follows a descriptive and correlational scientific perspective [46], and includes the definition and analysis of variables that can affect the mobility systems of emerging cities (defined as the unit of analysis), in terms of sustainability, as a basis for the creation of a model for supporting policy design and assessment.

Through a *system dynamics* approach, we attempt to establish the relationship between the variables used as indicators to measure sustainability, and the impact of the public policies adopted by planning managers, This approach is non-experimental in the sense that existing conditions of the unit of analysis will not be modified.

Our research is mainly inductive, making it possible to obtain general conclusions from particular facts, in this case by comparing and analyzing the data collected from various observations and their possible relationships. However, it presents characteristics of deductive approaches, in establishing predictions to explain particular observable phenomena [46]. We therefore follow a mixed approach, that combines quantitative and qualitative methods, using data collection to establish patterns of behavior and test theories, as well as data collected through interviews and surveys to refine research questions or reveal new questions in the interpretation process [46], [47].

A conceptual *analysis structure* is developed, that integrates the three common dimensions of sustainability (environmental, social and economic [48]–[52]) with other dimensions, such as operational, fiscal and governance, and mobility systems effectiveness and land use. Moreover, a *decision support system* is sketched for policy design and assessment of sustainable mobility, based on the interactions between the identified factors and the expected impacts of transportation public policies. This tool can be used to optimize public investments, as well as to prioritize the set of actions to be implemented.

Our research methodology follows four mains stages: i) developing an *analysis structure* to assess the sustainability of mobility systems in emerging cities; ii) developing a *conceptual framework* for prioritizing the elements that make up the *analysis structure*; iii) measuring the sustainability of urban mobility systems; and iv) developing a *decision support system* for policy design and assessment of sustainable mobility (see Figure 2.3).

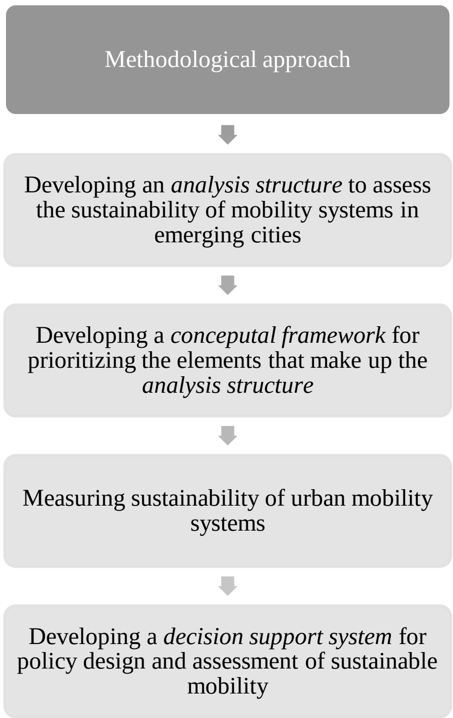


Figure 2.3 Methodological approach of the research

2.3.1 An *analysis structure* to assess the sustainability of mobility systems in emerging cities

A promising approach to design sustainable mobility systems is planning through indicators. Indicators are capable of generating information for decision-making processes, and enable tracking and monitoring goals, benefits, effectiveness and efficiency of the proposed actions [14]. They also help to guide policy design, and planning and management activities, across multiple sectors and stakeholders. Sustainable transport indicators should be developed and be used to monitor transport sustainability, as well as to compare and analyze sustainability between different cities in the world [53].

In our context, and due to the overabundance of sustainability indicators, the descriptive scientific perspective followed in this research design is largely based on the separate definition of each component of the proposed sustainability measurement *analysis structure*. This research is framed by the specific context of emerging cities and, therefore, the variables considered here refer to this type of cities.

A comprehensive systematic review was done on sustainability and sustainable mobility indicators (based on scientific articles, thesis and policies on sustainable development and sustainable transport, as well as reports on sustainable mobility). This review resulted in the identification of many indicators that were duly scrutinized, removing those that were identical or were essentially measuring the same variables, and others that were either poorly defined, reflected less essential issues, or would likely require a large effort to be applied in practice.

The proposed *framework* was circulated, in three phases (preliminary, exploratory and confirmatory) (see Figure 2.4), among experts from academia, and from consultancy and government organizations. In the first iteration, the *preliminary phase*, five 2-hour recorded face-to-face meetings were held, in English, with sustainability experts from Copenhagen, Malmo and Lund, between March 2019 and April 2019, with the purpose of discussing how to measure sustainability in transportation systems of emerging cities.

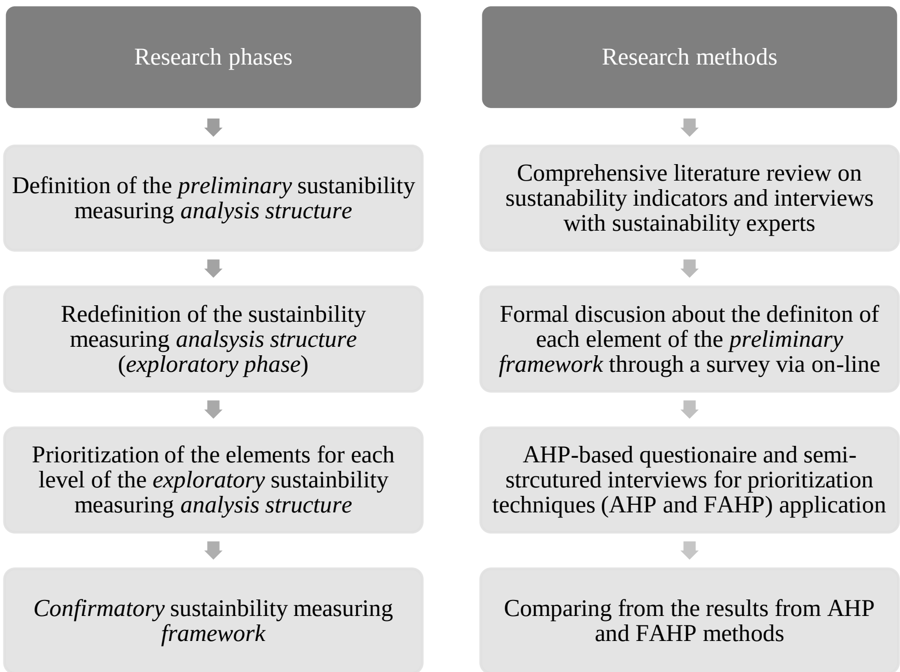


Figure 2.4 Research phases and research methods used for defining the *confirmatory* sustainability measurement framework

After an initial consolidation of 5 dimensions and 26 indicators, a formal discussion about the definition of each element of the proposed *analysis structure* was held through an on-line survey (see Appendix A and B) with relevant experts in the field, considered as an *exploratory phase*. The survey was distributed to people with interest in sustainability topics. In *expert judgement*, experts having similar domain knowledge are consulted to estimate sustainability in transportation systems in the specific context of emerging cities. This means that the field of knowledge covers everything related to the sustainability of transport systems, as well as in mobility systems in general.

The respondents discussed the *analysis structure* proposed, in terms of their relevance, feasibility, and applicability to urban transport planning in emerging cities. The information gathered (with 105 respondents – see their characterization in chapter 3 and 4) was analyzed using descriptive statistics, to redefine and assess that *analysis structure*.

The main criticism to the proposed *analysis structure* was that the performance and operation of the mobility systems were not sufficiently well represented in the framework, to assess sustainability. System performance is essential for agencies responsible for implementing urban transport policies [21]. Also, additional factors were found to be important for the sustainable management of mobility systems, and were therefore included in the final *analysis structure*. Respondents had the opportunity to propose additional dimensions and indicators, if they considered the original proposal was not adequate.

Consequently, as result of this first stage, the "*measuring sustainability of mobility systems in emerging cities*" structure was consolidated as level 0 of the proposed framework. This level is, in turn, supported in 5 sustainability dimensions (environmental and human health; economic and social; operation; fiscal and governance; and mobility systems and land use) that make up level 1, and these dimensions, in 42 sustainability indicators, as level 2.

2.3.2 A *conceptual framework* for assigning priorities

Sustainability indicators have become increasingly important in terms of research and practice [54]. However, their validity is heavily dependent on how their components are weighted. In such context, [54] stated that the typology and applicability of the existing weighting methods remain poorly understood. As a result, there is a need to consolidate a *framework* of *prioritized* sustainability measures, that serves as a guidance of how sustainability can be assessed in transportation systems, and that can be easily adaptable to any city context.

Therefore, a third phase of expert-based consultations, considered as a *confirmatory phase*, used two Multi-Criteria Decision Analysis (MCDA) methods (analytic hierarchy process – AHP, and fuzzy analytic hierarchy process – FAHP) in order to prioritize the elements in the sustainability measurement *analysis structure*.

First, 19 experts in sustainability topics (from different entities and countries – see Appendix C) responded to an AHP-based questionnaire and participated in semi-structured interviews (see chapter 5). The interviews were also used to define sustainable transport policies that could be used for the last stage of the research. The experts were asked to assess the relative importance of one element of the sustainability measurement analysis structure over another in the same level, with respect to the goal, established as level 0 ("measuring sustainability in mobility systems of emerging cities") (see Appendix D and E). This was done through pairwise comparison evaluations between the elements, to compute weights at each level – sustainability dimensions at *level 0*, and sustainability indicators at *level 1*.

The information gathered by this questionnaire was confirmed and analyzed in 7 recorded face-to-face semi-structured interviews (in English) in Copenhagen, Malmo and Lund, and in 12 recorded virtual semi-structured interviews (2 in English and 10 in Spanish) by *skype*, (between November 2019 and December 2019).

Surveys as a primary data collection have the advantage of comparability between the responses of the different subjects. The interviews, due to the open ended and flexible nature of questions, are more likely to drift towards the interests of the interviewee [55], and are also subject to bias and shortcomings in terms of reliability and validity of the information [56]. However, they are a flexible research tool that can be used at any stage of the research process, and can be combined with other approaches, in a mixed method design [55], as it is the case. This type of interviews gives the researchers freedom to address any topic they consider interesting for the research [56], and allow the interviewed people to convey information that they deem important for the issues under analysis [57]. Moreover, they allow researchers to collect relevant information outside the previously defined topics [55].

The interviews were recorded with the permission of the interviewees. For all interviews there was a guiding script, but we were open to discuss more topics than those set in the script. The script guides were studied beforehand in order to pose the questions and frame the answers of the interviewees, according to the role and expertise of the interviewed.

The results of the questionnaire are subject to AHP and Fuzzy AHP (FAHP) approaches. First, AHP is used to determine the weights of criteria (sustainability dimensions, at level 0) and sub-criteria (sustainability indicators, at level1) of the proposed *prioritized framework*. Then, Fuzzy AHP is also used. Finally, the results obtained with the two approaches are analyzed and compared.

AHP has been extensively applied by academics and professionals in many fields and problems, as it is the case of transport engineering [58]–[62]. The top level of the hierarchy is associated with the global goal considered in the problematic situation under analysis, and each level denotes the factors contributing to the associated upper levels. Meanwhile, the bottom level contains the alternatives or actions considered as individual factors [63]–[65].

However, AHP has been criticized for its inability to deal with imprecision and subjectivity, in the pairwise comparison process, when the number of alternatives is relatively high [66]. To overcome these problems, several researchers have integrated fuzzy theory with AHP to improve its outcomes. The Fuzzy AHP (FAHP) approach can deal with the vagueness of linguistic judgments by establishing an imprecise prioritization [67]. Therefore, FAHP sets provide more efficient and realistic results because they mimic human reasoning more closely, overcoming limitations of bounded rationality [68]–[73].

Initially AHP is used for the determination of weights of the elements that compose the sustainability measurement *analysis structure,* but Fuzzy AHP seemed (in our experiments) to be a better choice to prioritize these elements. Consequently, the second step in the *confirmatory analysis* involves evaluating the proposed *analysis structure* applying the Fuzzy AHP methods for level 0 (measuring sustainability in mobility systems) and for each level 1 (dimensions).

The results of this research stage provide the input for the model developed in the last stage. The framework was applied to four case studies in order to carry out an evaluation of the sustainability of mobility systems in actual cities: Copenhagen, Lund, Porto and Ibague. The case studies were used to show how the framework can be applied, and allow comparing results at a disaggregated level, per indicator. They can also be used to inspire decision makers to track and compare systems performance, and to discuss both, data issues, and policy needs and results.

This conceptual *framework* to assess the sustainability of mobility systems in emerging cities successfully consolidates and integrates quantitative and qualitative methods. Thus, the formal data collection activities like the ones used in this research (surveys and interviews) have strongly influenced the building blocks of the developed framework.

2.3.3 Measuring sustainability of urban mobility systems in emerging cities

Currently, there is no comprehensive system in place to measure and report on sustainable transport across emerging cities. Therefore, to validate the use of our approach, we have applied this new sustainability measurement framework in the referred four case studies: Lund, Copenhagen, Porto and Ibague.

Lund is an intermediate size city in Sweden, and it also plays an important role in the dynamics of sustainable transport in southern Sweden (Malmo) and in the greater Copenhagen. Copenhagen was chosen as a benchmark city for sustainable transport practices. Porto, an intermediate size city in Portugal, with less than 2 million inhabitants in the greater metropolitan area, is also an interesting case to apply the proposed sustainability measurement framework. Finally, Ibague as an emerging city in Colombia, with less than 600,000 inhabitants appears to have the most unsustainable and inefficient mobility system, when compared to the other cases.

Qualitative methods were combined with a detailed analysis of primary data collected in each city. Therefore, meetings with the relevant transport authorities were scheduled. In the cases of Copenhagen and Lund, these meetings were conducted in person, and in the other cities the data was obtained from available open databases.

The framework proposed in this work can be viewed as a tool to help summarize, compare and track the performance of emerging cities, in terms of their sustainability. It intends to be an instrument to measure what is necessary to support transport planning, with data likely to be operationally available in many different emerging cities.

2.3.4. A decision support system for policy design and assessment of sustainable mobility

The final stage in the research aims at integrating, in a *decision support system*, a model for the relationships between the measurement *framework*, as structural element of our approach, and the assessment of the impacts for alternative policies. A *system dynamics* approach is used to dissolve the rigid allocation of each indicator to a single dimension, integrating all possible relationships between the elements, as some indicators are related to several dimensions. This is in line with [74], as the dimensions of sustainability are more to be seen as mental constructs than as separate physical systems. Therefore, the notion of building a rigid framework within the overall model was abandoned.

Consequently, the framework to assess sustainability (developed in stages 1 and 2) was articulated with public policies, actions, strategies and variables, using the software iMODELER [75]–[77] as the simulator engine. This tool was selected because it allows for qualitative and quantitative modelling of different scenarios.

The *system dynamics* model is based on relationships between *state and flow variables*, organized in *feedback loops* [78]. This model assumes that the mobility system will evolve to achieve "*a more sustainable mobility* system", as desired goal at level 0, according to a set of identified relationships between sustainability dimensions, considered as level 1 with the level 2 (sustainability indicators) (see the left branch of Figure 2.5). These levels are mutually integrated through vertical and horizontal "links". These indicators are, in turn, connected with high sustainability policies and strategies-actions through variables (see the right branch of Figure 2.5), defined by the decision-makers. Then, a *decision support system* (*DSS*) for policy design and assessment was designed, applying the developed conceptual framework. The proposed model offers a way to visualize and analyze complexity in determining how public policies to promote sustainability can affect the performance of the mobility system, according to the measurement framework.

The levels 0 and 1 of the model structure (see Figure 2.5), "sustainability dimensions" and "sustainability indicators", result from a comparative analysis of the FAHP and the AHP approaches. Then, the other model factors, "strategies – actions – variables" and "high-level sustainability policies", are the result of the interviews made with different representatives from the academy, and consultancy and government organizations, as well as the findings from the policies implemented in the case studies.

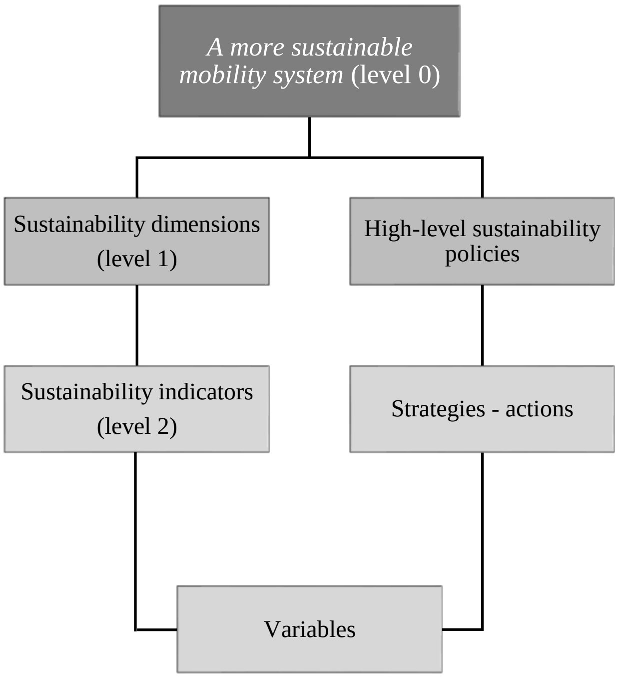


Figure 2.5 Conceptual structure of the *system dynamics model*

3 Sustainability assessment in mobility systems: multidimensional characterization

3.1 An analysis structure to evaluate sustainability in mobility systems of emerging cities

In urban transportation systems, policy analysis and planning normally require quite accurate information. This is particularly important for sustainability planning, which considers diverse, indirect and long-term impacts. Therefore, it would be desirable for decision makers in emerging cities to have a "baseline" broad *analysis structure* that integrates the several dimensions that can affect the performance of the mobility system in terms of sustainability. The main dimensions of sustainability, usually referred to as *the triple bottom line* – environmental, economic, and social – should form the basis for any research work in the area. However, as discussed in chapter 2, we have identified other relevant dimensions. In this direction, different researchers have proposed new approaches on sustainable transport, such as [37] who have emphasized *accessibility* as the main feature to take into account, but did not provide elements concerning the economic and environmental dimensions of sustainability.

Other research works concentrate on the environmental impacts of motorized transportation modes [79], but there are clear limitations if sustainable development is only concerned with environmental impacts [80]. This barrier was mentioned by [5], who stated that for a comprehensive transportation planning, it is usually better to choose a balanced structure that integrates a broad vision of the factors that can affect the mobility systems in terms of sustainability. Indeed, an approach that focuses too much on one type of impact, or overlooks other important impacts, is not overall optimal.

Therefore, the goal of this research is to present a process that can assist transportation authorities to evaluate their mobility systems regarding sustainability, as well as a conceptual *framework* that integrates a broader vision on the problems. The design of such framework is supported by an extensive literature review about sustainability in the transportation sector.

3.1.1 Preliminary phase

Transport sustainability dimensions were identified based on the literature review, and on 5 (2-hour) recorded face-to-face interviews with experts from Copenhagen, Malmo and Lund, held in 2019 (see Table 3.1), as well as on the sustainability reports of mobility systems from these cities. The process to define suitable sustainability dimensions included the following steps:

- identify and redefine existing sustainable transport-related dimensions, and evaluate their relevance considering the actual factors that can affect the sustainability of mobility systems, taking into account other variables that may also be relevant;
- identify and propose sustainability dimensions not previously considered in our comprehensive literature review (including scientific articles, thesis, policy documents and other reports);
- develop a *preliminary* conceptualization; and
- use the *preliminary* conceptualization in formal discussions with experts in sustainability topics, and consolidate an *exploratory* analysis structure for further prioritization (see chapters 4 and 5).

Table 3.1 Face to face interviews with sustainability experts

name *[country]*	*sector* *[topics]*	*current institution* *[position]*	*interview place* *[date]*
Henrik Gudmunsson [Denmark]	Academia/consultancy [Sustainability indicators]	CONCITO [Senior consultant]	Aalborg University [March 2019]
Sidsel Kjems [Denmark]	Academia/Government [Sustainable public policies]	Københavns Kommune [Chief consultant]	Københavns Kommune [April 2019]
Andres Valderrama [Denmark]	Academia [Sustainable public policies]	Aalborg University [Associate professor]	Aalborg University [March 2019]
Per Eneroth [Sweden]	Government [Sustainable public policies]	Lunds kommun [head of the road and traffic division]	Lunds kommun [April 2019]
Anna Karlsson [Sweden]	Government [Sustainable public policies]	Lunds kommun [head of the traffic and mobility department]	Lunds kommun [April 2019]

3.1.2 Preliminary conceptualization of sustainability dimensions

Accordingly, this research defined a preliminary conceptualization based on 5 dimensions (see Table 3.2). These findings were the direct result of the process of dimensions extraction from the literature, as well as from the recommendations made at the interviews.

Table 3.2 Preliminary conceptualization of sustainability dimensions to evaluate sustainable mobility

sustainability dimensions	*preliminary conceptualization*
Environment and human health	The impact of activities related to urban transport on the environment and the population
Economy and social	Potential economic vulnerabilities due to the mobility system, and the ability of the system to promote equality and social inclusion
Operational	Technical attributes to evaluate the operation of urban mobility systems
Fiscal and governance	Management of public spending by transport-related authorities and degree of independence of those entities
Efficiency of the mobility system	Transport policies that can reduce externalities of the mobility systems, such as fatalities and congestion

3.2 Exploratory phase

This preliminary conceptualization was subject to an appraisal by experts on transport and mobility systems, using an *on-line* survey, via Survey Monkey (see Appendix B). The survey was sent via *e-mail* and *WhatsApp* (see Appendix A), first to the people involved in the preliminary conceptualization, as well as those who already had knowledge about the research, and then to people from academia, consultancy and government organizations. These people were selected based on a detailed review of professionals and researchers with sustainable transportation background, in the available databases at universities and transportation entities.

The survey used a kind of Likert scale (see Table 3.3), in order to score the relative importance of the sustainability dimensions. Potentially missing or unnecessary items were collected through optional open-ended questions, such as “additional comments” and “other”.

Table 3.3 Example of a five-point scale for relative importance of the sustainability dimensions

unimportant 1	2	3	4	*important* 5
absolutely unimportant	somewhat unimportant	neither important nor unimportant	very important	absolutely important

The survey was responded by 105 participants from different world-regions, with a focus on South America and Europe (see Table 3.4), with different roles or positions (see Table 3.5), mainly researchers or faculty members, and consultants, and mostly men (see Figure 3.1). The information gathered was analyzed using descriptive statistics, as shown in Figure 3.2 and Table 3.6.

Table 3.4 Summary of respondents by location in the *exploratory* survey

location	*responses (%)*	*total*
Africa	0.00	0
Asia	4.76	5
Central America and the Caribbean	0.95	1
Europe	34.29	36
Middle East	0.95	1
North America	4.76	5
Oceania	0.95	1
South America	53.33	56
Total	**100**	**105**

Table 3.5 Summary of respondents by occupation in the *exploratory* survey

current position	*responses (%)*	*total*
Academic/Researcher	59.05	62
Activist/Citizen	4.76	5
Consultant	25.71	27
Decision maker	4.76	5
Policy maker	5.71	6
Other	7.62	8
Total	**100**	**105**

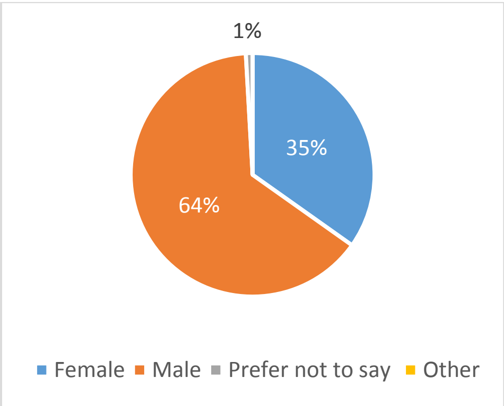
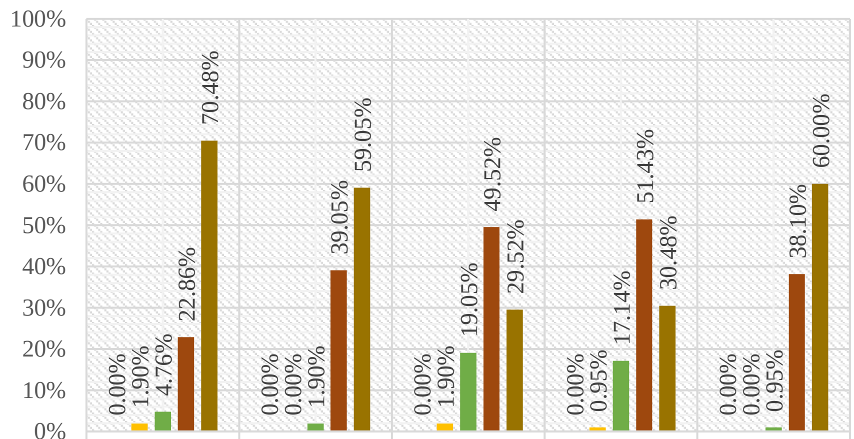


Figure 3.1 Summary of respondents by gender in the *exploratory* survey



	Environment and human health	Economy and social	Operational	Fiscal and governance	Efficiency of the mobility system
Absolutely unimportant (1)	0.00%	0.00%	0.00%	0.00%	0.00%
Somewhat unimportant (2)	1.90%	0.00%	1.90%	0.95%	0.00%
Neither important nor unimportant (3)	4.76%	1.90%	19.05%	17.14%	0.95%
Very important (4)	22.86%	39.05%	49.52%	51.43%	38.10%
Absolutely important (5)	70.48%	59.05%	29.52%	30.48%	60.00%

Figure 3.2 Results from the *exploratory* survey on the proposed sustainability dimensions

Table 3.6 Descriptive statistics from the survey questions, on the dimensions related to sustainability

dimension	*minimum*	*maximum*	*median*	*mean*	*standard deviation*
Environment and human health	2.00	5.00	5.00	4.62	0.67
Economy and social	3.00	5.00	5.00	4.57	0.53
Operational	2.00	5.00	4.00	4.07	0.75
Fiscal and governance	2.00	5.00	4.00	4.11	0.71
Efficiency of the mobility system	1.00	5.00	5.00	4.56	0.62

3.2.1 Multidimensional characterization for sustainability assessment

According to the descriptive statistics shown in Table 3.6, as well as to the feedback obtained from the open questions, the proposed dimensions seem to be intuitively appropriate and relevant (important) to define an *analysis structure* for measuring sustainability in mobility systems (taking into account the obtained median and mean values).

The dimension “efficiency of the mobility systems” was restructured. Efficiency is not usually defined as reducing externalities because if it were, then there might be some overlap with the first two dimensions. Therefore, this dimension was defined as “mobility systems effectiveness and land use”, according to the analysis of the question “*do you consider any other dimension should be included in the study?*”

Survey respondents highlighted the importance of expanding the basic *analysis structure* supported on the three traditional dimensions (environmental, economic and social) to take into account the nested model of sustainability where environmental integrity is considered a *sine qua non* condition. On the other hand, they also argued it is important to define relative priorities, instead of just considering the dimensions to be important or not (see chapter 5).

Accordingly, 5 sustainability dimensions (that integrate the relevant aspects identified in the literature review with the new ideas validated and discussed in the survey) were ultimately identified. The impact of activities related to urban transport on the population (*human health*) was defined as an element aggregated to the *environmental* dimension. In addition, the *analysis structure* proposed (see Figure 3.3) incorporated the *operational* dimension with the main goal of evaluating the technical attributes that can affect the performance of urban transport in terms of sustainability.

We have also included a *fiscal and governance* dimension, that integrates variables related with the way public spending is managed in transport-related initiatives, as well as the degree of independence in planning activities of transport entities, and how are these processes developed (to contribute to the sustainability of the system).

In the same way, the dimension *effectiveness and land use* was defined to integrate variables that support the transport policies formulation processes, assuming effectiveness is an important component of the definition of sustainability; therefore, any mobility system that is considered "sustainable" must also have the capacity to be effective.

The importance of the *land use* dimension is naturally justified by the analysis of the available information on how land use is integrated with transportation planning processes. This is often forgotten by transport planners, but land use and land fragmentation have clear and big impacts on transportation systems.

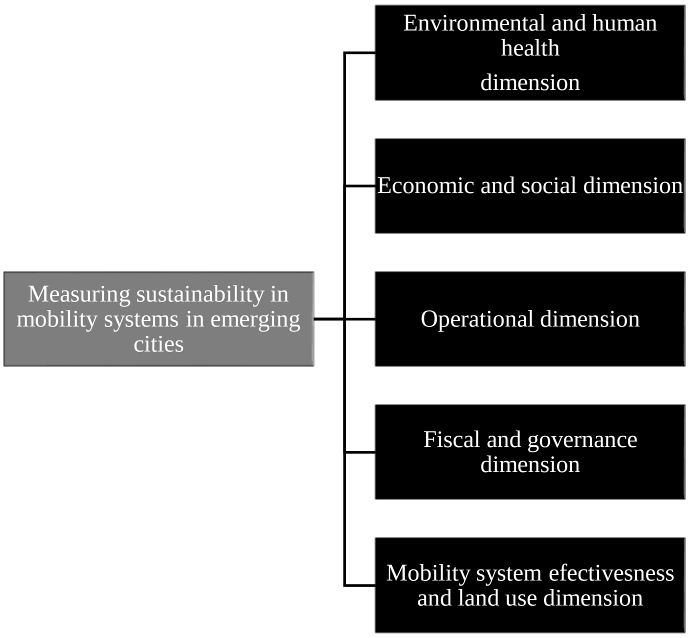


Figure 3.3 Proposed sustainability dimensions in the context of mobility systems

3.2.2 Environmental and human health dimension

Over the last decades, the world has become increasingly aware of the environment's limited ability to cope with the unrestrained development of humanity [81]. Air and water pollution, as well as climate change, are having a significant effect on human health and quality of life [82], [83]. In this context, carbon emissions are considered to be the main source of global warming, and transport strongly contributions to these emissions. The transportation sector accounts for almost one fourth of world's total CO_2 emission. [84]. It is, therefore, necessary to adequately assess these impacts, depending on the type of transport solutions deployed.

Environmental impacts include various types of air pollution (including gases that contribute to climate change) and noise, as well as health impacts derived from activities related to transport, such as injuries, illnesses and premature deaths associated to pollution and transport safety (or lack thereof).

According to [5], efforts must be made to develop transportation systems that minimize physical and biological stress, staying within the assimilative and regenerative capacities of ecosystems, and respecting the habitat requirements of many species. Transportation needs must be met without generating emissions that threaten public health, global climate, biological diversity, or the integrity of essential ecological processes.

Furthermore, this dimension encompasses one of the important negative externality related to the loss of life or abilities, and consequent economic deprivation and mental trauma, caused by transport accidents. Thus, sustainable transportation systems must explicitly include and target road safety. Therefore, it will be necessary to take policy measures that ensure the safety of pedestrians and cyclists, so that more and more people prefer these soft modes of transport. Greening of transport should not end with addressing the issues related to pollution caused by carbon emission. The transport community, including policy-makers, must consider issues related to road safety, noise pollution and their human health effects [84].

In summary, transportation consumes scarce natural resources, emit dangerous pollutants, generates undesirable wastes and causes loss of life, thus endangering sustainability [84]. Along these lines, this dimension aims at measuring the impact of activities related to urban transport on the environment and the population, as a way to support the formulation of innovative sustainability policies.

3.2.3 Economic and social dimension

To be sustainable, a transportation system must be reasonably affordable for every individual, in terms of the monetary and time costs associated with using the system, and as a way to promote social equity [2]. In this context, previous research has indicated that the changes in mobility patterns promoted by public policies or strategies can reduce or increase economic productivity [85], [86]. The economic dimension should, therefore, reflect both the benefits and costs of the mobility system. According to [5], increased mobility that provides little or no benefits to society does, in fact, reduce sustainability, while policies that increase net benefits can, in general, be considered positive, in terms of sustainability.

Consequently, [85] discuss the economic aspects of a sustainable performance evaluation of mobility systems, stating this dimension must integrate elements such as: affordability (transportation is affordable to individuals); mobility (transportation provides efficient movement of people and goods for economic activities); finance equity (transportation is financed in an equitable manner); and resilience (transportation is resilient to economic fluctuations). This dimension recognizes that transportation systems not only must be affordable for individuals and locally self-sufficient, but they must not contribute to the economic vulnerability of society.

On the other hand, the social dimension of sustainability includes *equity* and *social inclusion*. Equity is about transport options, service quality and impacts on different groups, particularly on economically, physically and socially disadvantaged people. Concerns on social inclusion should lead us to identify policies or strategies that promote the inclusion of all stakeholders of the mobility system, for example by promoting non-motorized travelling, improving mobility for disadvantaged people and increasing physical fitness [87].

This dimension assumes that transportation systems must meet access needs of all individuals, in a way that is consistent with human health and safety, promoting social interaction and social equity [2].

We have integrated the *economic* and *social* aspects into a single dimension, based on a set of relationships identified between those two aspects. According to [5] in cities with a large automobile dependency, transportation costs can increase with little or no gain in accessibility or individual's social welfare; but if a city becomes good for walking, cycling and public transit, people's transport demands can be satisfied relatively cheap [5]. Therefore, transportation initiatives should reflect these general patterns.

Consequently, we consider the economic dimension is nested within the social dimension, since, economy is only valuable as a creation of society, as society determines the value of things [88]. Hence, in our approach, this dimension analyses potential economic vulnerabilities associated to the mobility system, and the ability of transportation to promote equality and social inclusion.

3.2.4 Operational dimension

We have already discussed the links between development and transport, as key contributors for sustainable development, in terms of economic, social and environmental dimensions. However, beyond dealing with isolated social, economic and environmental aspects, new approaches must tackle features such as integration, long-term planning and wide-spread ranges of actors [14].

Hence, a system that operates efficiently must maximize access, while minimizing waste and resource usage. Therefore, transport agencies, services providers and facilities should be managed efficiently to minimize costs and maximize service quality [5].

These goals require the adoption of an integrated approach to evaluate the performance of transport infrastructure and facilities, as well as the technical and operational capabilities of the modes of transport that make up the mobility system. Since mobility systems have in general been basically evaluated as technical solutions for adjusting the supply of infrastructure and services to the demand for mobility, other aspects, such as sustainability, have often been ignored.

This integrated approach to transport planning tries to go beyond the mere availability of a variety of transport modes. Therefore, this *operational* dimension provides technical attributes to evaluate the operation of urban mobility systems, since assessing system performance is essential for agencies that are responsible for implementing urban transport plans and strategies.

Operational issues, such as *interoperability*, should also be considered, as well as the way services are offered in order to improve sustainability performance. For example, how easy / convenient a traveler can shift between transport systems (walking, biking, train, public transport, car) can significantly contribute to the sustainable use of transportation. But other technical themes should be included in this dimension, such as age of the public transport fleet, proportion of clean energy in public transport, or efficiency of public transportation, among others.

This operational approach helps to make the definition of sustainable transport more practical and useful. It may also help in setting medium or long term objectives for transportation planning and policy making [89].

3.2.5 Fiscal and governance dimension

The growing importance of municipal governance and fiscal performance factors for citizens [8] has motived the consolidation of this dimension, with the integration of topics not previously taken into account, and with the redefinition of existing subjects. This integration takes into account that planning and management of transportation systems incorporate different levels of government and community input [2].

Among the main motivations for considering this dimension is the perception that, with weak fiscal sustainability and poor governance, it is not possible to consolidate sustainable mobility systems [8]. Moreover, in emerging cities there is, in general, a limited institutional and operational capacity of local and regional governments regarding transportation planning.

This dimension incorporates different aspects, with the ultimate goal of formulating a comprehensive framework to evaluate mobility systems in terms of sustainability. In other words, the fiscal and governance situation will give us guidelines to determine the appropriate strategies to improve sustainability in mobility systems.

In this sense, the fiscal and governance dimension is an indispensable requirement in building the proposed framework, by addressing aspects such as the institutional capacity of those entities in charge of planning transportation systems. This approach should allow decision-makers to carry out a broader sustainability evaluation of transport-related activities.

Most of the transportation agencies or authorities in local and regional governments are not yet fiscally independent and have clear problems in managing their mobility projects. Hence, they present weak fiscal and poor governance [8], and it is often critical to understand whether sustainable mobility projects can be adequately carried out. In this sense, this dimension aims at assessing the way public spending is managed in transport-related initiatives, and the degree of independence in planning activities of those entities that are expected to contribute to the sustainability of the systems.

3.2.6 Mobility system effectiveness and land use dimension

Effectiveness is an important component of the definition of sustainability, and therefore, any mobility system that is considered sustainable must also be effective [2]. In such context, transportation systems must make an efficient use of land and other natural resources, while ensuring the preservation of vital habitats and other requirements for maintaining biodiversity, conserving natural resources through sustainable land use [5].

This fifth dimension refers to the performance of the mobility system itself, that may have consequences in all other dimensions. Transport is to play a critical role as a facilitator in achieving the targets of other sectors to promote sustainability. Hence, there is a growing recognition that transport systems must take into account the costs of environmental degradation and social damage, as a way to promote sustainable development and sustainable transport systems [84].

In fact, transport systems are designed to maximize land use efficiency, but their effectiveness is related to ensuring that transport demand is met effectively. Without the right transport policies, the interactions between supply and demand do not generally result in effective transport systems. Excessive traffic congestion is an example of ineffectiveness, as drivers only consider their own travel costs and disregard the additional travel time they impose on other vehicles [42]. Since every additional vehicle reduces the available road space, excessive traffic congestion can easily occur, possibly with an inefficient distribution of costs among users [42]. Therefore, public transport, consuming significantly less road space than cars, contributes to a more efficient allocation of road space, thus reducing traffic and helping achieve an optimal level of road use. That is why this dimension integrates different aspects that are essential to support the formulation processes of transport policies, aiming at reducing the externalities of the mobility system.

The proposed *analysis structure* is intended to support the development of indicators to measure and track the performance of emerging cities, regarding sustainability. Nonetheless, due to the inherent complexity in determining the factors that affect the sustainability of mobility systems, this work should be viewed as an initial basis that can be modified to integrate further relevant concepts, if useful.

3.3 Summary

Our literature review has shown the lack of a comprehensive *analysis structure* to assess sustainability for mobility systems in emerging cities. Hence, a new framework was designed to integrate the three basic dimensions of sustainability (environment, economic and social), as defined in previous research, with other dimensions taking into account some additional relevant aspects (the impact of activities related to urban transport in the human health as an element aggregated to the environment; operational attributes; fiscal and governance; and mobility systems effectiveness and land use).

In fact, an evaluation of sustainability in mobility systems based solely on the three traditional dimensions is surely a narrow and limited conceptualization, that may generate confusion in the decision-making processes. For example, an option may seem good and desirable when evaluated using those dimensions, but may be considered harmful if other relevant aspects are incorporated in the analysis. Such situations may lead to investments in sustainability projects that are not effective and do not achieve the expected goals.

We expect therefore that the conceptualization of sustainability dimensions proposed in this chapter can help transportation managers and policy-makers better understand local and global sustainability issues and the potential conflicts and trade-offs between those issues [2]. Moreover, this knowledge can guide us in the development of a more comprehensive sustainability framework [51].

The proposed *analysis structure* should not be understood as a single vision of how to evaluate sustainability in the mobility systems of emerging cities. But there is a growing demand for suitable planning tools, and this research outcome can be very useful to support policy design and assessment of sustainable mobility, in emerging cities. Thus, it will serve as a basis for the second stage in this work: developing an *assessment framework* based on indicators for each of the five dimensions defined herein.

4 A conceptual framework to assess sustainability in mobility systems of emerging cities

4.1 Introduction

Based on the findings of the previous chapter, we describe here a conceptual framework to define and select consistent indicators. We discuss to consider when selecting sustainability indicators, present a sustainability indicator set in two phases (*preliminary and exploratory phase*) and provide guidelines on these phases. Finally, we develop a comprehensive framework to measure and assess the performance of mobility systems in terms of sustainability indicators.

4.2 The role of indicators as a measurement tool for transport systems

According to [90], a critical component of sustainable transport planning is the development of a comprehensive evaluation framework to assess the performance of mobility systems with regard to sustainability, based on an appropriate set of indicators, grouped by dimensions as proposed in this research.

In such context, [24] stated that the "*transportation planning activities must rely on indicators (standardized information suitable for analysis) for guidance. Just as people rely on senses such as sight, hearing and touch, indicators let us analyze trends and model impacts. Therefore, they are an important tool for decision making and measuring progress*".

Such indicators have many uses for planning and management, as well as in decision-making processes. This data can help establish baselines, identify trends, predict problems, assess options, set performance targets, and evaluate a particular jurisdiction or organization [5].

Indicators are capable of generating information for decision-making processes which enable tracking and monitoring goals, benefits, efficacy and efficiency of the proposed actions [91]. Indicators simplify, measure and communicate trends and events [92], and can reflect whether trends are positive or negative with respect to objectives. They also serve to define problems and to establish goals and objectives, as well as to support the development of policies, plans and programs, establishing performance targets and measuring impacts [5].

According to [3], indicators are composed of qualitative and quantitative sets of measurement that allow cities to evaluate their performance and assess progress over time. Indicators are variables selected and defined in order to evaluate progress towards goals and objectives [5]. They also help to guide policy, planning and management, across multiple sectors and stakeholders [3].

Indicators are tools or quantitative measures that can illustrate and communicate complex phenomena simply, including trends and progress over time [93]. Taking into account that transport is a priority area of sustainability, the selection of indicators for measurement and assessment of transport activities plays an important role in the decision and policy-making process [89]

In such context, [89] observes that indicators are useful for highlighting problems, identifying trends, contributing to priority-setting, policy formulation and evaluation and monitoring of processes and, in this way informing the public and the decision-makers.

4.3 Indicator selection criteria

According to [89], the selection of indicators is generally based on certain internationally established and commonly used quality criteria. In addition, [3] concluded that the "*selection of sustainability indicators for transportation could provide an important framework for the transportation sustainability measurement and for the development and improvement of the strategies to eliminate negative impacts from transport activities*".

Indicators should be carefully selected to provide useful information. In most situations, no single indicator is adequate, so a set should be selected, reflecting various goals and objectives. The Canadian Victoria Transport Policy Institute (VTPI) [5] suggests that the selection of indicators to measure transportation performance should take into the account the following criteria:

- *comprehensiveness*: indicators should reflect various impacts derived from transportation related activities;
- *data quality*: data collection practices should reflect high standards to ensure that information is accurate and consistent;
- *comparability:* data collection should be standardized so that the results are suitable for comparisons between various jurisdictions, times and groups (indicators should be clearly defined);

- *easiness to understand:* indicators must be useful to decision makers and understandable to the general public;
- *accessibility and transparency:* indicators (and the data they are based on) and analysis details should be available to all stakeholders;
- *cost effectiveness*: indicators should be cost effective to collect (the decision-making worth of the indicators must outweigh the cost of collecting them);
- *net effects:* indicators should differentiate between net (total) impacts and shifts of impacts to different locations and times; and
- *performance targets:* indicators should be suitable for establishing useful performance targets.

Therefore, selecting the appropriate indicators to guide sustainable transport assessment is a challenge for transportation planners. Hence, this research describes a process to define the sustainability measurement *analysis structure* supported in dimensions and indicators of sustainability, under a clear methodology that integrates the two following main concerns.

The first concern is related to the completeness of the *analysis structure*. According to [1], a broad set of indicators can ensure more quality in terms of completeness, but this condition has a big issue on the data collection costs and serious difficulties of interpretation. On the other hand, our literature review shows that a limited and easily available set of indicators is more convenient to be used, but can have problems with the lack of variables that may overlook important impacts, thus distorting planning decisions [1].

Consequently, a second concern has to do with the indicator selection processes due to the overabundance of sustainability indicators and the difficulty to understand their relevance for sustainability. Therefore, a successful sustainability assessment will depend on a careful selection of indicators [3]. Hence, there is a clear tension between convenience and comprehensiveness, when selecting indicators [5].

In this context, [94] states that, to take full advantage of their attractive qualities and their applicability, indicators must be carefully selected because unsuitably selected indicators will unavoidably lead to ambiguous conclusions. A particular policy may rank high when evaluated using one set of sustainability indicators, but low when ranked using another set [5].

Therefore, due to the complexity in addressing the sustainability of mobility systems, a complete *analysis structure* of sustainability indicators is required in terms of completeness, efficacy and effectiveness, taking into account as much as possible all the variables that can affect the performance of the systems.

According to [5], individual indicators should be selected based on their decision-making usefulness and ease of collection. By defining indicators early in a planning process, it is often possible to minimize data collection costs. Sustainability indicators can be integrated with other types of accounting statistics. Indicator sets should be derived as much as possible from existing accounting data sets, but these data sets should be extended to encompass sustainable development requirements.

From this overview, we can conclude that there is a need for developing clear methodologies to evaluate the mobility systems of emerging cities regarding sustainability. Consequently, the aim of this research is to provide guidance about which measuring tools can improve sustainability policies design, and not necessarily to provide a final list of indicators for measuring sustainability in the mobility systems of emerging cities.

In such context, instead of dealing with isolated social, economic and environmental aspects, new indicators must tackle plans involving characteristics such as integration, long-term planning, and a wide-spread range of actors [14].

Nevertheless, the use of indicators is just one step in the overall planning process, therefore this research incorporates the proposed sustainability measurement *analysis structure* as a useful element in the design of a *decision support system* for policy design and assessment of sustainable mobility of emerging cities (see chapter 7).

4.4 Conceptual framework: preliminary phase

The *analysis structure* proposed here addresses all major dimensions of transport sustainability, such as environmental, economic and social sustainability, and incorporates a new vision of sustainability, including dimensions in the areas of operational sustainability, fiscal and governance sustainability, mobility systems effectiveness and land use, connecting human health with the environmental dimension, as well as linking the economic and the social dimensions.

Appropriate transport sustainability indicators were identified as described in section 3.1.1 "*preliminary phase*". The process to define suitable indicators includes the following steps:

1. identify and redefine existing sustainable transport-related indicators and evaluate their relevance, considering the current factors that can affect the sustainability of mobility systems, taking into account other variables that, due to the inherent complexity in determining sustainability in the mobility sector, may also be relevant;
2. identify and propose new sustainability measurement indicators according to the availability, accessibility, quality of data, comparability and cost to collect;
3. design and develop a *preliminary analysis structure*; and
4. use the *preliminary analysis structure* in a formal discussion with experts, and consolidate an *exploratory analysis structure* for further prioritization.

The *preliminary analysis structure* contains 5 dimensions, and 26 indicators (see Table 4.1 to Table 4.7). It was the direct result of the process of indicator extraction from literature, as well as from the recommendations made at interviews with planners and experts.

The next step was to compile and organize this extensive list of topics and indicators to eliminate similar and overlapping candidate indicators from the set. Many were renamed and consolidated as they were essentially measuring the same variables, while others were eliminated because they were either poorly defined, reflected less essential issues, or would likely require extensive data or analytical work to be applied.

The number of indicators was therefore significantly reduced, in order to reach a small set of a manageable size. This concise indicator list was tentatively grouped in 5 sustainability dimensions (see chapter 3): environment and human health; economic and social; operational; fiscal and governance; and efficiency of the mobility system.

Table 4.1 Preliminary *analysis structure* of indicators to measure the *environmental and human health* dimension

dimension	*indicator*	*measurement*	*reference values*		*source*
			worst	*best*	
Environmental and human health	Air quality (PM10) ($\mu g/m^3$)	Annual average daily concentrations of PM10	40	0	Redefinition from literature review
	NO_x concentration ($\mu g/m^3$)	Annual daily concentration of NO_x	40	0	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Transport related CO_2 emissions (*t/person/year*)	Average carbon dioxide (equivalent) emitted per person from transport activities	3	0	Redefinition from literature review
	Traffic noise pollution (*dBA*)	Annual average sound pressure resulting from traffic noise	53	10	Redefinition from literature review
	Traffic related fatalities (*deaths / 100,000 inhabitants*)	Road fatalities per 100,000 inhabitants	35	0	Redefinition from literature review

Table 4.2 Preliminary *analysis structure* of indicators to measure the *economic and social* dimension

dimension	*indicator*	*measurement*	*reference values*		*source*
			worst	*best*	
Economic and social	Direct trip cost for user (*%*)	Average monthly cost of an urban trip in public transport, compared to minimum wage	20	3.5	Redefinition from literature review
	Indirect trip cost for user (*minutes*)	Average time spent in a trip for work in public transport, during a typical week	62.1	18.4	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Population density (*inhabitants/km*^{2})	Ratio between the population and the urban area	0.7	17.8	Redefinition from literature review
	Variation of public transport in the modal split (*%*)	Variation of the percentage of the trips made by public transport compared to its share in the previous measurement	0	100	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews

Table 4.3 Preliminary *analysis structure* of indicators to measure the *economic and social* dimension (continued)

dimension	*indicator*	*measurement*	*reference values*		*source*
			worst	*best*	
Economic and social	Variation of non-motorized modes in the modal split (*%*)	Variation of the percentage of the trips made by non-motorized modes compared to its share in the last previous measurement	0	100	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Transport security (*users / 1,000 passengers*)	Proportion of transport users that have been subject of petty crime and other security related incidents	10	0	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews

Table 4.4 Preliminary *analysis structure* of indicators to measure the *operational* dimension

dimension	*indicator*	*measurement*	*reference values*		*source*
			worst	*west*	
Operational	Public transport frequency (*buses/day*)	Frequency of the public transport route with the highest load	32	515	Redefinition from literature review
	Bike sharing performance (*bicycles / 1,000 inhabitants*)	Ratio between the total quantity of bicycles in public shared system and the population	84	238	Redefinition from literature review
	Road network density (*km/km^2*)	Ratio between the total length of the urban road network and the urban area	11	3.7	Redefinition from literature review
	Efficiency of public transportation (MJ*/passenger.km*)	Energy consumption of public transport per passenger kilometer	18.46	0.54	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Parking capacity (*number of parking spaces / inhabitant*)	Number of parking spaces (on and off-street) available in the central area	0.54	0.01	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Parking cost (*%*)	Average cost of short-term parking (up to 2 hours) as a proportion of daily minimum wage	5	30	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews

Table 4.5 Preliminary *analysis structure* of indicators to measure the *fiscal and governance* dimension

dimension	*indicator*	*measurement*	*reference values*		*source*
			worst	*best*	
Fiscal and governance	Financial attractiveness of public transport (*cost public transport / cost private car*)	Ratio between the price of a 5 km journey with public transport and the cost of a 5 km journey with own private car	6.7	0.2	Redefinition from literature review
	Public expenditures and investment in transport system (*%*)	Share of local authority's financing devoted to transport; running five-year average	10	50	Redefinition from literature review
	Financial autonomy (*score between 0 (not) – 1 (yes)*)	Financial autonomy for investment in mobility projects	0	1	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Master plan (*score between 0 (not) – 1 (yes))*)	Existence of a master plan covering mobility and sustainability	0	1	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews
	Debt ratio (*%*)	Ratio between average annual debt derived from mobility projects and the annual budget allocated to the mobility sector	-	-	Definition proposed by this research supported in the literature review, as well as from feedback of the interviews

Table 4.6 Preliminary analysis structure of indicators to measure *the efficiency of the mobility system* dimension

dimension	*indicator*	*measurement*	*reference value*		*source*
			worst	*best*	
Efficiency of the mobility system	Impact of transport public policy (*scale 0 – 10*)	Qualitative assessment of public policies in mobility	0	10	Redefinition from literature review
	Satisfaction with the mobility services (*%*)	Percentage of users satisfied with urban mobility services	30	95	Redefinition from literature review
	Pathways for pedestrians (*m^2/inhabitant*)	Ratio between the total length of protected pedestrian infrastructure and the total inhabitants in the urban area	3.5	10	Redefinition from literature review

Table 4.7 Preliminary analysis structure of indicators to measure the *efficiency of the mobility system* dimension (continued)

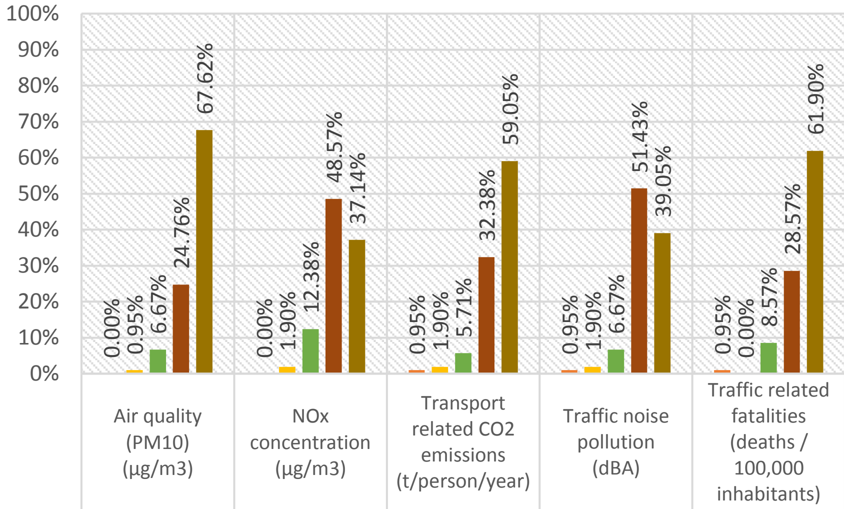
dimension	*indicator*	*measurement*	*reference value*		*source*
			worst	*best*	
Efficiency of the mobility system	Cycle path network density (*bikes/inhabitant*)	Ratio between the total length of cycle infrastructure and the total inhabitants	0	4.6	Redefinition from literature review
	Motorization rate (*vehicles / 1,000 inhabitant*)	Ratio between the quantity of motorized vehicles and the population	750	110	Redefinition from literature review

4.5 Conceptual framework: exploratory phase

After grouping the indicators into the 5 dimensions, the next step was to redesign the *preliminary* sustainability *analysis structure* based on the analysis of the information gathered through an *on-line* survey via Survey Monkey (see Appendix B), (see section 3.1.1).

The information gathered by the survey was processed using quantitative and qualitative analyses of descriptive statistics, considered as an *exploratory analysis*, as presented in Figure 4.1 to Figure 4.5 and Table 4.8 to Table 4.12, and described for each dimension in the following sections.

4.5.1 Analysis of the indicators to measure the *environment and human health* dimension



	Air quality (PM10) (µg/m3)	NOx concentration (µg/m3)	Transport related CO2 emissions (t/person/year)	Traffic noise pollution (dBA)	Traffic related fatalities (deaths / 100,000 inhabitants)
Absolutely unimportant (1)	0.00%	0.00%	0.95%	0.95%	0.95%
Somewhat unimportant (2)	0.95%	1.90%	1.90%	1.90%	0.00%
Neither important nor unimportant (3)	6.67%	12.38%	5.71%	6.67%	8.57%
Very important (4)	24.76%	48.57%	32.38%	51.43%	28.57%
Absolutely important (5)	67.62%	37.14%	59.05%	39.05%	61.90%

Figure 4.1 Relative importance of indicators to measure the *environment and human health* dimension

Table 4.8 Statistics for the indicators to measure the *environment and human health* dimension

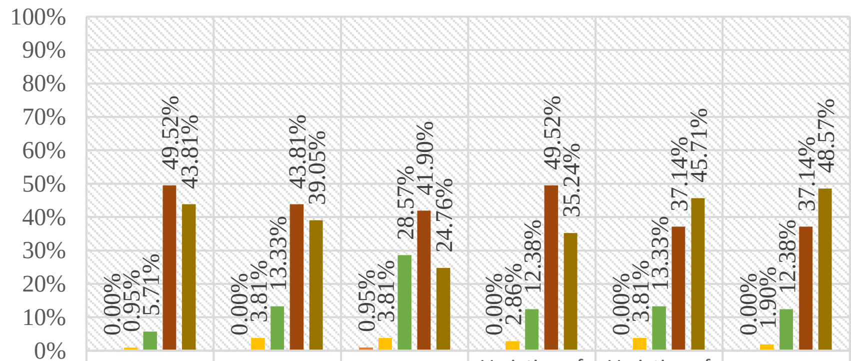
indicator	*minimum*	*maximum*	*median*	*mean*	*standard deviation*
Air quality (PM10) (*µg/m³*)	2.00	5.00	5.00	*4.59*	0.66
NOx concentration (*µg/m³*)	2.00	5.00	4.00	*4.21*	0.73
Transport related CO_2 emissions (*t/person/year*)	1.00	5.00	5.00	*4.47*	0.77
Traffic noise pollution (*dBA*)	1.00	5.00	4.00	*4.26*	0.74
Traffic related fatalities (*deaths / 100,000 inhabitants*)	1.00	5.00	5.00	*4.50*	0.73

According to the surveys statistics in Table 4.8, and the feedback obtained from the open questions, *traffic related fatalities* and *air quality* indicators had a higher score, which is consistent with the recommendations of the literature.

Other indicators related to *air pollution resulting from transport activities* were suggested by the participants, but according to the selection criteria, and to avoid the list of indicators from going back to the initial stage of the *preliminary phase* (where many indicators were eliminated, and renamed, or redefined, because they were measuring the same variables), all the indicators in the *exploratory phase* for the *environment and human health* dimension were retained.

The two indicators with the lowest score were ratified due to their significant impact on human health, and the *transport related CO_2 emissions* indicator was defined as relevant because it was considered one of the critical planetary boundaries. In summary, this sustainability dimension, with its indicators, was considered intuitively good, and all its components were rated as very important, as presented in Table 4.13.

4.5.2 Analysis of the indicators to measure *the economic and social* dimension



	Direct trip cost for user (%)	Indirect trip cost for user (minutes)	Population density (inhabitants/ km2)	Variation of public transport in the modal split (%)	Variation of non-motorized in the modal split (%)	Transport security (users / 100,000 passengers)
Absolutely unimportant (1)	0.00%	0.00%	0.95%	0.00%	0.00%	0.00%
Somewhat unimportant (2)	0.95%	3.81%	3.81%	2.86%	3.81%	1.90%
Neither important nor unimportant (3)	5.71%	13.33%	28.57%	12.38%	13.33%	12.38%
Very important (4)	49.52%	43.81%	41.90%	49.52%	37.14%	37.14%
Absolutely important (5)	43.81%	39.05%	24.76%	35.24%	45.71%	48.57%

Figure 4.2 Relative importance of indicators to measure the *economic and social* dimension

Table 4.9 Statistics for the indicators to measure the *economic and social* dimension

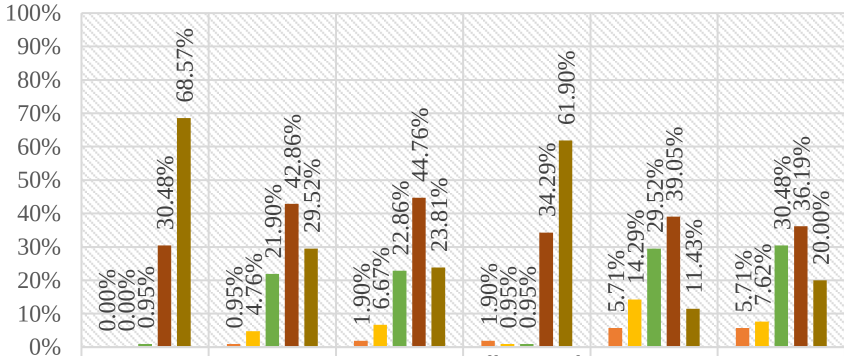
indicator	*minimum*	*maximum*	*median*	*mean*	*standard deviation*
Direct trip cost for user (*%*)	2.00	5.00	4.00	*4.36*	0.63
Indirect trip cost for user (*minutes*)	2.00	5.00	4.00	*4.18*	0.80
Population density (*inhabitants/km²*)	1.00	5.00	4.00	*3.86*	0.87
Variation of public transport in the modal split (*%*)	2.00	5.00	4.00	*4.17*	0.75
Variation of non-motorized in the modal split (*%*)	2.00	5.00	4.00	*4.25*	0.83
Transport security (*users / 1,000 passengers*)	2.00	5.00	4.00	*4.32*	0.76

The exploratory proposal for this dimension was changed, following the results of rather interesting discussions. Indicators of shifts (variations) were generally accepted as a good idea, as well as the proposal of the indicator related to *direct trip cost* for the user (that is typical in transport). Here we have considered cost compared to wage, with the name of the indicator being changed to *public transport (PT) affordability*, with the incorporation of new aspects in the definition of its relevance, as described in Table 4.15.

The *indirect trip cost for user* seems to be a quite relevant indicator, and can be measure in an interesting way by the duration the trip (time in minutes). The *transport security* indicator was defined as a societal issue more related to inequity and poverty, but interesting to evaluate, when consolidating sustainable transport systems in the particular context of emerging cities. The indicator with the lowest score was kept due to its relevance, (see Table 4.15).

In summary, indicators related to the *economic and social* dimension could be an endless discussion, not easily boiled down to a few indicators. Therefore, this sustainability dimension incorporates new indicators in the *analysis structure*, considering the criteria previously described.

4.5.3 Analysis of the indicators to measure the *operational* dimension



	Public transport frequency (vehicle/day)	Bike sharing performance (Bicycles / 100,000 habitants)	Road network density (km/km2)	Efficiency of public transportation (MJ/passenger.km)	Parking capacity (Number of parking spaces)	Parking cost (%)
Absolutely unimportant (1)	0.00%	0.95%	1.90%	1.90%	5.71%	5.71%
Somewhat unimportant (2)	0.00%	4.76%	6.67%	0.95%	14.29%	7.62%
Neither important nor unimportant (3)	0.95%	21.90%	22.86%	0.95%	29.52%	30.48%
Very important (4)	30.48%	42.86%	44.76%	34.29%	39.05%	36.19%
Absolutely important (5)	68.57%	29.52%	23.81%	61.90%	11.43%	20.00%

Figure 4.3 Relative importance of indicators to measure the *operational* dimension

Table 4.10 Statistics for the indicators to measure the *operational* dimension

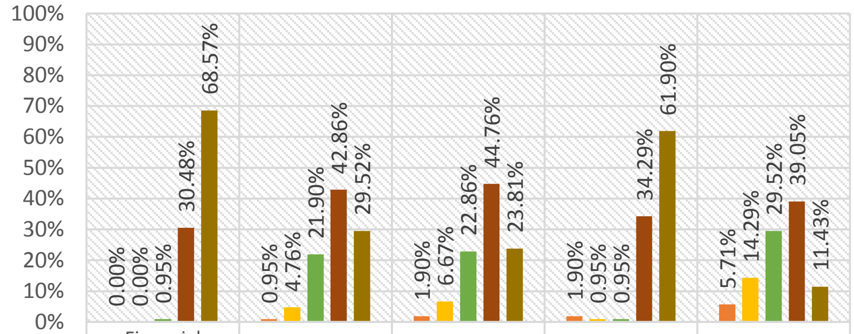
indicator	*minimum*	*maximum*	*median*	*mean*	*standard deviation*
Public transport frequency (*buses/day*)	3.00	5.00	5.00	*4.68*	0.49
Bike sharing performance (*bicycles / 1,000 habitants*)	1.00	5.00	4.00	*3.95*	0.89
Road network density (*km/km^2*)	1.00	5.00	4.00	*3.82*	0.93
Efficiency of public transportation (megajoule/*passenger.km*)	1.00	5.00	5.00	*4.53*	0.74
Parking capacity (*number of parking space/inhabitant*)	1.00	5.00	4.00	*3.36*	1.04
Parking cost (%)	1.00	5.00	4.00	*3.57*	1.07

As shown in Table 4.10, the indicators proposed to measure the *operational* dimension were not entirely clear. This was mainly due to the definition of inappropriate reference values. Therefore, new indicators were incorporated, and other indicators that had been defined within other sustainability dimensions were switched to this one.

In addition, the reference values were redefined based on the fact that *land use* is a major contributor to environmental (un)sustainability, while abundant *free parking* is a major driver for car use and dependency (to be reduced or minimize)

In general, this proposal was rethought, taking into account that indicators should clearly support a shift towards more sustainable transport modes. This means active/semi-active mode safe infrastructure provision, then public transport, with priority given to rail and electric, and at the very bottom of the reverse traffic pyramid, the car [95], (see Table 4.18).

4.5.4 Analysis of the indicators to measure the *fiscal and governance* dimension



	Financial attractiveness of public transport (cost public transport/cost private car)	Public expenditures and investment in transport system (%)	Financial autonomy (score between 0 (not) – 1 (yes))	Master plan (score between 0 (not) – 1 (yes)))	Debt ratio (%)
Absolutely unimportant (1)	0.00%	0.95%	1.90%	1.90%	5.71%
Somewhat unimportant (2)	0.00%	4.76%	6.67%	0.95%	14.29%
Neither important nor unimportant (3)	0.95%	21.90%	22.86%	0.95%	29.52%
Very important (4)	30.48%	42.86%	44.76%	34.29%	39.05%
Absolutely important (5)	68.57%	29.52%	23.81%	61.90%	11.43%

Figure 4.4 Relative importance of indicators to measure the *fiscal and governance* dimension

Table 4.11 Statistics for the indicators to measure the *fiscal and governance* dimension

indicator	*minimum*	*maximum*	*median*	*mean*	*standard deviation*
Financial attractiveness of public transport (*cost public transport/cost private car*)	2.00	5.00	4.00	*4.30*	0.68
Public expenditures and investment in transport system (*%*)	1.00	5.00	4.00	*4.31*	0.76
Financial autonomy (*score between 0 (not) – 1 (yes)*)	1.00	5.00	4.00	*3.98*	0.88
Master plan (*score between 0 (not) – 1 (yes))*)	1.00	5.00	5.00	*4.43*	0.77
Debt ratio (*%*)	1.00	5.00	4.00	*3.75*	0.94

For this case, the idea of an upstream indicator based on principles (the *master plan*) was considered as a positive addition. This aspect was consider very interesting, by some stakeholders, who made some specific recommendations on how to measure the associated indicator (see Table 4.20).

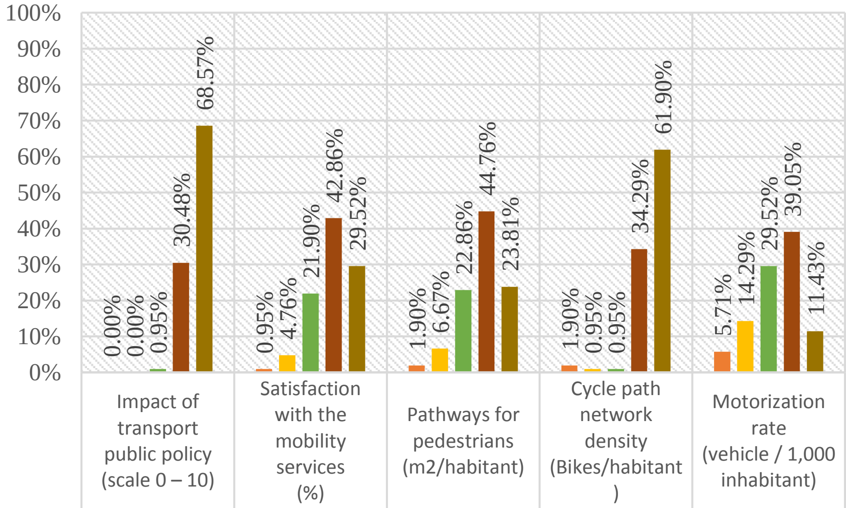
The use of a qualitative scale was well accepted but with some suggested modifications, e.g. the *master plan* indicator could be defined as a continuous value (as opposed to a binary one) depending on the objectives it contains, which should strive for high share of active / semi-active modes, in a relatively short time.

The *debt ratio* indicator was eliminated for not being considered important from the perspective of sustainability for transport systems, since quality and sustainable transport requires investments and therefore debts. In the sector of governance, the *level of engagement with stakeholders* was considered to be important, given that decision making should not happen in a vacuum, but it should rather engage civil society and academia. Such indicator could be measured with a ranking from 1 to 5.

For the same sector, the *diversity and educational background of planners* was considered important, because typically they are male highway engineers and male economists and modelers, which was generally considered quite negative. Therefore, the planning team should include women, social scientists and ecologists.

In summary, decision-support should not only rely on economic or traffic models, but also on more complex qualitative data and multi-criteria analysis tools, based on sustainability principles.

4.5.5 Analysis of indicators to measure the *efficiency of the mobility system* dimension



	Impact of transport public policy (scale 0 – 10)	Satisfaction with the mobility services (%)	Pathways for pedestrians (m2/habitant)	Cycle path network density (Bikes/habitant)	Motorization rate (vehicle / 1,000 inhabitant)
Absolutely unimportant (1)	0.00%	0.95%	1.90%	1.90%	5.71%
Somewhat unimportant (2)	0.00%	4.76%	6.67%	0.95%	14.29%
Neither important nor unimportant (3)	0.95%	21.90%	22.86%	0.95%	29.52%
Very important (4)	30.48%	42.86%	44.76%	34.29%	39.05%
Absolutely important (5)	68.57%	29.52%	23.81%	61.90%	11.43%

Figure 4.5 Relative importance of indicators to measure the *efficiency of the mobility system*

Table 4.12 Statistics for the indicators to measure the *efficiency of the mobility system*

indicator	*minimum*	*maximum*	*median*	*mean*	*standard deviation*
Impact of transport public policy (scale 0 – 10)	2.00	5.00	4.00	4.41	0.66
Satisfaction with the mobility services (%)	2.00	5.00	5.00	4.43	0.73
Pathways for pedestrians (m^2/habitant)	1.00	5.00	5.00	4.45	0.69
Cycle path network density (Bikes/habitant)	1.00	5.00	4.00	4.32	0.74
Motorization rate (vehicle / 1,000 inhabitant)	1.00	5.00	4.00	3.92	0.89

This dimension seems to be well defined and reflects the general comments about prioritizing focus on active modes and public transport. The fist indicator (*impact of transport public policy*) despite the fact that it was marked as "*very important*" was restructured and its definition was combined and redefined in a new indicator, due to the ambiguity in the way it is formulated. In what concerns the motorization rate of vehicles, we could conclude that it is only important if accompanied with a goal for reduction, and expanded to measure the motorization rate in motorcycles.

Moreover, this dimension was renamed, and new aspects were incorporated in its definition (see chapter 3). In general, we have concluded that the indicators mentioned here must be focused on the level of success in shifting mobility from least sustainable modes to more sustainable modes (in terms of CO_2 and energy use, space use, natural resources use, and equity and quality of the travel experience). Therefore, other indicators were incorporated according to the selection criteria, as presented in Table 4.22.

4.5.6 Exploratory *analysis structure* of sustainability measurement

The *exploratory analysis structure* is still based on 5 dimensions (as discussed in chapter 3), but now with 42 indicators (see Figure 4.6), For this redefinition, the results of the preliminary research phase were coupled with an extended literature review.

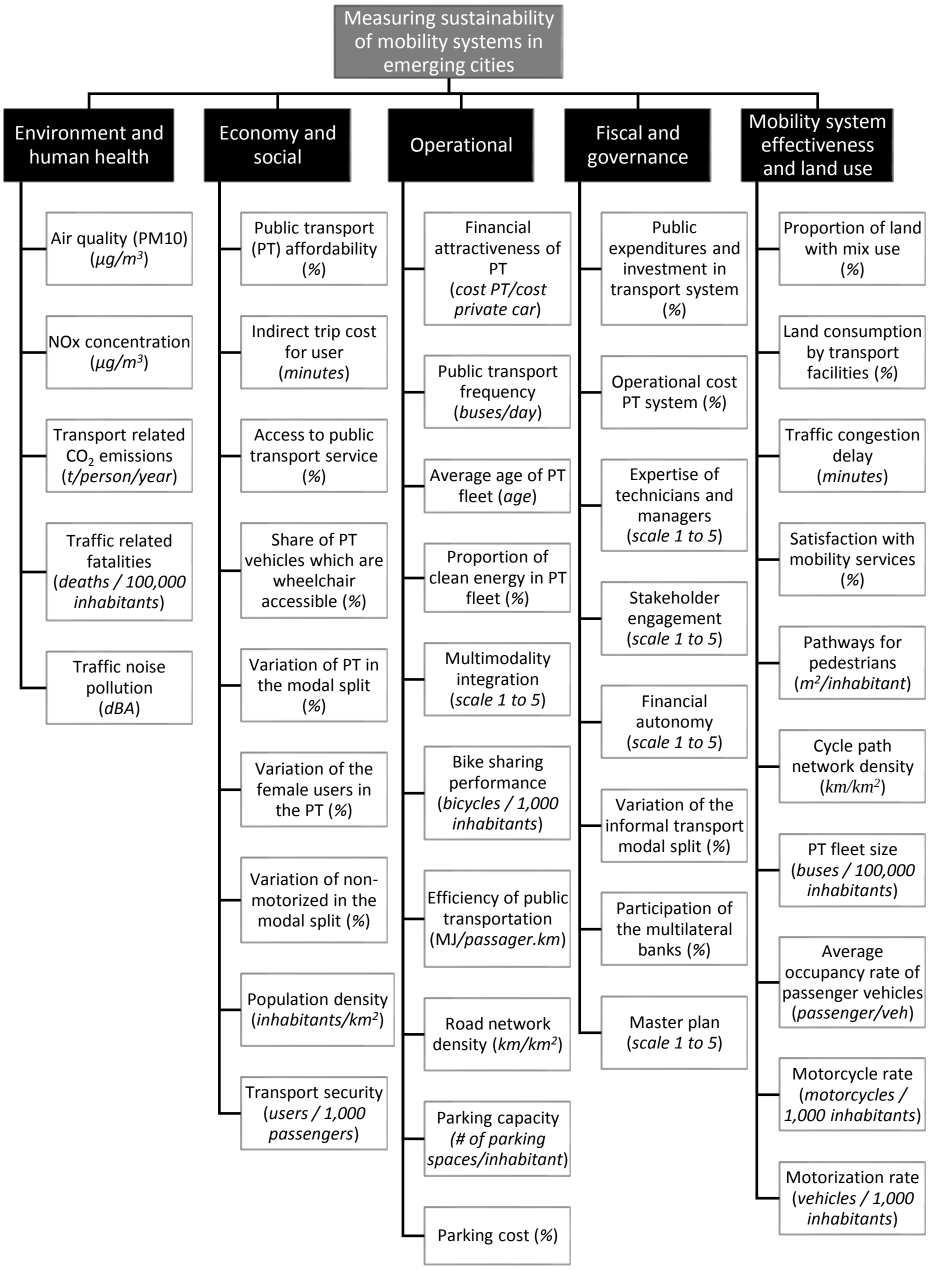


Figure 4.6 *Exploratory analysis structure* (dimensions and indicators) for assessing sustainability of mobility systems in emerging cities

At this stage, the resulting framework seemed to be sound, useful, and practically relevant for assessing the sustainability of mobility systems in emerging cities. An example to illustrate its application is presented in chapter 6.

4.5.7 The exploratory *analysis structure*

This section describes all the indicators that make up the measurement *analysis structure* (see Table 4.13 to Table 4.24), providing specific information and using the following five elements:

1. *Indicator name:* the name proposed for each indicator.
2. *Unit of measurement*: the metrics needed to actually measure and report the indicator.
3. *Relevance for sustainable transport:* this element explains why the topic and indicator is relevant for sustainable transport, and provides the overall justification for including the indicator in the *exploratory analysis structure*.
4. *Proposed definition:* the specific definition of what is measured.
5. *Worst and best reference values of indicator scale:* for each indicator, *worst* is understood as the poorest performance of an indicator in a mobility system of the city, whereas *best* is considered the best possible value in practice. These *reference values* are derived from an extensive literature review, and from reports on what can be considered as the worst and best-case scenarios for emerging cities. In some cases, the worst and best values are defined based on the feedback gathered on the interviews. According to [21], these scales must reflect a complete and realistic range so that the comparison across indicators is not distorted – if the best value for some indicators were set by an ideal goal far above what is realistic, all cities would perform almost equally poor for that indicator, with almost no differences among cities. However, [21] also established that the precise definition of the worst or best scale is not necessarily that critical for results – as long as the scales are fairly comparable, the ranking among cities will not be affected significantly.

In general terms, the desired direction of change of each indicator should obviously be towards the best value reference defined. The definition of indicators in some cases is drawn directly form the literature, even if different definitions have been proposed, but some indicators are defined for the specific context of this research based on the analysis of the primary information gathered through the survey and the interviews.

Table 4.13 Indicators to measure the *environment and human health* dimension

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Air quality (PM10)	Micrograms per cubic meter *(μg/m³)*	Traffic is a major source of air pollution in cities causing significant health problems that affect both people and the planet. Moreover, more than 80% of the world population lives in urban areas exposed to air quality levels that exceed World Health Organization (WHO) limits [21]. According to the database of measurements by WHO, more cities are covered for PM10 (used here), whereas PM2.5 is more accurate as a health indicator. Particulate matter does not only reflect pollution from traffic but also from other sources. However, traffic is a major contributor [21]. This indicator is useful for estimating effects of sustainable transport policies [96].	Annual arithmetic average daily concentrations of (PM10) in the air (population weighted)	40	0
NOx concentration	Micrograms per cubic meter (*μg/m³*)	This indicator is to be applied to monitor Sustainable Development Goal (SDG) target 11.6 by 2030, "reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management" [21].	Annual arithmetic average daily concentration of NO_x in the air	40	0
Transport related CO_2 emissions	Ton CO_2 equivalent emitted/person/year *(t/person/year)*	According to [21] transport contributes worldwide to around one quarter of the global CO_2 emissions. CO_2 is one of the critical planetary boundaries [97]. A major proportion is emitted in cities. This indicator is essential for all strategies to avoid, shift or improve transport systems from the point of view of climate change [21].	Average carbon dioxide (equivalent) emitted per person from transport activities	3	0
Traffic related fatalities	Deaths per 100,000 inhabitants (*deaths / 100,000 inhabitants)*	Traffic accidents are a critical element in public health because they are a leading cause of death in some countries, that generate substantial health and material costs [21]. This indicator serves to monitor the impact of strategies and actions to decrease the probability of the occurrence of traffic accidents with dead or serious injuries.	Road fatalities per 100,000 inhabitants	35	0

Table 4.14 Indicators to measure the *environment and human health* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Traffic noise pollution (dBA)	Decibel levels (*dBA*)	There are many externalities caused by activities related to transport. Traffic noise is one of them that increasingly affects cities. Therefore, planning managers must consider ways to address traffic noise through advance planning. This indicator provides data to support planning processes that minimize the adverse effects of traffic noise.	Annual average sound pressure level related to transport activities	53	10

Table 4.15 Indicators to measure the *economic and social* dimension

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Public transport affordability	Percentage (*%*)	According to [21], transport costs represent a significant share of a typical household budget. Affordability is a commonly recognized feature of a sustainable transport system [21]. This indicator relates to the social and economic dimension and is according to SDG target 11.2 of providing by 2030 affordable transport systems for all.	Average monthly cost of an urban trip in public transport, compared to minimum wage	20	3.5
Indirect trip cost user	Minutes (*minutes*)	High travel costs, in terms of time, can also increase the costs of labor to businesses. Therefore, this indicator aims to measure the time spent in a trip for work in public transport, understating that this type of transport is especially used by people from low income households.	Average time spent in a trip for work in public transport during a typical week	62.1	18.4

Table 4.16 Indicators to measure the *economic and social* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Access to public transport service	Percentage (%)	According to [21], access to public transport is a key requirement for equitable access in a sustainable city. This indicator is relevant in social terms.	Percentage of the population living within walking distance of public transport (stop or station) or shared mobility (car or bike), defined as living 500 meters or less from a public transport stop or 1000 meters or less from a subway transport	30	100
Share of public transport which are wheelchair accessible	Percentage (%)	According to SDG target 11.2 of providing by 2030 accessible transport systems for all. This indicator aims to monitor the offer for access to public transportation for people with reduced mobility.	Ratio between the total number of wheelchair accessible public transport vehicles and the total number of public transport vehicles	10	30
Variation of public transport in the modal split	Percentage (%)	Visions, goals, objectives and targets are key components of a plan, and useful to demonstrate commitment to sustainable transport. Therefore, goals are stronger if they are quantified and accompanied by a performance monitoring process. In this case, the desired increase of the modal share of public transport will be monitored to measure the effectiveness and the impact of the strategies implemented.	Variation of the percentage of the trips made by public transport compared to its share in the previous measurement	0	100
Variation of female users in the public transport	Percentage (%)	One of the main characteristics of sustainable mobility systems is equity, therefore this indicator is intended to monitor the impact of public policies that promote more inclusive transportation systems.	Variation of the percentage of female users in the PT compared to its share in the previous measurement	0	100

Table 4.17 Indicators to measure the *economic and social* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Variation of non-motorized in the modal split	Percentage (*%*)	In response to transport externalities, such as CO_2 emissions, air pollution, energy consumption and congestion, increasing cycling must be one of the main goals to be met by sustainable mobility systems. Therefore, this indicator is relevant to evaluate the fulfillment of this goal.	Variation of the percentage of the trips made by non-motorized compared to its share in the previous measurement	0	+100
Population density	Population per urbanized surface area (*inhabitants/km*^{2})	This indicator is a measure of population per unit of area and serves as the basis for land use planning and transport planning. It is related to SDG target 9.1 "develop quality, reliable, sustainable and resilient infrastructure". Based on this indicator, sustainable public policies can be designed to meet the sustainability goals of mobility systems, such as reducing land consumption, energy consumption, distance travelled, need to travel, car use in urban areas, and increase walking, cycling and share of public transport.	Ratio between the population and the urban area	-	75
Transport security	Public transport users per 1,000 passengers (*users / 1,000 passengers*)	According to SDG target 11.2 of providing access to safe and sustainable transport system for all, this indicator measures the safety in transportation systems, in terms of citizen security.	Proportion of public transport users that have been subject of petty crime and other security related incidents	10	0

Table 4.18 Indicators to measure the *operational* dimension

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Financial attractiveness of public transport	Price of public transport journey over cost of private car journey (*non-dimensional*)	In accordance with SDG target 11.2 of providing by 2030 access to affordable and sustainable transport systems for all. The cost of public transport to the user is critical when selecting the transport mode, therefore public transport must provide affordable, efficient and competitive transport services. This indicator measures the degree of attractiveness of public transport, based on the fact that a high participation of public transport modes supports urban sustainability.	Ratio between the price of a 5 km journey with public transport and the cost of a 5 km journey with own private car	6.7	0.2
Public transport frequency	Number of buses per day (*buses/day*)	Many measures of public transport quality exist. Focus on operational attributes, such as frequency may help to improve its performance [98], [99]. This aspect is often referred to as one of the most critical elements in service quality.	Frequency of the public transport route with the highest load	32	515
Average age of public transport fleet	Age in years (*age*)	This indicator indirectly relates the change to a public transport fleet with clean energy, as well as the satisfaction of the public transport users in safety, quality and comfort.	Average arithmetic age of public transport fleet	15	5
Proportion of clean energy in public transport fleet	Percentage (*%*)	According to SDG target 11.2 this indicator monitors the use of clean energy by the public transport as an important step to consolidate sustainable transport systems for all.	Percentage of clean energy vehicles of total public transport fleet	50	100
Multimodality integration	Qualitative assessment (*scale 1 to 5*)	According to most studies and policy documents, sustainable transportation systems must provide a multimodality integration, preferably including public transport, walking, and cycling.	Existence and effectiveness of bus stops or subways stations with facilities that promote multimodality	1	5
Bike sharing performance	Number of bicycles per 1,000 inhabitants (*bicycles / 1,000 inhabitants*)	According to the hierarchy of mobility users [95] one of the main objectives of a sustainable mobility system is increasing alternative transport modes, such as, cycling. Therefore, this indicator monitors the performance of public bicycle systems to measure the impact of sustainable strategies and develop new situations.	Ratio between the total quantity of bicycles in public shared systems and the population	59	238

Table 4.19 Indicators to measure the *operational* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Efficiency of public transportation	Megajoule per passenger kilometer (*MJ/passenger.km*)	According to [95] one of the objectives of sustainable mobility systems is to reduce energy consumption. This indicator monitors the energy consumption particularly for public transport.	Energy consumption of public transport per passenger kilometer	18.46	0.54
Road network density	Kilometers of road per urbanized surface area (*km/km²*)	According to [95] sustainable mobility systems must reduce car use in urban areas, reduce distance travelled, as well as reduce need to travel. Therefore this indicator monitors the performance of road network density. This indicator is also relevant for SDG target 9.1 "develop quality, reliable, sustainable and resilient infrastructure".	Ratio between the total length of the urban road network and the urbanized surface area	3.7	11
Parking capacity	Number of parking spaces per inhabitant *(number of parking / inhabitant*)	A sustainable mobility system must prioritize transport modes, as follows: active travel (walking, cycling, scooters), rideables (electric scooters, segway, hover boards), public transport (buses, trams, trains, subways) and finally vehicles (trucks, taxis, car, motorcycles). Therefore, the parking capacity for vehicles must be regulated by the planning managers and changed from the minimum required to the maximum allowed.	Ratio between the number of parking spaces (on and off-street) available in the central area and the urban population	0.54	0.01
Parking cost	Percentage (*%*)	Reduce car use in urban areas, reduce congestion and increase walking and cycling are goals of a sustainable mobility system. Therefore, this indicator serves as a measure for meeting these goals.	Average arithmetic cost of short-term parking (up to 2 hours) as a proportion of daily minimum wage	5	30

Table 4.20 Indicators to measure the *fiscal and governance* dimension

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Public expenditures and investment in transport system	Percentage (*%*)	This indicator relates to the fiscal dimension of sustainability. It is proposed to focus investments on public transport, non-motorized modes and in road safety.	Share of local authority's financing devoted to public transport, non-motorized and road safety; running five-year average	10	40
Operational margin of public transport	Percentage (*%*)	According to [21] the operational cost of the public transport system is critical for the ability of a city to provide affordable, efficient and competitive transport services. The cost can be related to the revenue generated form fares to indicate financial sustainability. It relates to the fiscal dimension of sustainability.	Ratio between the fare revenue and the operating cost for public transport systems ("fare box ratio")	22	75
Expertise of technicians and managers	Qualitative assessment (*scale 1 to 5*)	In governance, the diversity and educational background of planners also matter. Typically, they may all be male highway engineers and male economist and modelers. The planning team should include women, social scientists and ecologists.	Level of diversity and educational background of the planners in the transport-related projects	1	5
Stakeholder engagement	Qualitative assessment (*scale 1 to 5*)	Decision-making should not happen in a vacuum, but it should engage with civil society and academia as well.	Level of engagement of the stakeholders in transport-related decision-making process	1	5
Financial autonomy	Qualitative assessment (*scale 1 to 5*)	Transport projects need investments and may involve different costs for their implementation. This indicator shows the degree of financial autonomy of the transport entities to get the financial resources required for the execution of the transport projects.	Degree of financial autonomy for investments in mobility projects	1	5
Variation of the informal transport modal split	Percentage (*%*)	Due to increased informal transport in some emerging cities [100], this indicator aims to monitor the performance of these new transport modes to design sustainable public policies that control and regularize this type of activity, avoiding the impact on the entire transportation system in financial and governance terms.	Variation of the percentage of the trips made by informal transport compared to its share in the previous measurement	1	0

Table 4.21 Indicators to measure the *fiscal and governance* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Participation of the multilateral banks	Percentage (%)	Transport projects must have budget secured. Some budget may be local (tax, revenues), other parts may be from central government, lending institutions (multilateral banks), or innovative finance schemes. This indicator shows both the participation of the multilateral banks in transport projects and indirectly the development towards a sustainable mobility system as a prerequisite for support by this type of lending institutions.	Ratio between the budget provided by multilateral banks for transport-related projects and the public budget assigned to transport-related projects	0	+70
Master plan	Qualitative assessment (*scale 1 to 5*)	Planning and policy documents are an essential element in urban sustainable transport planning. These documents should provide for alternatives to motorized individual transport including public transport, walking, and cycling. This indicator refers to the shift strategy in the sustainable mobility paradigm.	Existence, quality and implementation of the master plan of mobility and sustainability for development of the city	1	5

Table 4.22 Indicators to measure the *mobility system effectiveness* and land use dimension

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Proportion of land with mixed use	Non-dimensional (-)	Space efficiency is often forgotten by transport planners, but land use and land fragmentation have big impacts on biodiversity. Therefore, planning land use with the goal to reduce travel needs can improve residents' quality of life.	Area (m^2) of commercial, industrial, and public land uses in the neighborhood, divided by the number of housing units; the higher the ratio, the greater the land use mix	-	+
Land consumption by public transport facilities	Percentage (%)	[95] defines increased land consumption by transport facilities as one of the main goals to achieve sustainable mobility systems. Therefore, this indicator serves to monitor this goal.	Percentage of the total land consumed by public transport	6.4	21

Table 4.23 Indicators to measure the *mobility system effectiveness and land use* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Traffic congestion delay	Minutes (*minutes*)	Congestion has become one of the main externalities of transport-related activities. Therefore, reduced congestion is defined as one characteristic of sustainable mobility systems. This indicator measures congestion in terms of time.	Average arithmetic travel time of representative routes during peak hours minus average travel time of the same routes during non-peak hours	45	15
Satisfaction with mobility services	Percentage (*%*)	The user's positive experience of the service is critical for the choice of transport mode [101]. Understanding that a sustainable mobility system is based on the use of public transport and alternative modes, such as walking and cycling as the preferred transport modes, this indicator monitors user satisfaction to gain insights about the users' experience, pointing out areas for improvement, and encouraging the use of public transport and alternatives modes.	Percentage of user satisfied with urban mobility	40	100
Pathways for pedestrians	Pedestrian areas in m^2 per inhabitant (m^2*/inhabitant*)	Reduce car use in urban areas, reduce distance travelled, reduce congestion, reduce CO_2 emissions, reduce air pollution and reduce energy consumption are some of the goals of sustainable mobility systems. Hence, increasing alternative modes, such as walking has become the basis of mobility systems that seek sustainability. Therefore, this indicator measures the development of the pathways for pedestrians as an important step for achieving sustainability in the mobility systems.	Ratio between the total length of protected pedestrian infrastructure and the total inhabitants in the urban area	3.5	10
Cycle path network density	Kilometers per urbanized surface area in km^2 (km/km^2)	A transport plan usually identifies projects and measures to be adopted. Hence, this indicator aims to carry out a detailed evaluation of the policies implemented to promote and encourage using the bicycle as a daily alternative mode of transportation. For example, planning dedicated bike lanes along one of the city's main transport corridors.	Ratio between the total length of cycle infrastructure (protected and no protected) and the urbanized surface area	0	4.6

Table 4.24 Indicators to measure the *mobility system effectiveness and land use* dimension (continued)

indicator	*unit*	*relevance*	*definition*	*reference values*	
				worst	*best*
Public transport fleet size	Number of buses per 100,000 inhabitants (*number of buses / 100,000 inhabitants*)	According to [21], in the long term, providing high quality service in urban public transport is essential for attracting more passengers and limiting individual motorized transport. In such context, having the required public transport fleet is essential to guarantee a quality transport service in terms of frequency. However, a number that is larger than the required, in terms of the public transport fleet, can generate negative consequences for the public transport service.	Total number of public transport vehicles expressed in number, or public transport vehicles per 100,000 inhabitants	190	130
Average occupancy rate of passenger vehicles	Number of passengers per vehicle (*passenger/vehicle*)	This indicator explains changes in the level of vehicle ownership and illustrates the efficient usage of private vehicles. Utilization efficiency is one of the main parameters that determine energy and emissions efficiency, as well as congestion in the mobility system, meaning that the average occupancy rate of passenger vehicles is important for the consolidation of sustainable mobility systems.	Arithmetic mean of passengers travelling in private vehicles in urban trips	1.67	2.6
Motorization rate (motorcycles)	Number of motorcycles per 1,000 inhabitants (*motorcycles / 1,000 inhabitants*)	Owing to transport externalities related to the use of the motorcycle as a transport mode, such as major factor in traffic accidents with fatalities and serious injuries, this indicator is relevant to control the high increase of the motorization rate of motorcycles.	Number or motorcycles divided by population, expressed in number of motorcycles per thousand inhabitants	142	82
Motorization rate (automobiles)	Number of private passenger vehicles per 1,000 inhabitants (*vehicles / 1,000 inhabitants*)	A sustainable mobility system aims to reduce car use in urban areas, reduce distance travelled, as well as reduce the need to travel. This indicator is relevant to evaluate the performance of sustainable public policies aimed at controlling the increase in the motorization rate of private vehicles per 1.000 inhabitants.	Ratio between the quantity of motorized vehicles and the population, expressed in number of motorized vehicles per thousand inhabitants	750	110

4.6 Summary

Issues related to sustainability and sustainable transportation are of critical importance for transportation planners and policy makers. We, therefore, need to have mechanisms to measure sustainability, taking into account the different components of urban mobility systems. Based on an extensive literature about indicators and tools to measure sustainability, we have developed a *framework of indicators* within the 5 dimensions defined in chapter 3.

This research concluded that there is no standard sustainable transport evaluation process. Although different researchers have proposed approaches to establish sustainable transport performance programs, there are currently no widely accepted standards, and many cities do not yet have a structured methodology to measure the performance of their mobility systems with regard to sustainability. This is particularly critical in the case of *emerging cities*.

The *exploratory analysis structure* proposed in this chapter is composed of 42 indicators covering key aspects of sustainable urban transport for emerging cities. These indicators are organized in 5 dimensions. This *analysis structure* may help monitor the impact of public policies, and is the basis for a decision support system for policy design and assessment of sustainable mobility in emerging cities, that is described in the remaining chapters.

However, the approach proposed here should not be viewed as an ultimate and unique indicator set, but rather as a support guide for planners and managers, as a way to deal with the inherent complexity in determining the factors that affect the sustainability of mobility systems. Moreover, considering uncertainty about future developments in the area, other variables may become more relevant. Therefore, we expect this framework to simplify the task of evaluating sustainable transportation and to be easily adapted to more specific contexts of different mobility systems in emerging cities.

Overall, translating sustainable transport and sustainability values into a set of indicators grouped in dimensions, should allow decision makers to focus on the main challenges mobility systems face to achieve sustainability. With a more detailed and comprehensive assessment of the entire mobility system and its different components, structuring actions and strategies to improve sustainability becomes more straightforward.

In line with these findings, and with the aim of improving the robustness of the proposed *analysis structure*, the next step in this research (that can be viewed as a *confirmatory phase*) develops a hierarchical framework, refined with expert-based validation and elements prioritization.

5 Prioritizing measurement indicators to assess sustainability

5.1 Introduction

In order to measure sustainability in mobility systems for emerging cities, we have developed a *confirmatory* process (2 phase in the methodology) that prioritizes the previously presented dimensions and indicators. This process was developed around two multi-criteria decision-making (or analysis) methods (MCDM or MCDA), as explained in detail in this chapter. In this work, the following steps were taken:

- discuss the reasons to use multi-criteria decision analysis techniques in this context;
- choose some MCDA techniques for prioritizing criteria, as required in our case;
- collect primary information, and apply the selected MCDA methods;
- present and discuss the results of the approach to allocate weights at each level of the proposed *analysis structure*;
- derive the *confirmatory* sustainability *measurement framework*, hierarchized for mobility systems of emerging cities;
- derive general recommendations and guidelines in the use of the methodology in real situations; and
- define how this *measurement framework* can be used in the case studies (described in chapter 6).

5.2 Multi-criteria decision analysis (MCDA) for sustainability indicators

As shown throughout this research, sustainability is one of the biggest current challenges faced by transportation planners [102]. They are expected to achieve a dynamic balance and trade-offs between ecological dimensions (environmental sustainability), social dimensions (social sustainability), and economic dimensions (economic sustainability), along with the dimensions proposed by this research: technical dimensions (operational sustainability), fiscal dimensions (fiscal and governance sustainability) and mobility systems dimensions (mobility system effectiveness and land use sustainability).

However, as the public's desire for more sustainability grows stronger, so does the need to accurately assess the sustainability of transportation systems, which is no easy task [54], [103]. In such context, to capture the complexity of sustainability, assessment forms often require the integration of multiple indicators into clusters [104], [105], as proposed in our work. As [54] stated, that sustainability indicators have become increasingly important to research and practice. [8] and [9] concluded that while developing sustainability indicators is a critical tool for assessing and ultimately attaining sustainability, the way this is done can radically impact the measured sustainability of a transportation system (see chapter 4).

In this context, measuring sustainability in transportation systems of cities requires selecting appropriate indicators, but it also includes weighting each level (sustainability dimensions at *level 0*, and sustainability indicators at *level 1*).

Finding indicators to measure sustainability is surely easy to do, due to the overabundance of indicators and analysis frameworks in the literature, but selecting appropriate indicators can be challenging, because the process of indicator integration is an inherently subjective procedure [108]. Hence, it is important to recognize that the very choice of an weighting method introduces subjectivity int our analyses [109].

In this sense, [54] concluded that *weighting indicators and dimensions* is a critically important step in any sustainability assessment process. Therefore, their prioritization is also critical. Weights for sustainability indicators and sustainability dimensions reflect the relative importance in their contributions to the sustainability performance of a transportation system. This challenge can be approached using multi-criteria decision analysis (MCDA) methods, here used with the purpose of "weighting" and for ranking of the criteria.

Most MCDA applications include fewer than a dozen criteria, that may be quantitative or qualitative in nature, with 5 / 7 criteria being typical. In such context, [54] concluded that "*while the validity of structures of sustainability measurement is heavily dependent on how their components are weighted, the typology and applicability of the existing weighting methods remain poorly understood*".

However, the wide variety of weighting approaches often introduces subjectivity and uncertainty. Therefore, it is important to select an approach that is consistent with the transportation manager's information needs [109]. Some authors have pointed to this variety as a reason why MCDA is not well-used in sustainability decision making [110], and according to [109] it is not a one-size fits-all tool.

Choosing appropriate weighting methods for a specific sustainability assessment approach is therefore a rather challenging task, in particular, because there is currently no standardized methodology for that purpose. But, due to its effectiveness in supporting decisions involving trade-offs between conflicting objectives, multicriteria decision analysis (MCDA) has been widely used [111].

Therefore, our research proposes a hierarchized measurement approach structured in three levels (sustainability dimensions at *level 0*, sustainability indicators at *level 1*, for measuring sustainability in mobility systems of emerging cities at the top of the hierarchical framework). This approach is based on the application of MCDA, and intends to close the referred knowledge gap, by providing a clear methodology for the application of weighting methods to be used by sustainability transportation analysts.

For this purpose, a specific literature review has been performed, aiming at providing a prioritized sustainability *measurement framework* (based on quantitative data and experts' opinions) for transportation systems, in the specific context of emerging cities.

5.2.1 Weighting methods for sustainability indicators

In MCDA approaches, expert judgment is often used for the estimation of the weights of criteria and sub-criteria, in a hierarchical framework [112]. The estimated values are based on the intuition of experts [113], [114] and [115]. Formal models should, therefore, support expert judgement for producing more reliable estimates [116].

Several weighting approaches have been used for prioritizing elements in a sustainability measurement analysis structure, and sometimes using equal weights produces results nearly as good as optimal weighting methods [117]. This has been the most popular approach used in sustainable transportation assessment, due to the minimal additional input required to conduct the analysis [111]. But, with this approach, there are no real insights on the relationships between indicators, and there is a risk of double weighting [54].

In such context, [111] states that weighting methods based on subjective approaches can provide a clearer explanation of the evaluation process, with the judgments provided by the respondents depending on their level of knowledge or information.

According to the goals of our research, sustainability is defined to measure how far a mobility system is from its targets, or how well aligned a mobility system is with a desired development path. In such context, sustainability *indicators* being grouped in *dimensions* are fundamental for measuring current or expected levels of sustainability, gauging whether implemented strategies are effectively accomplishing their objectives, and supporting the design of strategies that target a sustainable development [54].

The tenets of sustainability require that constructing a sustainability *measurement framework* is a transparent process, leading to results that are easily communicable and interpretable, in order to be embraced by decision makers and the non-expert community [118]. Consequently, weighting is an important step.

There are various weighting methods that could be used for prioritizing criteria in our context. Partially based on [54], for this purpose, we have selected the Analytic Hierarchy Process (AHP), an approach that has been widely used as a multiple-criteria decision analysis tool, and can be a useful method for weighting sustainability indicators [119], [120].

AHP has a hierarchical structure, which is aligned with the way most sustainability frameworks are organized, and is, in general, easy to understand by the stakeholders [121], [122]. AHP is simple and flexible, allowing an easy combination with other techniques such as mathematical programming, or even data envelopment analysis [123].

Unlike other participatory methods [54], AHP provides a consistent verification step, which can be considered a feedback mechanism for experts or decision-makers to review and revise their judgments [124]. On the other hand, it can be used with both qualitative and quantitative data [125], this being in line with the variables that make up our proposal.

Nevertheless, AHP has disadvantages that include the high number of pairwise comparisons and the requirement for a parsimonious number of indicators in each analyzed cluster, but there are ways to partially overcome these weaknesses, as we do in our work. In particular, we incorporate *fuzziness* in the decision-making process, by using the so-called Fuzzy Analytic Hierarchy Process (FAHP), an extension of the AHP method aimed at improving the data consistency, and avoiding rank reversal. Moreover, a large number of papers (more than 50) from our literature review show a consistent use of the AHP and Fuzzy AHP methods in similar applications.

As already mentioned, the basic AHP method suffers from issues related to imprecision and subjectivity in the pairwise comparison process, these problems being effectively handled by FAHP [126], [127]. In FAHP, a range of values is used in place of a single crisp value, in order to incorporate decision maker’s uncertainty [128], [129]. From this range, the value depicting the confidence level of the decision maker can be selected. FAHP has been used in various domains of transportation engineering including planning and quality evaluation.

In our work, we compare the results obtained by the two approaches (AHP and FAHP) in prioritizing and weighting dimensions and indicators, for sustainability measurement in mobility systems of emerging cities.

5.3 The need for prioritizing sustainability indicators

The validity of sustainability indicators is heavily dependent on how their components are weighted. In such context, [54] states that the typology and applicability of the existing weighting methods remain poorly understood. It is, therefore, urgent to design a sound framework of prioritized indicators, serving as a flexible and adaptable guidance on how sustainability can be measured in transportation systems. Such a framework will support transportation managers in their policy making processes.

In this research, AHP and FAHP are used (in a comparative way) to prioritize the elements in the *exploratory* sustainability measurement *analysis structure* defined in chapter 4. The resulting *confirmatory* framework can then be useful for transportation managers for the generation of bottom-up (rather top-down) policies that come from lower-level government organizations. Therefore, in cities with lower institutional capacity, this prioritization can be used to determine which interventions would have the greatest impact. And this is valid even for quite different geo-spatial contexts, as it is the case of Europe, where top-down policies can be designed taking into account the specific features of each transportation system.

Regarding data acquisition, for testing and validating the proposed *exploratory* analysis structure, an AHP-based questionnaire to experts was used in measuring the relative importance of the different elements at different levels, through pairwise comparisons evaluations between those elements.

5.4 Experts' profiles

An *on-line* questionnaire was circulated among 19 sustainability experts from academia, consultancy companies, and government organizations (see Table 5.1). These experts were asked to assess the relative importance of one element in the *exploratory* analysis structure over another in the same level, with respect to the established *level 0* goal "measuring sustainability in mobility systems of emerging cities".

The information gathered by this questionnaire was confirmed and analyzed in 7 (2-hour) recorded face-to-face semi-structured interviews (in English) hold in Copenhagen (Denmark), Malmo and Lund (Sweden), and other 12 recorded virtual semi-structured interviews (2 in English, and 10 in Spanish) by *skype,* between November and December 2019 by the same 19 sustainability experts.

In this *expert judgement*, experts having a similar domain knowledge were consulted to estimate sustainability in transportation systems, in the specific context of emerging cities.

Table 5.1 Experts who responded the questionnaire

Name *[country]*	*Sector* *[topics]*	*Current institutions* *[position]*	*Interview place* *[date]*
Henrik Gudmunsson [Denmark]	Academia/consultancy [Sustainability indicators]	CONCITO [Senior consultant]	Aalborg University [November 2019]
Sidsel Kjems [Denmark]	Academia/Government [Sustainable public policies]	Københavns Kommune [Chief consultant]	Københavns Kommune [November 2019]
Thomas Nielsen [Denmark]	Academia/Government [Sustainability indicators]	The Danish Road Directorate [Senior consultant]	The Danish Road Directorate [November 2019]
Jens Stissing Jensen [Denmark]	Academia [Sustainability indicators]	Aalborg University [Associate professor]	Aalborg University [November 2019]
Andres Valderrama [Denmark]	Academia [Sustainable public policies]	Aalborg University [Associate professor]	Aalborg University [November 2019]
Per Eneroth [Sweden]	Government [Sustainable public policies]	Lunds kommun [head of the road and traffic division]	Lunds kommun [November 2019]

Table 5.2 Experts who responded the questionnaire (continued)

Name [*country*]	*Sector* [*topics*]	*Current institutions* [*position*]	*Interview place* [*date*]
Anna Karlsson [Sweden]	Government [Sustainable public policies]	Lunds kommun [head of the traffic and mobility department]	Lunds kommun [November 2019]
Todd Litman [Canada]	Academia/consultancy [Sustainability indicators]	Victoria Transport Policy Institute [Executive director]	*skype* [November 2019]
Yannick Cornet [Slovakia]	Academia [Sustainability indicators]	University of Žilina [Senior researcher]	*skype* [November 2019]
Luis Felipe Lota [Colombia]	Academia/Government [Sustainability indicators]	Agencia Nacional de Seguridad Vial [Director]	*skype* [December 2019]
Jonathan Bernal [Colombia]	Academia/Government [Sustainable public policies]	Departamento Nacional de Planeación [Director]	*skype* [December 2019]
Sonia Mangones [Colombia]	Academia [Sustainability indicators]	Universidad Nacional de Colombia [Associate professor]	*skype* [November 2019]
Lenin Bulla [Colombia]	Academia/Consultancy [Sustainability indicators]	Universidad Nacional de Colombia [Associate professor]	*skype* [November 2019]
Diego Cabrera [Colombia]	Academia [Sustainability indicators]	Universidad de Bogotá Jorge Tadeo [Associate professor]	*skype* [November 2019]
Carmen Rosales [Colombia]	Consultancy [Sustainable public policies]	Steer Davies Gleave [Associate and planning market leader]	*skype* [November 2019]
Daniel Perez [Colombia]	Academia/Government [Sustainable public policies]	Ministerio de Transporte [Adviser]	*skype* [November 2019]
Ximena Cantor [Colombia]	Government [Sustainable public policies]	Departamento Nacional de Planeacion [Adviser]	*skype* [December 2019]
Oscar Andres Patiño [Colombia]	Government [Sustainable public policies]	Departamento Nacional de Planeacion [Adviser]	*skype* [December 2019]
Jorge Riveros [Colombia]	Government [Sustainable public policies]	Agencia Nacional de Seguridad Vial [Adviser]	*skype* [December 2019]

5.5 Applying AHP and Fuzzy AHP

As referred, the AHP and Fuzzy AHP methods were used to prioritize the elements in the framework, with the results being subject to a descriptive analysis (a brief description of these two methods can be found in Appendix F and G).

Multi-criteria decision analysis with pairwise comparison aims at supporting decision makers to deal with the prioritization of multiple and sometimes conflicting attributes [130]. Pairwise comparison is widely adopted in practice because of its simplicity. This approach is popular in capturing subjective judgments, since it is much easier for the human brain to compare two items at one time, than assign scores or weights to the criteria, when the number of criteria exceeds three.

In our work, we start by using AHP for determining the weights of the criteria (sustainability dimensions, at level 0) and sub-criteria (sustainability indicators, at level1). Then, Fuzzy AHP is also used for the same purpose. The results of both methods are, then, analyzed and compared.

The adoption of this hierarchical framework will hopefully lead to a sustainability improvement in the transportation systems of emerging cities, thus contributing to generate bottom-up (rather than top-down) policies, launched by lower-level social organizations or authorities, cities or even smaller neighborhoods or communities. Therefore, in cities with lower institutional capacity, authorities or citizen organizations can use this prioritization to determine which interventions would have the greatest impact.

As referred above, imprecision and subjectivity are not properly dealt in traditional AHP [112]. Moreover, any change in the relative values of the choices results in changed weights, possibly causing a the a *rank reversal* [131]. Fuzzy AHP can overcome these limitations [112] by incorporating the fuzziness involved, while considering relative importances. Instead of using single crisp values, FAHP uses a range of values to incorporate decision makers uncertainty.

Our work uses these two approaches in an innovative way, to perform the prioritization process, based on the knowledge of a representative set of experts in sustainability assessment for transportation systems (see Figure 5.1). The weights for criteria (sustainability dimensions at *level 0*) and sub-criteria (sustainability indicators at *level 1*) were computed using both FAHP and AHP techniques, with the results depending on the specific application, and on the experts' individual point of view.

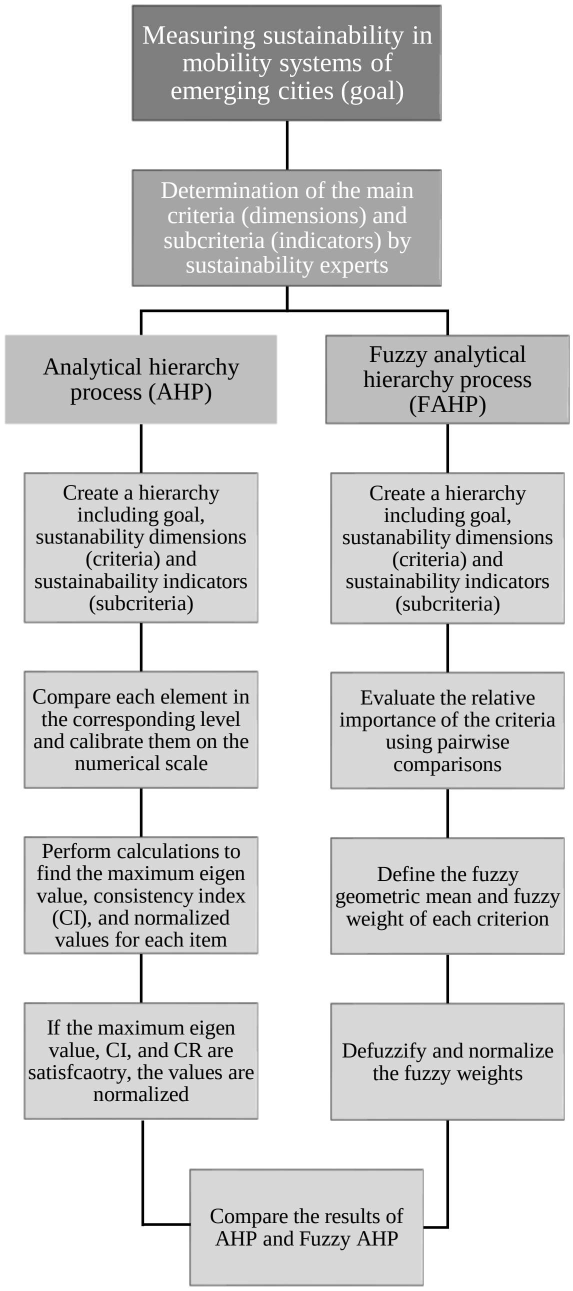


Figure 5.1 Applying AHP and Fuzzy AHP

5.6 Analytical Hierarchy Process (AHP)

One “side” but important advantage of AHP (the Analytical Hierarchical Process) [132] is to break down a problem into smaller constituent parts. By diluting the problem, the decision maker can focus on a limited number of items, at a time, decomposing a large complex task (criteria) into smaller and manageable subtasks (sub-criteria) [130].

In AHP, decision judgments, as articulated by pairwise comparison, are the fundamental inputs [133] and, therefore [134], these judgments have great influence on the success of the method. AHP has been successfully used in different fields and disciplines [130]. Its ability to handle both qualitative as well as quantitative data makes the method an ideal approach for some prioritization problems.

AHP involves ranking of decision elements and then making comparisons between pairs of clusters (of the elements). In our research context, we use the method to determine the weights for the five sustainability dimensions at *level 0*, and for the 42 sustainability indicators at *level 1* (for each sustainability dimensions at *level 0*).

Each pairwise comparison assessment is obtained by comparing two elements at a time, and a relative value is assigned to each pair according to the scale of a relative importance [64] (see Table 5.3). Using AHP, a priority vector of the elements is developed from the synthesis of the pairwise comparisons. The AHP scale consists of verbal judgments, ranging from “equal” to “extreme” importance, and corresponding numerical judgments often ranging from 1 to 9.

Table 5.3 Scale of relative importance in AHP

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over the other	Experience and judgment slightly favor one over the other
5	Essential or strong importance	An activity is strongly favored, and its dominance demonstrated in practice
7	Demonstrated importance	The evidence favoring over another is of highest possible order of affirmation
9	Absolute importance	When compromise is needed
2, 4, 6, 8	Intermediate values	

After the elements in the sustainability measurement *analysis structure* are defined, sustainability experts are asked to make pairwise comparisons for the elements, for each level. (see Table 5.3).

In our work, we create a hierarchical framework, consisting of an overall goal (in this case, “measuring sustainability in mobility systems of emerging cities” at the top of the hierarchical framework), several criteria contributing to this goal (in this case, 5 sustainability dimensions at *level 0*), and a number of attributes (in this case, 42 sustainability indicators at *level 1*, distributed in each sustainability dimension from the *level 0*). Then, comparisons (in a pairwise fashion) of each cluster at the same level in the hierarchy, are performed by sustainability experts, who answer questions such as: with respect to measuring sustainability of mobility systems, which criterion is more important, and how much on a scale from 1 to 9? for *level 0*; and with respect to "environment and human health", which criterion is more important, and how much more important on a scale from 1 to 9?

Some degree of inconsistency may occur due to careless errors or overstated judgments during the process of comparisons [135]. However, AHP tolerates these inconsistencies only if the consistency ratio (CR), an index measuring the consistency of a matrix, does not exceed a threshold of 0.10 [122]. This index can be used to identify the need for an additional evaluation process.

Finally, we may summarize the AHP method in the following seven main steps [133]:

- *Step 1,* state the problem.
- *Step 2,* broaden the objectives of the problem or consider all actors, objectives and their outcomes.
- *Step 3,* identify the criteria that influence the behavior.
- *Step 4,* structure the problem in a hierarchy of different levels, including the goal, criteria and sub-criteria.
- *Step 5,* compare each element in the corresponding level and reflect these comparisons into a numerical scale; this requires $\frac{n\,(n-1)}{2}$ pairwise comparisons, where N is the number of elements with the considerations that diagonal element are equal to 1 and the other elements are the reciprocals of the earlier comparisons.
- *Step 6,* perform calculations to find the maximum *eigen-value*, consistency index (CI), consistency ratio (CR).
- *Step 7,* if the maximum *eigen-value*, CI, and CR are satisfactory, then the normalized values are considered; else the procedure is repeated till these values lie in a desired range.

5.6.1 AHP computational results

The tables and figures in this section present the results obtained by using the AHP method as described. Results are organized by the levels (criteria and sub-criteria) of the hierarchical *framework* developed for measuring sustainability in mobility systems of emerging cities. This is considered as the goal at the top of this *framework*, with sustainability dimensions at *level 0*, and sustainability indicators at *level 1*, for each sustainability dimension (see Appendix F for an example of the mathematical process).

Sustainability of mobility systems of emerging cities (level 0 - dimensions) – AHP

Table 5.4 Using AHP at *level 0* (*dimensions* for measuring sustainability in mobility systems of emerging cities)

dimension	*weight (%)*	*rank*
Environmental and human health	48.30	1
Economic and social	23.40	2
Mobility systems effectiveness and land use	14.30	3
Operational	8.20	4
Fiscal and governance	5.70	5

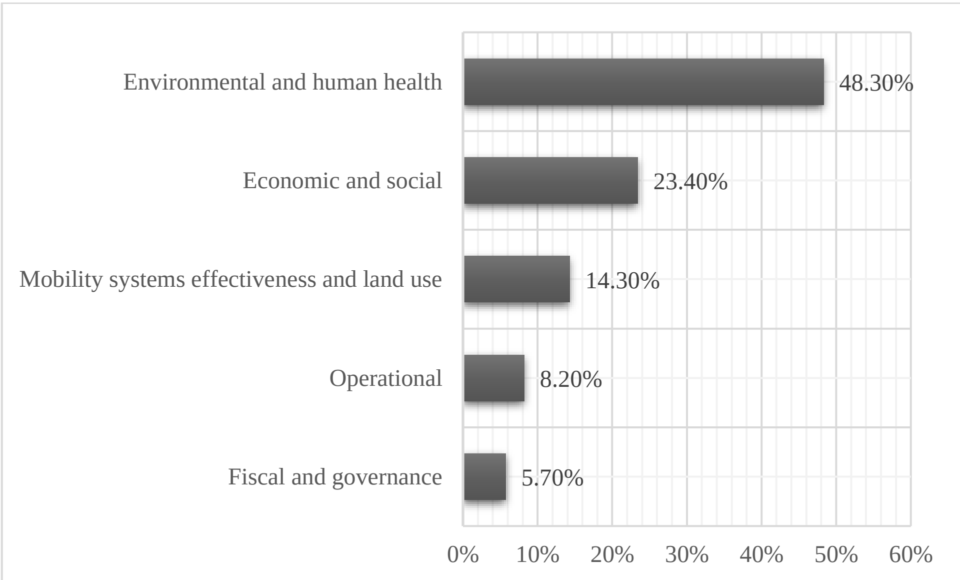


Figure 5.2 Performance at *level 0* (*dimensions*) with AHP analysis

Environmental and human health dimension (level 1 - indicators) – AHP

Table 5.5 Using AHP at *level 1* (indicators to measure the *environmental and human health* dimension)

indicator	*weight (%)*	*rank*
Traffic related fatalities (*deaths / 100,000 inhabitants*)	34.00	1
Air quality (PM10) (*μg/m³*)	29.07	2
Transport related CO_2 emissions (*t/person/year*)	21.00	3
NOx concentration (*μg/m³*)	10.60	4
Traffic noise pollution (*dBA*)	4.70	5

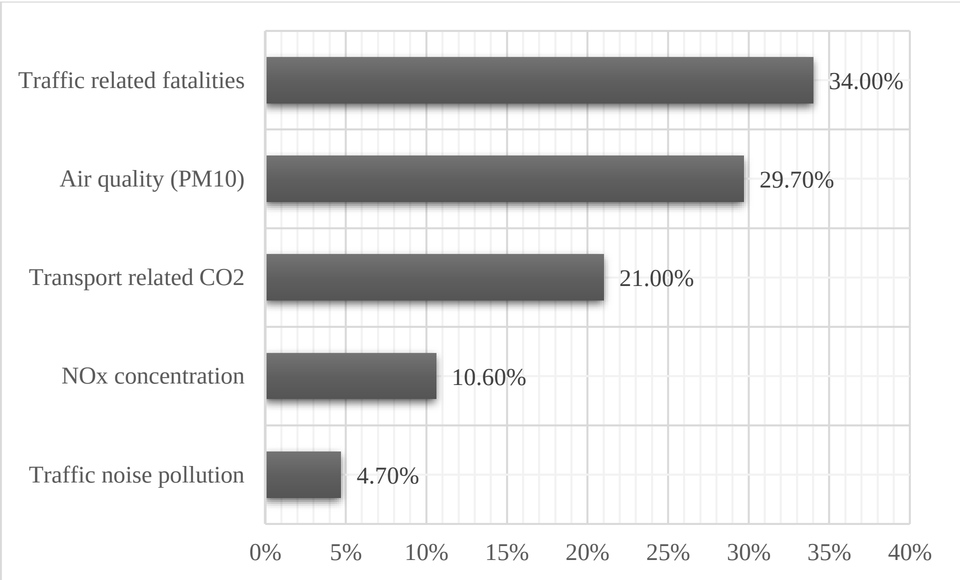


Figure 5.3 Performance at *level 1* (indicators of the *environmental and human health* dimension)

Economic and social dimension (level 1 - indicators) – AHP

Table 5.6 Using AHP at *level 1* (indicators to measure the *economic and social* dimension)

indicator	*weight (%)*	*rank*
Access to public transport service (*%*)	22.00	1
Public transport (PT) affordability (*%*)	16.60	2
Variation non-motorized in modal split (*%*)	14.60	3
Variation PT in the modal split (*%*)	12.50	4
Transport security (*users / 100,000 passengers*)	9.90	5
Population density (*inhabitants/km²*)	7.00	6
Indirect trip cost for user (*minutes*)	6.90	7
Share PT which are wheelchair accessible (*%*)	6.10	8
Variation of the female users in the PT (*%*)	4.50	9

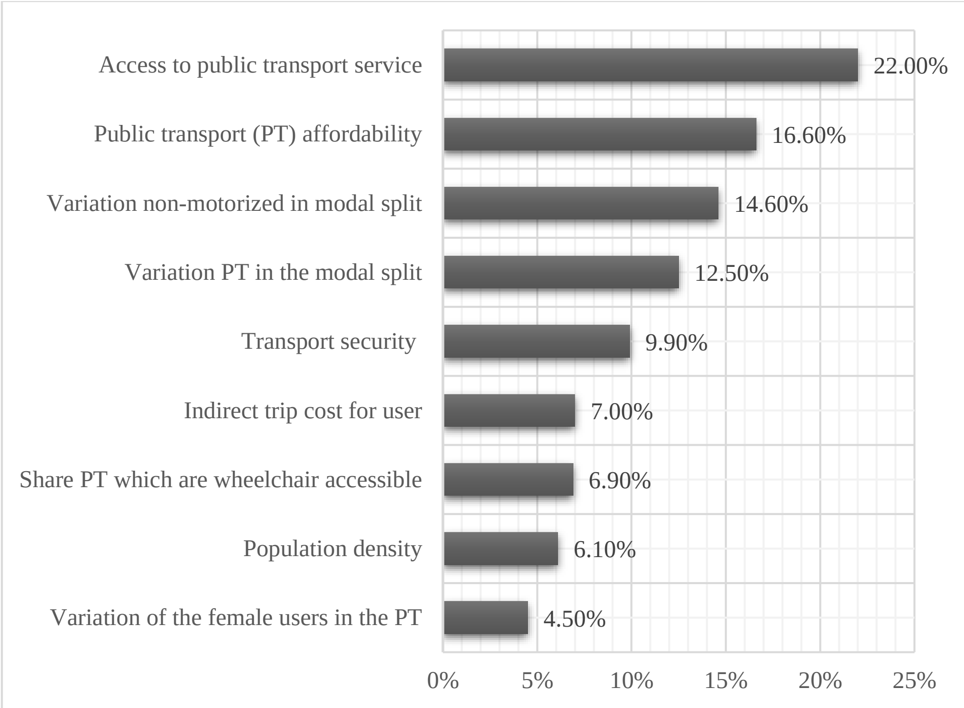


Figure 5.4 Performance at *level 1* (indicators of the *economic and social* dimension)

Mobility systems effectiveness and land use dimension (level 1 - indicators) – AHP

Table 5.7 Using AHP at *level 1* (indicators to measure the *mobility system effectiveness and land use* dimension)

indicator	*weight (%)*	*rank*
Pathways for pedestrians (*m^2/inhabitant*)	22.00	1
Satisfaction with mobility services (*%*)	20.00	2
Cycle path network density (*bikes/inhabitant*)	18.50	3
Proportion of land with mix use (*%*)	9.00	4
PT fleet size (*buses/ 100,000 inhabitants*)	8.30	5
Average occupancy rate of passenger vehicles (*%*)	6.60	6
Traffic congestion delay (*minutes*)	5.30	7
Land consumption by transport facilities (*%*)	4.60	8
Motorization rate (*vehicles / 1,000 inhabitants*)	3.10	9
Motorcycle rate (*motorcycles / 1,000 inhabitants*)	2.60	10

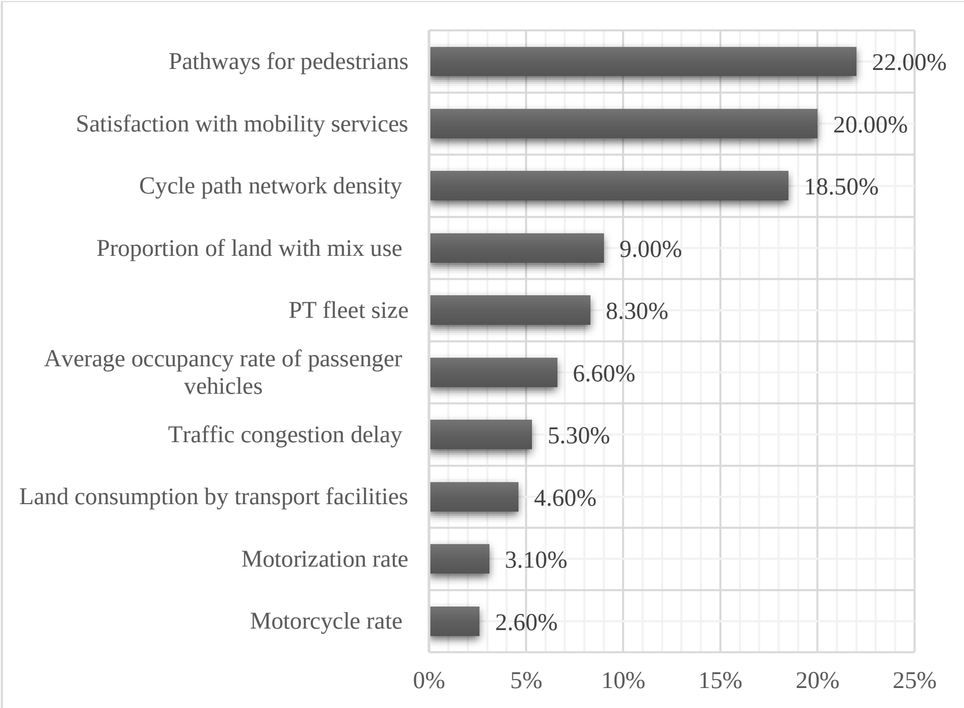


Figure 5.5 Performance of the *level 1* (indicators of the *mobility system effectiveness and land use* dimension)

Operational dimension (level 1 - indicators) – AHP

Table 5.8 Using AHP at *level 1* (indicators to measure the *operational* dimension)

indicator	*weight (%)*	*rank*
Efficiency public transportation (*megajoule/passager.km*)	17.60	1
Multimodality integration (*scale 1 to 5*)	16.90	3
Public transport frequency (*buses/day*)	15.10	3
Attractiveness of public transport (*cost public transport / cost private car*)	12.40	4
Proportion of clean energy in PT fleet (*%*)	11.40	5
Bike sharing performance (*bicycles/ 100,000 inhabitants*)	10.30	6
Average age of PT fleet (*age*)	7.30	7
Road network density (*km/km^2*)	4.20	8
Parking cost (*%*)	2.20	9
Parking capacity (*number of parking spaces/inhabitant*)	2.60	10

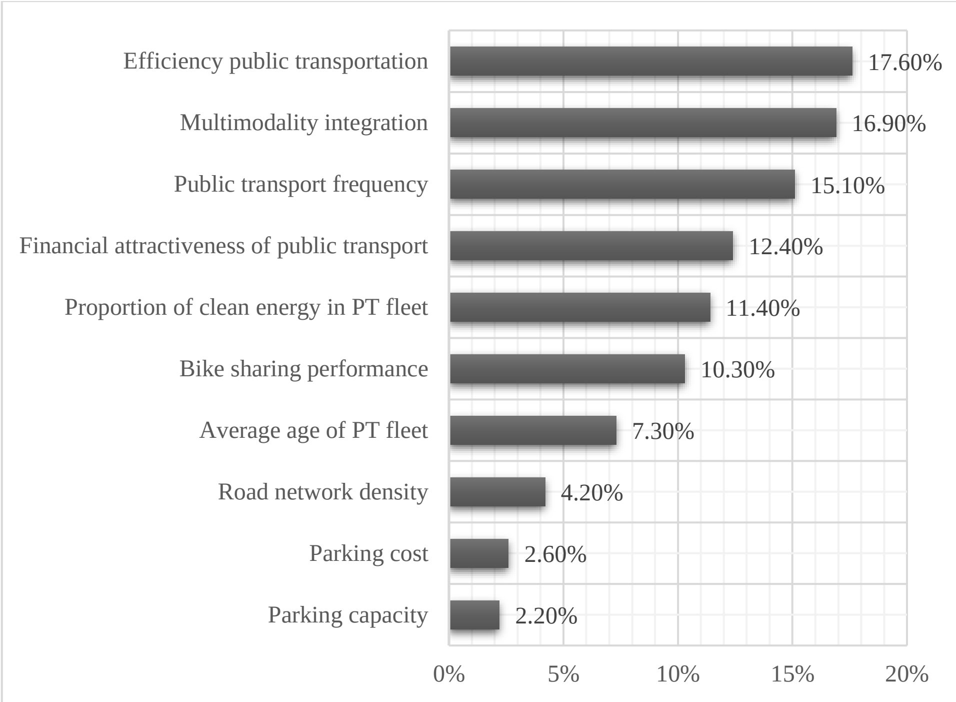


Figure 5.6 Performance at *level 1* (indicators of the *operational* dimension)

Fiscal and governance dimension (level 1 - indicators) – AHP

Table 5.9 Using AHP at *level 1* (indicators to measure the *fiscal and governance* dimension)

indicator	*weight (%)*	*rank*
Master plan (*scale 1 to 5*)	22.60	1
Public expenditures and investment in transport system (%)	20.80	2
Operational cost PT system (%)	17.30	3
Expertise technicians and managers (*scale 1 to 5*)	13.10	4
Financial autonomy (*scale 1 to 5*)	9.80	5
Stakeholders engagement (*scale 1 to 5*)	7.10	6
Participation of the multilateral banks (%)	5.70	7
Variation of the informal transport modal split (%)	3.50	8

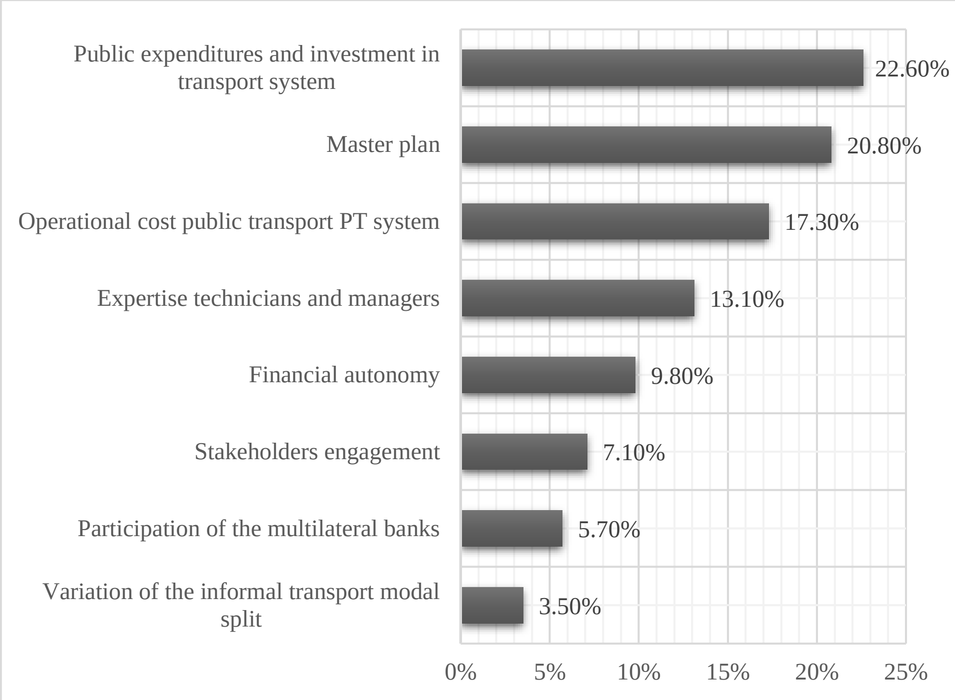


Figure 5.7 Performance at *level 1* (indicators of the *fiscal and governance* dimension)

These results seem to be meaningful and useful in practical terms, but in order to overcome the weaknesses of the AHP method referred above, we have also developed a Fuzzy Hierarchy Process (FAHP) approach, as already explained. This approach is described in the next section.

5.7 Fuzzy Analytic Hierarchy Process (FAHP)

In order to adequately cope with the uncertainty, subjectivity and imprecision involved in human assessments and judgements, fuzzy logic was incorporated in the classical AHP method. In this context, assessments are processed as fuzzy numbers. In contrast with classical set theory [136], fuzzy sets theory (FTS) allows for the assessment of the membership of elements with respect to a set represented by $\mu = [0, 1]$ [137]. The Fuzzy AHP method (FAHP) is an extension of the AHP technique that deals with qualitative and imprecise-real word decision problems [136]. I.e., in order to analyse the kind of uncertainty respondent's preferences, fuzzy values are associated with the pairwise comparison of AHP [132]. This extension of AHP has been adopted in many research works in quite different fields [138], [139].

Here [140], the basic AHP method is extend to the case where the evaluators are allowed to employ *fuzzy* ratios, to handle the difficulty for people to assign exact ratios when comparing two criteria [141]. FAHP can, in this way, be used for the evaluation and ranking of criteria

[142]. And according to [143] FAHP can be viewed as more systematic, accurate, and effective than traditional AHP, being a hybrid approach applicable for both qualitative and quantitative criteria comparisons [144].

In this context, we use a FAHP approach to assign weights to the elements that make up the sustainability measurement *analysis structure* at each level (as defined above) employing *fuzzy linguistic variables*. We also *fuzzify* the hierarchical analysis, by allowing fuzzy numbers for the pairwise comparison and by finding fuzzy weights. Fuzzy numbers can be viewed as a subset of real numbers, representing the expansion of the idea of the confidence interval [141].

In essence, a FAHP approach is comprised of the following steps [136]: (i) structuring of the hierarchy levels for decision making; (ii) prioritization based on fuzzy pairwise comparison; (iii) checking for consistency of the preference judgments by the experts; (iv) synthesis of pairwise priorities; and (v) *defuzzification* of the determined priorities. Defuzzification is necessary because the fuzzy arithmetic means are not crisp values, and hence cannot be directly ranked.

A FAHP decision problem [136] consists of a set of evaluation criteria $\left[C_J\ (j = 1, 2, \dots, n)\right]$, a linguistic judgement (r_{ij}) representing the relative importance of each pair of criteria, and a weighting vector $[W\ (w_1, w_2, \dots, w_n)]$. Like the classical AHP, FAHP also has a judgment matrix, but it uses Triangle Fuzzy Numbers (TFNs) instead of constant pairwise comparison values [145]. Here the analysis depends on the degree of possibilities of each criterion used in the decision process. TFNs for the linguistic variables from the judgments are defined according to the responses, and for a particular level on the decision hierarchy, for which the pairwise comparison matrix is constructed [146]. For the details of these methods, see e.g. [147].

In FAHP, experts' decision making uses a range of values rather than single discrete values [112]. In our work, we use nine fuzzy linguistic variables to capture the subjective judgments about the relative importance of a factor versus another factor. These linguistic variables are summarized in Table 5.10, with the lower, medium, and upper values of the underlying TFN. A *membership function* is defined as the degree of possibility of the value for each criterion, the minimum degree of possibility, and the weight of this criterions estimated before normalization

Table 5.10 Membership function linguistic scale, relationship between fuzzy numbers and degrees of linguistic importance, fuzzy number memberships of pairwise comparisons

Low/high level		*Fuzzy number*	*Definition*	*Membership function*	*Domain*	*TFN* (l, m, u)	*Inverse (TFN)* $\left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$
Label	*Linguistic term*						
J	Just equal	$\tilde{1}$	Diagonal elements			$(1, 1, 1)$	$(1, 1, 1)$
EI	Equal importance	$\tilde{1}$	Practical knowledge and experience imply that factor *i* is equally important, when compared to factor *j*	$\mu M(x) = \frac{(2-x)}{(2-1)}$	$1 \leq x \leq 2$	$(1, 1, 2)$	$\left(\frac{1}{2}, 1, 1\right)$
WI	Weak importance over the other	$\tilde{3}$	Practical knowledge and experience imply that factor *i* is moderately important, when compared to factor *j*	$\mu M(x) = \frac{(x-2)}{(3-2)}$ $\mu M(x) = \frac{(4-x)}{(4-3)}$	$2 \leq x \leq 3$ $3 \leq x \leq 4$	$(2, 3, 4)$	$\left(\frac{1}{4}, \frac{1}{3}, \frac{1}{2}\right)$
SI	Strong importance over the other	$\tilde{5}$	Practical knowledge and experience imply that factor *i* is more important, when compared to factor *j*	$\mu M(x) = \frac{(x-4)}{(5-4)}$ $\mu M(x) = \frac{(6-x)}{(6-5)}$	$4 \leq x \leq 5$ $5 \leq x \leq 6$	$(4, 5, 6)$	$\left(\frac{1}{6}, \frac{1}{5}, \frac{1}{4}\right)$
VI	Very strong importance over the other	$\tilde{7}$	Practical knowledge and experience imply that factor *i* is strongly important, when compared to factor *j*	$\mu M(x) = \frac{(x-6)}{(7-6)}$ $\mu M(x) = \frac{(8-x)}{(8-7)}$	$6 \leq x \leq 7$ $7 \leq x \leq 8$	$(6, 7, 8)$	$\left(\frac{1}{8}, \frac{1}{7}, \frac{1}{6}\right)$
EI	Extreme importance over the other	$\tilde{9}$	Practical knowledge and experience imply that factor *i* is extremely important, when compared to factor *j* and totally outweighs it.	$\mu M(x) = \frac{(x-8)}{(9-8)}$	$7 \leq x \leq 9$	$(8, 9, 9)$	$\left(\frac{1}{9}, \frac{1}{9}, \frac{1}{8}\right)$

Table 5.11 Membership function linguistic scale, relationship between fuzzy numbers and degrees of linguistic importance, fuzzy number memberships of pairwise comparisons (continued)

Low/high level		*Fuzzy number*	*Definition*	*Membership function*	*Domain*	*TFN* (l, m, u)	*Inverse (TFN)* $\left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$
Label	*Linguistic term*						
IV	Intermediate values	$\tilde{2}$	Practical knowledge and experience imply that factor i is $\tilde{1}$ and $\tilde{3}$, when compared to factor *j*	$\mu M(x) = \frac{(2-x)}{(2-1)}$ $\mu M(x) = \frac{(x-2)}{(3-2)}$	$1 \leq x \leq 2$ $2 \leq x \leq 3$	$(1, 2, 3)$	$\left(\frac{1}{3}, \frac{1}{2}, 1\right)$
		$\tilde{4}$	Practical knowledge and experience imply that factor i is $\tilde{3}$ and $\tilde{5}$,when compared to factor *j*	$\mu M(x) = \frac{(4-x)}{(4-3)}$ $\mu M(x) = \frac{(x-4)}{(5-4)}$	$3 \leq x \leq 4$ $4 \leq x \leq 5$	$(3, 4, 5)$	$\left(\frac{1}{5}, \frac{1}{4}, \frac{1}{3}\right)$
		$\tilde{6}$	Practical knowledge and experience imply that factor i is $\tilde{5}$ and $\tilde{7}$, when compared to factor *j*	$\mu M(x) = \frac{(6-x)}{(6-5)}$ $\mu M(x) = \frac{(x-6)}{(7-6)}$	$5 \leq x \leq 6$ $6 \leq x \leq 7$	$(5, 6, 7)$	$\left(\frac{1}{7}, \frac{1}{6}, \frac{1}{5}\right)$
		$\tilde{8}$	Practical knowledge and experience imply that factor i is $\tilde{7}$ and $\tilde{9}$, when compared to factor *j*	$\mu M(x) = \frac{(8-x)}{(8-7)}$ $\mu M(x) = \frac{(x-8)}{(9-8)}$	$7 \leq x \leq 8$ $8 \leq x \leq 9$	$(7, 8, 9)$	$\left(\frac{1}{9}, \frac{1}{8}, \frac{1}{7}\right)$
The value of the second element in comparison with the first would be by reciprocal of TFN given as $\left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$							

Triangular Fuzzy Numbers (TFN) provide an opportunity for deciding the weight of one criterion over the other. In Table 5.10, TFN $\left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$ means that the decision maker thinks the importance ratio of two criteria is about *Saaty fundamental 9-point ratio scale*. Here, linguistic assessments (fuzzy linguistic variables) are introduced to represent the underlying fuzzy numbers that are employed for factor evaluations. A linguistic variable is a variable whose values are words or sentences in a natural or artificial language (they are summarized in Table 5.10).

In these approaches, linguistic and subjective evaluations are normally based on questionnaires [148]. Each linguistic variable has its own numerical value in the predefined scale. In classical AHP, these values are exact number, whereas in FAHP they are intervals between two numbers, with a most likely value. Linguistic values are naturally subjective, and can change from person to person.

Therefore, the evaluation of the criteria and sub-criteria (when measuring sustainability aspects) can be affected by the characteristics of the involved person, and the conditions provided by the used platform. According to [148], pessimistic people may not give any grade more than four, and very optimistic people may easily give a five. These situations generate *fuzziness* within the decision-making processes, thus justifying the use of FAHP.

In practice, decision makers are asked to select the related linguistic variables; then for calculations, these variables are converted into TFN, and generalized for such analysis as presented in Table 5.10. The fundamental step here is the prioritization procedure, i.e. deriving the unknown priority vector from the judgement set $\tilde{A}$.

After obtaining the weights for each criterion, they are normalized, and viewed as the final importance degrees for the hierarchy level [132].

The basic FAHP procedure can be summarized in the following 5 main steps [136]:

- *Step 1*, developing and *structuring of the decision hierarchy*, including goal, criteria (sustainability dimensions) and sub-criteria (sustainability indicators) (see Figure 5.14). This step comprises restructuring the decision-making problem into a hierarchical framework. Our framework helps in understanding the interactions among the elements involved in each decision level, and aids the decision makers in exploring the impacts of the different decision components on the evaluation system.
- *Step 2*, building of the *fuzzy comparison matrices*. First, the relative importances of the criteria are determined through pairwise comparisons. After expert evaluations, these importances are transformed into triangular fuzzy numbers [136]. By considering a prioritization problem at a decision level with n elements, each set of comparisons for a given level requires $\frac{n\,(n-1)}{2}$ judgements, that are used to construct a positive fuzzy reciprocal comparison matrix $\tilde{A} = \{\tilde{a}_{ij}\}$ (see [149]).

$$\tilde{A} = (\tilde{a}_{ij}) \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & (1,1,1) \end{bmatrix} \tag{5.1}$$

$$= \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & (1,1,1) \end{bmatrix} \tag{5.2}$$

where:

$$\tilde{a}_{ij} = \begin{Bmatrix} \tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}, & i\ is\ more\ important\ than\ j \\ 1, & i = j \\ \tilde{1}^{-1},\tilde{3}^{-1},\tilde{5}^{-1},\tilde{7}^{-1},\tilde{9}^{-1}, & i\ is\ less\ important\ than\ j \end{Bmatrix} \tag{5.3}$$

- *Step 3*, *consistency check* and *fuzzy weights priorities derivation*. This step checks for decision consistency, and determines the priorities from the pairwise comparison matrices [136]. A fuzzy comparison $\tilde{A}_1 = \{\tilde{a}_{ij}\}$ is consistent if $\tilde{a}_{ik} \otimes \tilde{a}_{kj} \approx \tilde{a}_{ij}$, where $i,j,k = 1,2, \ldots, n$ [146]. After the consistency check, the fuzzy priorities $\widetilde{w}_i$ are calculated, with the priority vectors $(\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_n)^T$ being obtained from the comparison matrix, by applying a prioritization ranking approach [150].
- *Step 4*, *defuzzification* – conversion of the fuzzy weights to crisp weights. defuzzification can be made with the graded mean integration representation (GMIR) method by [141]. This step defines the fuzzy geometric mean and the fuzzy weight of each criterion:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in})^{1/n} \tag{5.4}$$

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \otimes \ldots \otimes \tilde{r}_n)^{-1} \tag{5.5}$$

where $\tilde{a}_{in}$ is the fuzzy comparison value of criterion i to criterion n, $\tilde{r}_i$ is the geometric mean of fuzzy comparison value of criterion i to each criterion, $\widetilde{w}_i$ is the fuzzy weight of the ith criterion, represented by a Triangular Fuzzy Number.

$$\widetilde{w}_i = (lw_1, mw_1, uw_1) \tag{5.6}$$

- *Step 5*, calculation and normalization of the *weight vector*, with the *crisp* values being normalized in this stage. This final step aggregates the local priorities obtained at the different levels of the decision framework hierarchy. The *fuzzy weight* of criterion i is subsequently transformed into a positive equivalent number through equation (5.7), that is then normalized by equation (5.8).

$$M_i = \frac{(l \times w_i \; + \; m \times w_i \; + u \times w_i)}{3} \tag{5.7}$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{5.8}$$

5.7.1 FAHP computational results

The tables and figures in this section present the results obtained by using the FAHP method, as described. Results are organized by the levels (criteria and sub-criteria) of our *hierarchical framework*, with the goal at the top, with sustainability dimensions at *level 0,* and sustainability indicators at *level 1*, for each sustainability dimension (see Appendix G for an example of the mathematical process). As referred, in section 5.8, we compare the results obtained by the two used approaches (AHP and FAHP).

Sustainability of mobility systems of emerging cities (level 0 - dimensions) – FAHP

Table 5.12 Using FAHP at *level 0* (*dimensions* for measuring sustainability in mobility systems of emerging cities)

dimension	*weight (%)*	*rank*
Environmental and human health	47.85	1
Economic and social	23.81	2
Mobility systems effectiveness and land use	14.14	3
Operational	8.35	4
Fiscal and governance	5.86	5

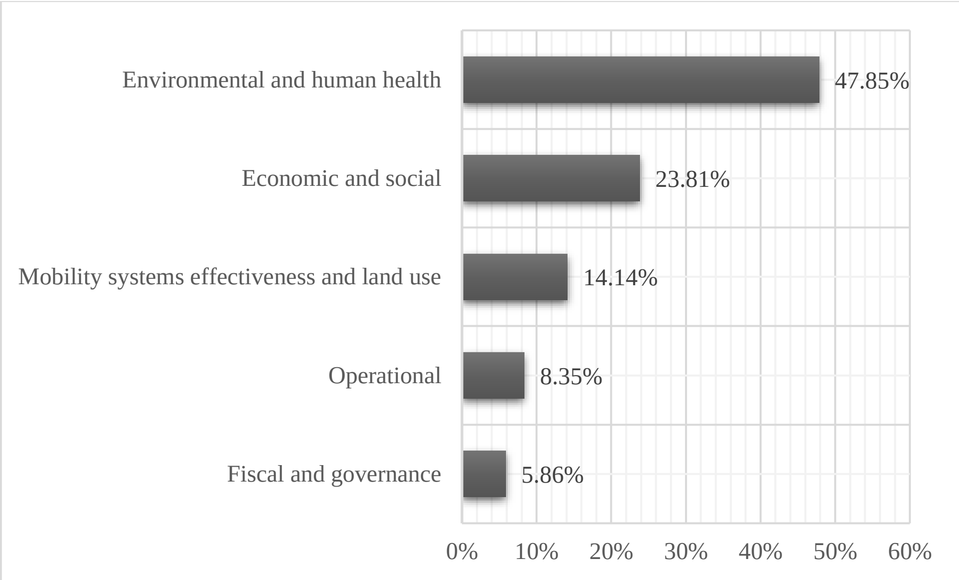


Figure 5.8 Performance at *level 0* (*dimensions*) with FAHP analysis

Environmental and human health dimension (level 1 - indicators) – FAHP

Table 5.13 Using FAHP at *level 1* (indicators to measure the *environmental and human health* dimension)

indicator	*weight (%)*	*rank*
Traffic related fatalities (*deaths / 100,000 inhabitants*)	32.29	1
Air quality (PM10) (*μg/m*^{3})	31.65	2
Transport related CO_2 emissions (*T/person/year*)	20.59	3
NOx concentration (*μg/m*^{3})	10.79	4
Traffic noise pollution (*dBA*)	4.68	5

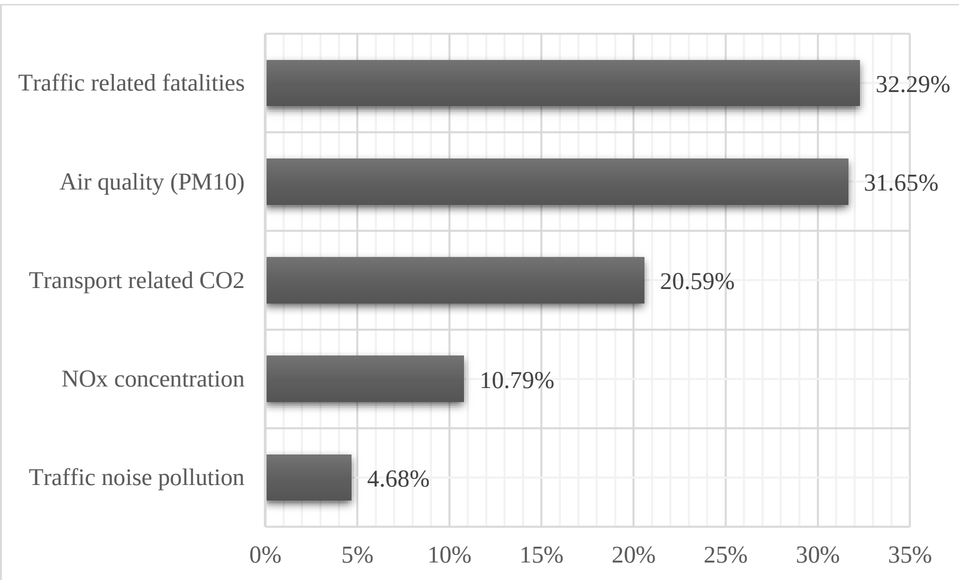


Figure 5.9 FAHP performance at *level 1* (indicators of the *environmental and human health* dimension)

Economic and social dimension (level 1 - indicators) – FAHP

Table 5.14 Using FAHP at *level 1* (indicators to measure the *economic and social* dimension)

indicator	*weight (%)*	*rank*
Access to public transport service (*%*)	21.24	1
Public transport (PT) affordability (*%*)	17.92	2
Variation non-motorized in modal split (*%*)	10.98	3
Variation PT in the modal split (*%*)	10.48	4
Transport security (*users / 100,000 passengers*)	9.29	5
Indirect trip cost for user (*minutes*)	8.36	6
Share PT which are wheelchair accessible (*%*)	8.13	7
Population density (*inhabitants/km^2*)	7.81	8
Variation of the female users in the PT (*%*)	5.80	9

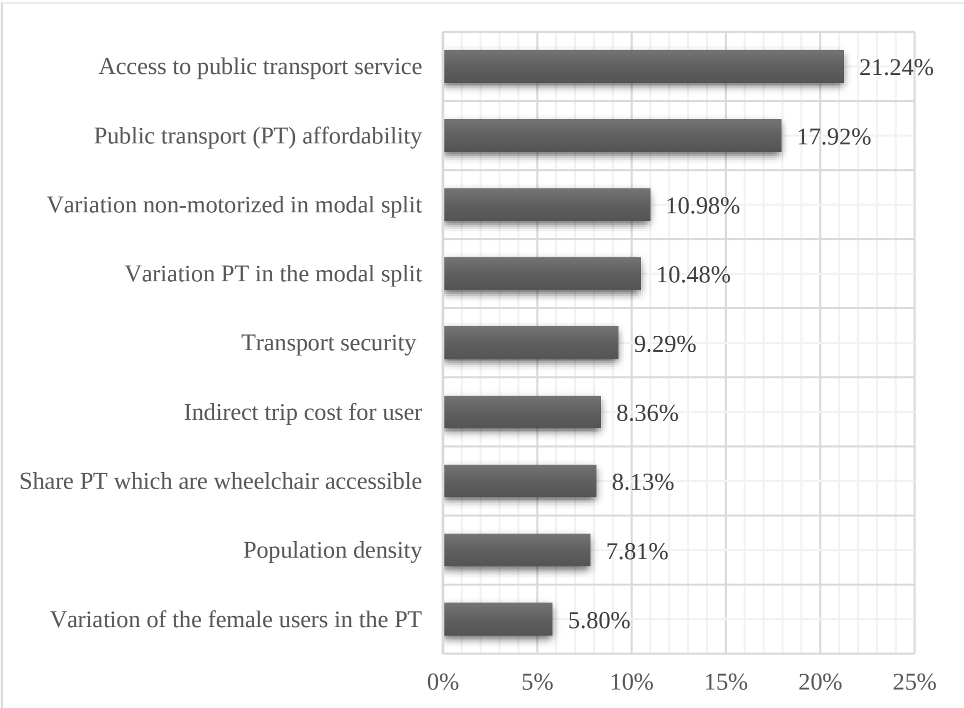


Figure 5.10 FAHP performance at *level 1* (indicators of the *economic and social* dimension)

Mobility systems effectiveness and land use dimension (level 1 - indicators) – FAHP

Table 5.15 Using FAHP at *level 1* (indicators to measure the *mobility system effectiveness and land use* dimension)

indicator	*weight*	*rank*
Pathways for pedestrians (m^2/inhabitant)	21.66	1
Satisfaction with mobility services (%)	20.20	2
Cycle path network density (bikes/inhabitant)	17.79	3
Proportion of land with mix use (%)	9.55	4
PT fleet size (buses/100.000 inhabitants)	8.30	5
Average occupancy rate of passenger vehicles (%)	6.57	6
Traffic congestion delay (minutes)	5.50	7
Land consumption by transport facilities (%)	4.91	8
Motorization rate (vehicles/1.000 inhabitants)	2.97	9
Motorcycle rate (motorcycles/1.000 inhabitants)	2.55	10

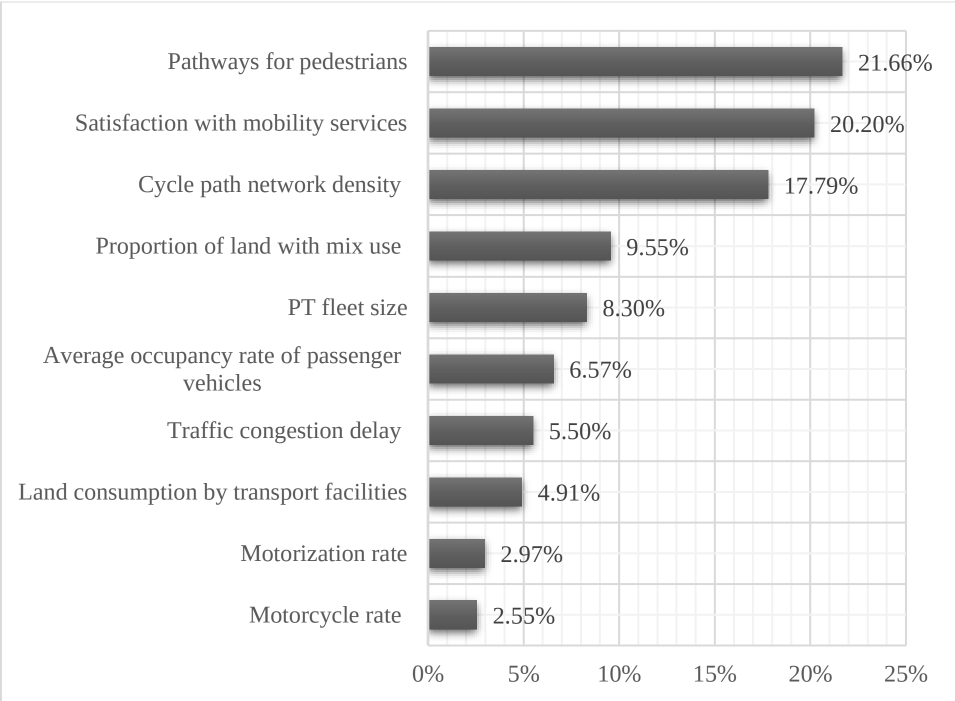


Figure 5.11 FAHP performance at *level 1* (indicators of the *mobility system effectiveness and land use* dimension)

Operational dimension (level 1 - indicators) – FAHP

Table 5.16 Using FAHP at *level 1* (indicators to measure the *operational* dimension)

indicator	*weight (%)*	*rank*
Efficiency public transportation (*megajoule/passager.km*)	16.68	1
Multimodality integration (*scale 1 to 5*)	16.68	1
Public transport frequency (*buses/day*)	15.88	3
Attractiveness of public transport (*cost public transport / cost private car*)	13.03	4
Proportion of clean energy in PT fleet (*%*)	11.61	5
Bike sharing performance (*bicycles / 100,000 inhabitants*)	10.24	6
Average age of PT fleet (*age*)	7.25	7
Road network density (*km/km^2*)	4.03	8
Parking cost (*%*)	2.48	9
Parking capacity (*number of parking spaces/inhabitant*)	2.14	10

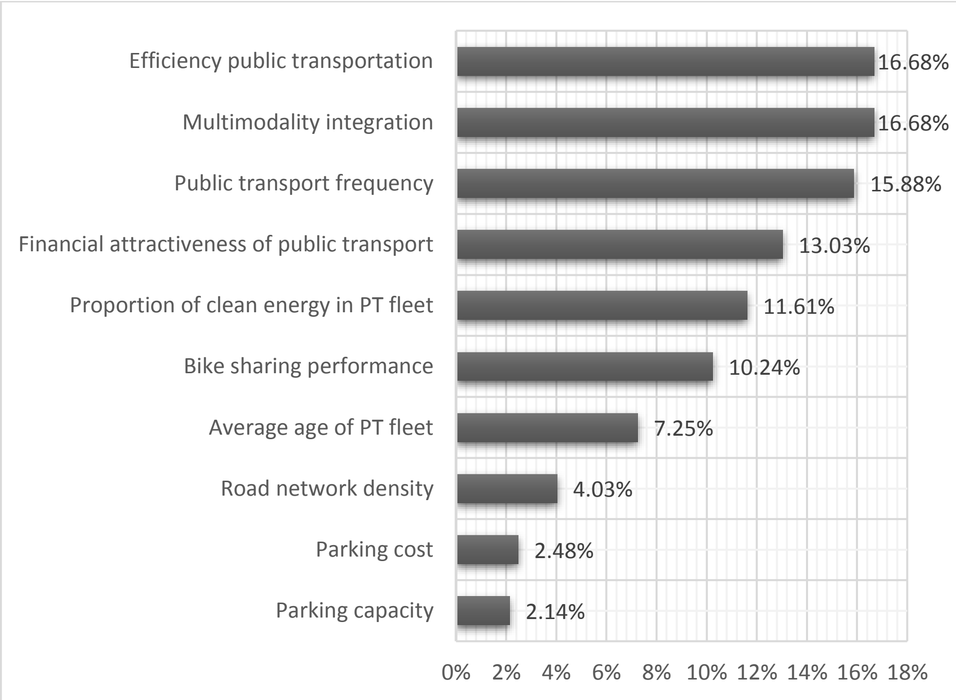


Figure 5.12 FAHP performance at *level 1* (indicators of the *operational* dimension)

Fiscal and governance dimension (level 1 - indicators) – FAHP

Table 5.17 Using AHP at *level 1* (indicators to measure the *fiscal and governance* dimension)

indicator	*weight (%)*	*rank*
Public expenditures and investment in transport system (%)	21.89	1
Master plan (*scale 1 to 5*)	20.86	2
Operational cost PT system (%)	17.77	3
Expertise technicians and managers (*scale 1 to 5*)	13.48	4
Financial autonomy (*scale 1 to 5*)	9.84	5
Stakeholders engagement (*scale 1 to 5*)	7.34	6
Participation of the multilateral banks (%)	5.33	7
Variation of the informal transport modal split (%)	3.50	8

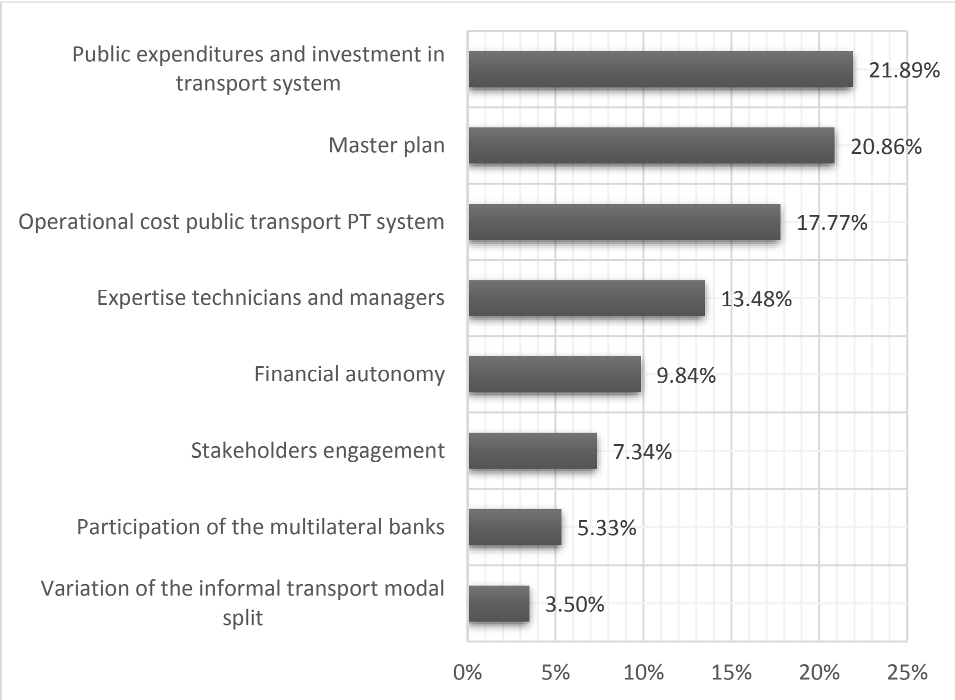


Figure 5.13 FAHP performance at *level 1* (indicators of the *fiscal and governance* dimension)

The obtained results seem to be meaningful in practical terms. Fuzzy AHP can rank a maximum of ten criteria and sub-criteria [151], thus seeming appropriate for prioritizing the elements of our *analysis structure*, since none of the five criteria has more than ten sub-criteria.

Finally, the weights obtained in this way for the criteria and sub-criteria have been found to be consistent with the individual preferences of the sustainability experts, as collected by surveys, questionnaires, semi-structured interviews and face to face meetings.

5.8 Comparison of the AHP and FAHP approaches

This section summarizes and compares the results obtained by the two used approaches (AHP and FAHP). Results are organized by the levels (criteria and sub-criteria) of our *hierarchical framework*. At the top of the framework, we have the "goal", with sustainability dimensions at *level 0*, and sustainability indicators at *level 1*, for each sustainability dimension (see Appendix F and G for an example of the mathematical process).

Sustainability of mobility systems of emerging cities (level 0 - dimensions)

Table 5.18 Comparison of AHP and FAHP results at *level 0* (*dimensions* for measuring sustainability in mobility systems of emerging cities)

dimension	*weigth (%)*		*rank*	
	AHP	*fuzzy AHP*	*AHP*	*fuzzy AHP*
Environmental and human health	48.30	47.85	1	1
Economic and social	23.40	23.81	2	2
Mobility systems effectiveness and land use	14.30	14.14	3	3
Operational	8.20	8.35	4	4
Fiscal and governance	5.70	5.86	5	5

The obtained results clearly show the importance of assessing sustainability in terms of *environmental and human health*. Moreover, even though the *fiscal and governance* dimension obtained the lowest priority, this dimension presents indicators that are relevant, due to a permanent shortage of investment resources and the resulting need for adequate fiscal management.

Environmental and human health dimension (level 1 - indicators)

Table 5.19 Comparison of AHP and FAHP results at *level 1* (indicators to measure the *environmental and human health* dimension)

indicator	*weight (%)*		*rank*	
	AHP	*fuzzy AHP*	*AHP*	*fuzzy AHP*
Traffic related fatalities (*deaths / 100,000 inhabitants*)	34.00	32.29	1	1
Air quality (PM10) (*µg/m³*)	29.70	31.65	2	2
Transport related CO_2 emissions (*t/person/year*)	21.00	20.59	3	3
NOx concentration (*µg/m³*)	10.60	10.79	4	4
Traffic noise pollution (*dBA*)	4.70	4.68	5	5

These results clearly show the importance of assessing *environment and human health* in terms of *traffic related fatalities and air quality* (PM10), generally highlighting the impact of the *transport related CO_2 emissions* in terms of this dimension, when measuring sustainability in mobility systems of emerging cities.

Economic and social dimension (level 1 - indicators)

Table 5.20 Comparison of AHP and FAHP results *at level 1* (indicators to measure the *economic and social* dimension)

indicator	*weight (%)*		*rank*	
	AHP	*fuzzy AHP*	*AHP*	*fuzzy AHP*
Access to public transport service (%)	22.00	21.24	1	1
Public transport (PT) affordability (%)	16.60	17.92	2	2
Variation non-motorized in modal split (%)	14.60	10.98	3	3
Variation PT in the modal split (%)	12.50	10.48	4	4
Transport security (*users/ 100,000 passengers*)	9.90	9.29	5	5
Population density (*inhabitants/km^2*)	7.00	7.81	6	8
Indirect trip cost for user (*minutes*)	6.90	8.36	7	6
Share PT which are wheelchair accessible (%)	6.10	8.13	8	7
Variation of the female users in the PT (%)	4.50	5.80	9	9

In what concerns the *economic and social* dimension *at level 1*, the results show the concern about *access to public transport service*, *public affordability*, as well as on the *variation of non-motorized and public transport in the modal split*, which is consistent with the reality of mobility systems of emerging cities. In this case the *transport security* sub-criterion becomes an important aspect to consider to improve the sustainability of transportation systems. Moreover, *shared wheelchair accessible public transport*, and the *variation of female users in public transport* have the lowest priority. Nevertheless, we believe this research is a small contribution to launch these issues for consideration by decision makers, taking into account the specific conditions of each mobility system, in particularly in emerging cities, where these aspects are, in general, more important.

Mobility systems effectiveness and land use dimension (level 1 - indicators)

Table 5.21 Comparison of AHP and FAHP results at the *level 1* (indicators to measure the *mobility system effectiveness and land use* dimension)

indicator	*weight (%)*		*rank*	
	AHP	*fuzzy AHP*	*AHP*	*fuzzy AHP*
Pathways for pedestrians (m^2*/inhabitant*)	22.00	21.66	1	1
Satisfaction with mobility services (*%*)	20.00	20.20	2	2
Cycle path network density (*bikes/inhabitant*)	18.50	17.79	3	3
Proportion of land with mix use (*%*)	9.00	9.55	4	4
PT fleet size (*buses / 100,000 inhabitants*)	8.30	8.30	5	5
Average occupancy rate of passenger vehicles (*passenger/vehicle*)	6.60	6.57	6	6
Traffic congestion delay (*minutes*)	5.30	5.50	7	7
Land consumption by transport facilities (*%*)	4.60	4.91	8	8
Motorization rate (*vehicles / 1,000 inhabitants*)	3.10	2.97	9	9
Motorcycle rate (*motorcycles / 1,000 inhabitants*)	2.60	2.55	10	10

According to these results, the *non-motorized* modes, as well as the *satisfaction with mobility services* have the highest scores. These aspects must, therefore, be taken into account by transportation planners in policy formulation processes, as a way to improve the performance of these indicators. This effort will surely contribute to consolidate more and more sustainable mobility systems, instead of continuing to measure sustainability in terms of motorized modes (*motorization rate for motorcycles* and vehicles that have been given the lowest priority in this criterion). In general, this is consistent with the ideal reverse traffic pyramid, where the non-motorized modes and public transport are located at the top of the pyramid and the private car at the bottom.

Operational dimension (level 1 - indicators)

Table 5.22 Comparison of AHP and FAHP results at *level 1* (sustainability indicators to measure *operational* dimension)

indicator	*weight (%)*		*rank*	
	AHP	*Fuzzy AHP*	*AHP*	*Fuzzy AHP*
Multimodality integration (*scale 1 to 5*)	16.90	16.68	1	1
Efficiency public transportation (*megajoule/passager.km*)	17.60	16.68	1	1
Public transport frequency (*buses/day*)	15.10	15.88	3	3
Financial attractiveness of public transport (*cost public transport/cost private car*)	12.40	13.03	4	4
Proportion of clean energy in PT fleet (*%*)	11.40	11.61	5	5
Bike sharing performance (*bicycles / 100,000 inhabitants*)	10.30	10.24	6	6
Average age of PT fleet (*age*)	7.30	7.25	7	7
Road network density (*km/km*^{2})	4.20	4.03	8	8
Parking cost (*%*)	2.60	2.48	9	9
Parking capacity (*number of parking spaces/inhabitant*)	2.20	2.14	10	10

These results clearly show the importance of *public transportation efficiency*, this being consistent with the literature that states the transportation sector accounts for almost one fourth of world's total CO_2 emission [84]. The results also show the need to consolidate mobility systems where *multimodal integration* prevails with an *efficient public transport* (in terms of frequency) and *bike sharing performance*. On the other hand, *parking cost* and *parking capacity* were assigned the lowest priority, this indicating these metrics are not really important when formulating policies for sustainable mobility. Therefore, efforts should be focused on improving the efficiency of the public transport and, in general, of all of the mobility system.

Fiscal and governance dimension (level 1 - indicators)

Table 5.23 Comparison of AHP and FAHP results at *level 1* (indicators to measure *fiscal and governance* dimension)

indicator	*weight (%)*		*rank*	
	AHP	*Fuzzy AHP*	*AHP*	*Fuzzy AHP*
Master plan (*scale 1 to 5*)	22.60	20.86	1	2
Public expenditures and investment in transport system (*%*)	20.80	21.89	2	1
Operational cost PT system (*%*)	17.30	17.77	3	3
Expertise technicians and managers (*scale 1 to 5*)	13.10	13.47	4	4
Financial autonomy (*scale 1 to 5*)	9.80	9.84	5	5
Stakeholders engagement (*scale 1 to 5*)	7.10	7.34	6	6
Participation of the multilateral banks (*%*)	5.70	5.33	7	7
Variation of the informal transport modal split (*%*)	3.50	3.50	8	8

Here it is clear the need for transport operators to have guidelines for the implementation of *sustainability policies or master plans,* that last for periods longer than the local political mandates. Moreover, the results highlighted the importance of including in the discussion topics such as *expert technicians and managers*, *financial autonomy,* and *stakeholders' engagement*. *Public expenditures and investment in transport systems,* and *operational cost of public transport systems* were also assigned a great priority. Finally, the participation of the *multilateral banks* and the *variations in informal transport modal split* were assigned the lowest priority. Nevertheless, these are aspects that should deserve further attention in the future.

We might finally say that both approaches (AHP and FAHP) could be successfully used TO prioritize the criteria and the sub-criteria in our framework, leading to realistic results that are in general more satisfactory than those proposed in the existing literature. Moreover, these approaches clearly benefit from the descriptive analysis of the surveys, questionnaires, semi-structured interviews, and face to face meetings.

We can observe that the two ranking procedures yielded very similar results. Nevertheless, some differences can be noticed. This is, for example, the case of the results at *level 1*, for sub-criteria (sustainability indicators) such as population density, indirect trip cost for user or share of PT which are wheelchair accessible, among others.

These processes enable decision-makers to formalize and effectively solve the complicated, multi-criteria and fuzzy/vague perception problem of defining the most appropriate criteria (sustainability dimensions at *level 1*) and sub-criteria (sustainability indicators at *level 2*) for measuring sustainability in transportation systems of emerging cities.

Nevertheless, and based on our comprehensive literature review, we might state that for dealing with qualitative attributes in subjective judgments, FAHP seems, in general, more appropriate to determine the weights of decision criteria for the associated interest groups (users, experts, decision makers and other stakeholders).

In this work, we have therefore adopted the results achieved with the FAHP approach. These results are compiled in Figure 5.14, that presents the final priorities assigned to the sustainability dimensions and indicators (sub-criteria at the *level 2*) proposed for the framework developed in this work.

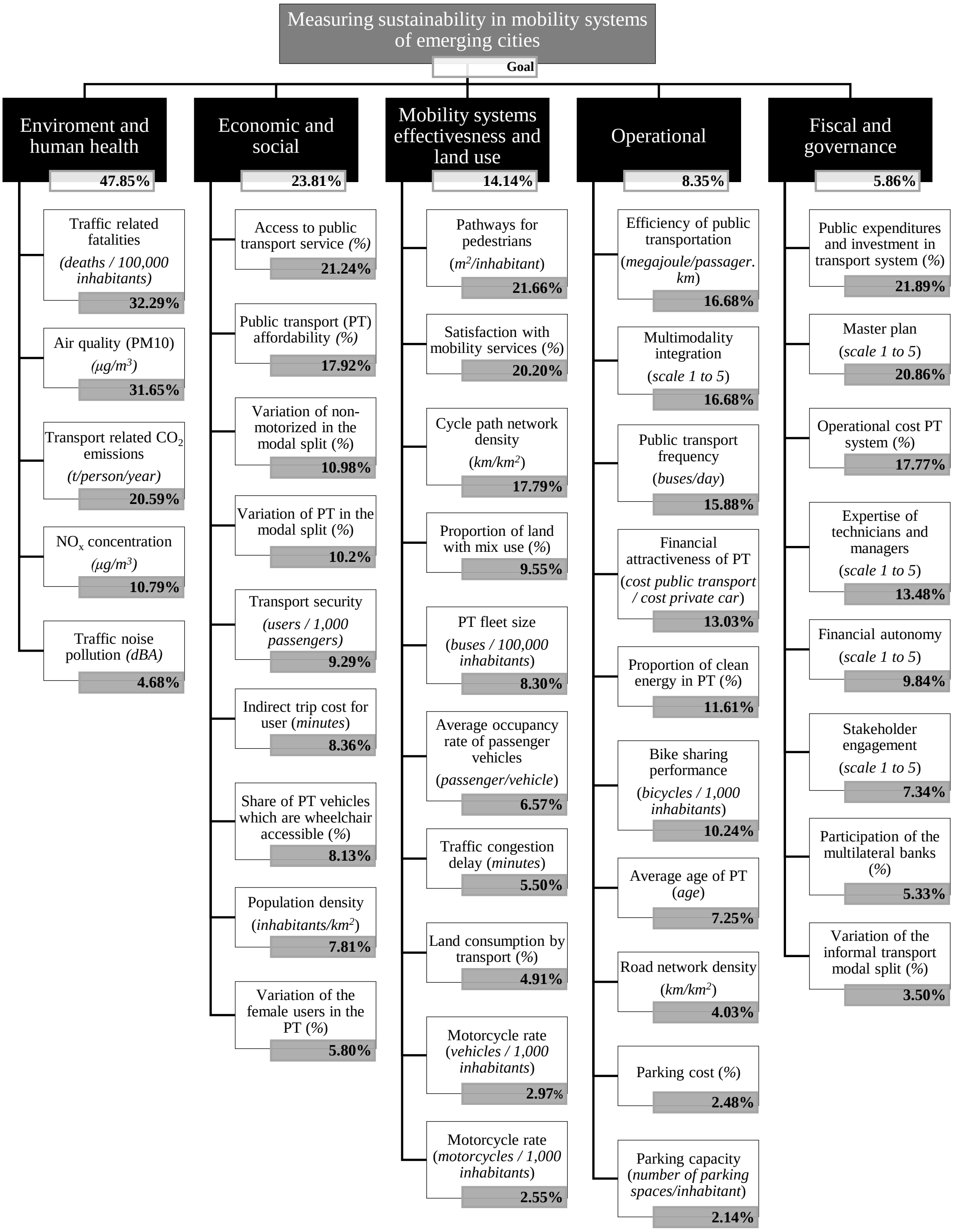


Figure 5.14 *Confirmatory* framework for measuring sustainability in mobility systems of emerging cities

5.9 Summary

In line with the global research objective of this doctoral project, we have, in this chapter (*confirmatory* phase of the process), developed and compared two approaches to prioritize the criteria and sub-criteria previously presented and discussed.

These criteria (sustainability dimensions at *level 0*) and sub-criteria (sustainability indicators at the *level 1* for each criterion at *level 0*) make up the *hierarchical framework* we propose to achieve the "goal", defined as measuring sustainability in mobility systems of emerging cities, at the top of the *framework*.

The approaches presented in this chapter were developed around two multi-criteria decision-making methods, one being based on the Analytic Hierarchy Process (AHP), and the other being a Fuzzy Analytic Hierarchy Process (FAHP) procedure.

This *prioritized framework* is intended to support the task of evaluating sustainable transportation, and has the potential to be adapted to more specific contexts of different emerging cities. It includes a wide list of variables, validated by sustainability experts and analyzed with the two approaches referred above.

We could show that the two ranking procedures yielded very similar results. Nevertheless, given the observed differences, and the findings of our literature review, FAHP seems, in general, a more appropriate approach to determine the weights of decision criteria for the associated interest groups (users, experts, decision makers, and other stakeholders).

In this work, we have therefore adopted the results achieved with the FAHP procedure, proposing the resulting priorities for the sustainability dimensions and indicators used in our framework.

By using different sets of fuzzy membership functions, the FAHP approach enables decision makers to perform the often challenging and complex transportation sustainability measurement prioritization procedure, in a more objective way. Future research can be carried out exploring and comparing other different multi-criteria decision analysis techniques.

Moreover, another general limitation of the proposed *prioritized framework* is the large quantity of information requested from the experts (174 pairwise comparisons per expert!), along with the difficulty in dealing with uncertainty and conflicts. Therefore, another interesting topic for future research might be the design of a “smart” software application to compute weights automatically, at least partially.

Finally, this framework (the *confirmatory* sustainability measurement framework) showed to be a useful tool on how sustainability can be measured in transportation systems, being easily adaptable to different city contexts. It can be useful to transportation managers in policy making processes, contributing to the generation of bottom-up (rather than top-down) sustainable mobility policies, and to determine which interventions would have the greatest impact.

The *confirmatory* sustainability *measurement framework* was later applied and “validated” in the four cities selected as case studies – Lund (Sweden), Copenhagen (Denmark), Porto (Portugal) and Ibague (Colombia). This *conceptual framework* is the basis for the *decision support system* described later in this thesis, to be used for policy design and assessment of sustainable transport in emerging cities.

6 Sustainability assessment in mobility systems – case studies

6.1. Introduction

This chapter presents the application of the assessment framework described in chapter 5 to four cities selected as case studies for their relevance in this research context. The case studies were Lund (Sweden), Copenhagen (Denmark), Porto (Portugal) and Ibague (Colombia).

Lund is an attractive municipality undergoing robust environmental, economic and social development. Within the context of Sweden, Lund may be considered an intermediate city, and for its location near cities such as Malmo and Copenhagen, is one of the cities in Sweden with the most intensive commuter traffic. Therefore, Lund plays an important role in the dynamics of sustainable transport in this context, and is an interesting case to analyze as an intermediate city that has achieved a sustainable development in its transport system.

In the case of Copenhagen, the city's existing policies and strategies also contain ambitious goals in relation to all 17 Sustainable Development Goals (SDGs), and it is well on its way to achieving them. Therefore, Copenhagen can be viewed as an interesting case study to analyze in this research, as a benchmark city of sustainable transport practices to follow.

Porto is also an interesting case to apply the proposed sustainability *measurement framework*, as intermediate city within the context of Portugal, with less than 2 million inhabitants in the greater Porto metropolitan area, and also, because it is here considered as conveying a vision of a transport system designed towards sustainability.

Finally, Ibague meets the conditions of an emerging city within of the Colombian context, with less than 600,000 inhabitants, discerning our attention since it appears to have the most unsustainable and inefficient mobility system when compared to the other case studies.

6.2. Lund (Sweden)

For this case, we had two (2-hour) recorded face-to-face semi-structured interviews in Lund (Sweden) between March 2019 and November 2019. These interviews were made with Per Eneroth (head of the road and traffic division) and with Ana Karlsson (head of the traffic and mobility department).

The interviews were quite useful in obtaining the data for the application of the proposed *framework*, as well as relevant information about policies and strategies implemented in the city for consolidating a sustainable transport system. Other sources were consulted, such as LundaMaTs (strategy for a sustainable transport system in Lund municipality) in their third version (see Table 6.2).

According to [152], in the next 20 years, Lund will grow from 121,000 habitants to approximately 160,000. During the last decade, Lund's population has increased by 14,000 inhabitants, and it is believed the population will continue to steadily increase. Sweden has the fastest rate of urbanization in Europe, and Lund is one of the municipalities that is growing the most [153]. Lund is therefore expanding, and its growing population and number of businesses require a more efficient use of land and transport. Hence, the city must remain focused and grow cautiously, in ecological, economic and social terms. In this context, [152] believes the city will grow through densification, in a sustainable and environmentally sound way.

In terms of transport, the Lund municipality has been, for a long time, working successfully in a more sustainable direction [152]. The negative impacts of traffic on the environment and health, such as the climate impacts, air pollutants and noise, are being kept to a minimum [152]. Walking (23% of trips), cycling (43% of trips) and using public transport (8% of trips) constitute the main part of all transports, and have been and are prioritized, making it possible to achieve a sustainable transport system.

In this context, Lund has adopted a strategy called LundaMaTs that has gone through three versions – the first (I) was developed in 1999, the second (II) was adopted in 2006, and the third (III) was implemented in 2014.

The focus of LundaMaTs I was the environmental adaptation of the transport system. Then this strategy was updated, and the approach was broadened from environmental adaptation to sustainability. Finally, the last version of the strategy went on creating favorable conditions for development, with the transport system ensuring a better quality of life for all the residents, visitors and business operators in the city.

Now, the changes in traffic conditions and in urban planning have led to a shift of the strategy focus, in order to achieve long-term sustainable social development and set targets for CO_2 emissions.

Therefore, Lund is a great opportunity to apply the *framework* proposed by this research (for sustainability measurement in transport systems), with the main purpose of encouraging a sustainable development, with a transport system that promotes good health in the form of traffic safety, security, movement, exercise and recreation. The consolidation of a sustainable transport system, as defined by this research, needs to provide good access for everyone, regardless of gender, age, ability, and should replace the car by other modes such as public transport, walking and cycling.

The vision of the Lund municipality (Lund 2025) emphasizes the importance of a sustainable development, an efficient transport system, and the obtention of significant savings in terms of energy and resources. Therefore, the results obtained by this research are meant to be used by the transport authorities of the municipality, to be analyzed and taken into account in the formulation of the new vision of the LundaMaTs, since the targets defined by the indicators in our *framework* closely follow the future vision of the transport system for the city.

6.3. Copenhagen (Denmark)

For the Copenhagen case, the approach pursued was similar to that in Lund, with three (2-hour) recorded face-to-face semi-structured interviews. These interviews were done with Sidsel Kjems, twice between March 2019 and November 2019, and with Thomas Sick Nielsen, in November 2019. Sidsel Kjems is the project manager for COMPASS (Strategic Transport Model) and a senior consultant from the department for traffic of the city of Copenhagen. Thomas Sick Nielsenis is a senior consultant, from the planning and analysis department of the Danish road directorate. Another interview was done with Jens Stissing Jensen, Associate Professor of Aalborg University, in Copenhagen.

The data used for this research phase and other information on sustainable transport policies implemented in the city, was obtained in these interviews, and complemented by sources such as CPH 2025 Climate Plan (Roadmap 2017-2020), and others, as presented in Table 6.3.

Copenhagen is a growing city with a population of 794,000. It forms the core of the wider urban area of Copenhagen (population 1,330,993) and the whole metropolitan area (population 2,057,142). The population is expected to have grown by 14% by 2025, with a significant impact on the whole of the surrounding region [154]. The city of Copenhagen is continuously transforming its urban infrastructure and the transportation systems that are used, and consequently the travel patterns of the citizens [155]. The bicycle network is growing, the metro network is being expanded, and the land use is changing.

According to [155], in the transport sector, the new technologies are further affecting travel behaviors, as seen through the significant rise of electric vehicles and electric bikes. Therefore, the planning of big infrastructure projects should be made in accordance to the forecasted, expected traffic impacts, both during development works and also afterwards. In such context, [156] stated that "*to meet the demands of citizens and businesses, Denmark is highly dependent on a well-integrated and modern infrastructure, as well as on efficient and reliable public transport*".

Although bicycles (29% of trips) and public transport (21% of trips) are used in the city center, it is also clear that the car remains the preferred mode of transport (33% of trips). Therefore, the key challenge will be to create he right conditions for more people to drop the car in favor of walking, cycling and public transport.

"*An efficient transport system is a key driver in establishing long term growth in Denmark and in Europe at large. Therefore, innovative thinking and major investments will be needed to create the Copenhagen of the future*" [156]. More people living in the region will mean more traffic. There will be more bicycles and more cars. According to [154], in 2025, bicycle usage is expected to be up 27%, and there will be 20% more cars. Congestion is expected to be twice as bad in and around the capital. The number of kilometers per person by public transport is expected to increase by 66%. Therefore, an even better mix and spread of modes of transport is needed, if Copenhagen is to remain a city in which it is easy to get around.

Currently, the city of Copenhagen is using transport macro models, where the calculations are performed by external parties. Most importantly, these tools are becoming increasingly out of date, and do not sufficiently address key areas that are important to the city [155], such as the estimation of sustainability from a multidimensional view, as proposed in this research. In this ever-changing landscape, there is an increased need for creating the right instruments for driving this transformation. Copenhagen has, therefore, become an interesting opportunity for applying the proposed *framework*, and the decision support tool developed by this research, in order to help robust decision-making.

6.4. Porto (Portugal)

For this case, the data used in the pilot application was obtained from government entities, academic research work, and recent reports on sustainability (in Portuguese), (see Table 6.4).

The city of Porto forms the core of a metropolitan area (AMP) that occupies an area of about 2,041 km^2 and where approximately 1.7 million people live, corresponding to about 17% of the total population of Portugal. According to [157], changing the mobility paradigm, based on individual transport, is an urgent endeavor. In the area, transport is responsible for around 25% of greenhouse gas emissions. The negative impacts on economic competitiveness, public health and the population's quality of life are too high to be ignored.

In the transport context, [158] showed that the automobile was the main means of transport used in the AMP (67.6% of trips), considering all days of the week. Trips by non-motorized modes (pedestrian or bicycle) appear as the second most expressive form of transportation in the total number of trips, registering a combined weight of 18.9% in the AMP, but with a limited bicycle contribution (0.4%).

Public transport represents 11.1% of the trips on the AMP. The use of the bus (public transport and company/school transport) represents 8.2% of the total trips in the area, while rail transport (heavy and light) corresponds to 2.8%.

Among the mobile population, the number of trips per day per resident in the AMP, is 2.72. This indicator of mobility per person can be associated with the person's economic capacity and easiness of movements. This is reflected in the results shown in see Table 6.4.

In such context, it is clear that Porto needs a set of legislative initiatives to provide clean mobility, emission reduction options, less polluting fuels, as well as to promote active mobility, by integrating the various modes of transport, mainly, walking, cycling and public transport.

Porto is therefore an interesting case to explore, and a good environment to develop a mobility system towards sustainability. That is why it was considered a good case study for testing and validating the approach developed in this work, with the purpose to support and recommend strategies or concrete interventions to promote sustainability.

6.5. Ibague (Colombia)

For the Ibague case, the data was obtained from government entities, academic research works, and reports on sustainability (as described in Table 6.5), as well as from a set of 2-hour recorded virtual semi-structured interviews by Skype between November 2019 and December 2019. These interviews were conducted with Luis Felipe Lota (director of the government agency "Agencia Nacional de Seguridad Vial") and with Jonathan Bernal (technical director of the government agency "Departamento Nacional de Planeacion") and Oscar Patiño (adviser of the government agency "Departamento Nacional de Planeacion").

Ibague, with about 560,000 inhabitants, is a strategic node in national logistics, for being an intermediate point of transit on the main Colombian freight axis. In the South American context, and according to the geo-spatial framing of this research, this city can be viewed as an "emerging city".

Ibague's inclusion in the "emerging and sustainable cities" initiative (ICES, for its initials in Spanish) from the Inter-American Development Bank (IDB), highlights the need to transform the city's transport sector. Currently, trips are made according to the following hierarchy of transport modes: public transport (35%); walking (27%); motorcycle (15%); private automobile (11%) and bicycle (1%).

It is undeniable that mobility has become a great challenge for cities, and Ibague is no exception. Since the second half of the last century, the automobile has been disproportionately favored as a means of transportation, in an increasingly noticeable trend in the last decade in Colombian cities. This trend has strengthened the idea that mobility primarily refers to the ease of moving quickly and by car.

The transport system of Ibague presents the characteristics of a monocentric city, where transport flows are concentrated on longitudinal road corridors, and due to the lack of structuring axes in the transverse direction, larger travel times are generated, with an intensification of private motorized transport modes and the saturation of the system's road capacity [159]. If this situation does not change, the city may experience strong negative externalities in the short and medium term, such as increased congestion, and pollution and noise at significance levels, that may be detrimental to the quality of life of the inhabitants, and to a sustainable and competitive development of the city.

Therefore, in order to reverse these trends, the municipality should promote the use of non-motorized modes, as a way to improve mobility, as well as to consolidate a sustainable public transport system that is accessible, affordable and reliable. Thus, Ibague is an interesting case to be studied from our research perspective, and to be analyzed, in comparative terms, with more sustainable transport systems (as described above). Such a study should be used to identify the main problematic issues regarding sustainability, as well as to recommend strategies to improve the results of the indicators proposed by our framework.

6.6. Selected indicators and data normalization

10 indicators were selected for the application of the proposed framework to assess the sustainability of the mobility system in each of the case studies.

In such context, two aspects have been considered to select these indicators: i) from the hierarchic framework defined in chapter 5, the two indicators with highest weight, for each dimension, were selected; and ii) taking into account the available data, the indicators that had measurable information were also selected. Table 6.1 shows the indicators identified for the case studies, with the associated weights (from the FAHP results), and the worst and the best reference values.

For each city, the analysis is based on data provided by the official entities, as well as on assumptions consolidated with the experts (through interviews) and processed for the sake of consistency.

Table 6.1 Selected indicators

dimension	*FAHP weight (%) / rank*	*indicator*	*natural units*	*FAHP weight (%) / rank*	*reference values*	
					worst	*best*
Environmental and human health	47.85 / 1	Traffic related fatalities	(*deaths / 100,000 inhabitants)*	32.29 / 1	35	0
		Air quality (PM10)	*(µg/m3)*	31.65 / 2	40	0
Economic and social	23.81 / 2	Access to public transport service	(*%*)	21.24 / 1	20	3.5
		Public transport affordability	(*%*)	17.92 / 2	50	100
Mobility effectiveness and land use	14.14 / 3	Satisfaction with mobility services	(*%*)	20.20 / 2	40	100
		Average occupancy rate of passenger vehicles	(*passenger/vehicle*)	6.57 / 6	1.67	2.6
Operational	8.35 / 4	Multimodality integration	(*scale 1 to 5*)	16.68 / 2	1	5
		Bike sharing performance	(*bicycles / 1,000 inhabitants*)	10.24 / 6	59	238
Fiscal and governance	5.86 / 5	Master plan	(*scale 1 to 5*)	20.86 / 2	1	5
		Expertise of technicians and managers	(*scale 1 to 5*)	13.48 / 4	1	5

Indicators on different scales need to be normalized before comparison is possible [21]. For this purpose, some authors [2], [125] recommend the use of a linear rescaling procedure, allowing a simple transformation to a linear scale 1/100, for each indicator (see equation (6.1)).

$$Z_{i,c} = \frac{(x_{i,c}) - (x_{min,i})}{(x_{max,i}) - (x_{min,i})} \times 100 \qquad (6.1)$$

Here $Z_{i,c}$ is the normalized indicator $x_{i,c}$ for topic i and city c. x_{min} is the lowest value of the indicator in actual units, whereas x_{max} is its highest value. In this context, *min* and *max* were defined as the “worst” and the “best” reference values (see Table 6.2 to Table 6.5).

6.7. Case studies analysis

Table 6.2 Lund

indicator	*min*	*max*	*Lund*		*source*
			real value	*normalized value*	
Traffic related fatalities (*deaths / 100,000 inhabitants*)	35	0	0	100	[160]
Air quality (PM10) *(μg/m³)*	40	0	11	72.5	[161]
Access to public transport service (*%*)	30	100	74	62.86	[152]
Public transport affordability (*%*)	20	3.5	2.51	106	[162]
Satisfaction with mobility services (*%*)	30	100	75	64.29	[152]
Average occupancy rate of passenger vehicles (*passenger/vehicle*)	1.67	2.6	1.7	3.23	[163]
Multimodality integration (*scale 1 to 5*)	1	5	5	100	defined based on the literature review and directly asked in the semi-structured interviews
Bike sharing performance (*bicycles / 1,000 inhabitants*)	59	238	1.98	-31.85	[164]
Master plan (*scale 1 to 5*)	1	5	5	100	defined based on the literature review and directly asked in the semi-structured interviews
Expertise of technicians and managers (*scale 1 to 5*)	1	5	5	100	defined based on the literature review and directly asked in the semi-structured interviews

Table 6.3 Copenhagen

indicator	*min*	*max*	*Copenhagen*		*source*
			real value	*normalized value*	
Traffic related fatalities (*deaths / 100,000 inhabitants*)	35	0	0.24	99.31	[165]
Air quality (PM10) *(μg/m³)*	40	0	15	62.50	[166]
Access to public transport service (*%*)	30	100	75	64.29	[167]
Public transport affordability (*%*)	20	3.5	2.70	104.85	[168]
Satisfaction with mobility services (*%*)	30	100	75	64.29	[167]
Average occupancy rate of passenger vehicles (*passenger/vehicle*)	1.67	2.6	1.68	1.08	[163]
Multimodality integration (*scale 1 to 5*)	1	5	5	100	defined based on the literature review and directly asked in the semi-structured interviews
Bike sharing performance (*bicycles / 1,000 inhabitants*)	59	238	1.21	-32.28	[169]
Master plan (*scale 1 to 5*)	1	5	5.00	100	defined based on the literature review and directly asked in the semi-structured interviews
Expertise of technicians and managers (*scale 1 to 5*)	1	5	5.00	100	defined based on the literature review and directly asked in the semi-structured interviews

Table 6.4 Porto

indicator	*min*	*max*	*Porto*		*source*
			real value	*normalized value*	
Traffic related fatalities (*deaths / 100,000 inhabitants*)	35	0	3.37	90.38	[170]
Air quality (PM10) (*μg/m³*)	40	0	17	57.50	[171]
Access to public transport service (*%*)	30	100	65	50	[158]
Public transport affordability (*%*)	20	3.5	6.30	83.04	[158]
Average occupancy rate of passenger vehicles (*passenger/vehicle*)	1.67	2.6	1.56	-11.83	[158]
Multimodality integration (*scale 1 to 5*)	1	5	3	50	defined based on the literature review
Bike sharing performance (*bicycles / 1,000 inhabitants*)	59	238	0.00	-32.96	defined based on the literature review
Master plan (*scale 1 to 5*)	1	5	4	75	defined based on the literature review
Expertise of technicians and managers (*scale 1 to 5*)	1	5	4	75	defined based on the literature review

Table 6.5 Ibague

indicator	*min*	*max*	*Ibague*		*source*
			real value	*normalized value*	
Traffic related fatalities (*deaths / 100,000 inhabitants*)	35	0	7.50	78.57	[172]
Air quality (PM10) (*μg/m³*)	40	0	32	20	[173]
Access to public transport service (*%*)	30	100	36	8.57	[159]
Public transport affordability (*%*)	20	3.5	9.3	64.85	[159]
Satisfaction with mobility services (*%*)	40	100	51	30	[174]
Average occupancy rate of passenger vehicles (*passenger/vehicle*)	1.67	2.6	1.30	-39.78	[159]
Multimodality integration (*scale 1 to 5*)	1	5	1	0	defined based on the literature review
Bike sharing performance (*bicycles / 1,000 inhabitants*)	59	238	0	-32.96	defined based on the literature review
Master plan (*scale 1 to 5*)	1	5	2	25	defined based on the literature review
Expertise of technicians and managers (*scale 1 to 5*)	1	5	2	25	defined based on the literature review

6.8. Comparative assessment

The diagram in Figure 6.1 shows the performance of the different cities in a normalized scale, for all 10 selected indicators, as part of our *sustainability measurement framework*. The spider diagram is useful in performing a simple comparative assessment of the performance of the cities in the different measures, when compared with the low and values of the reference range. This analysis can also be used to identify areas to potentially focus on for improvement [21]. The result (point) for each indicator toward or above 100 is interpreted as desirable and a value toward or below 0 is interpreted as an undesirable performance of what is being measured. The diagram (Figure 6.1) facilitates the comparison for each indicator.

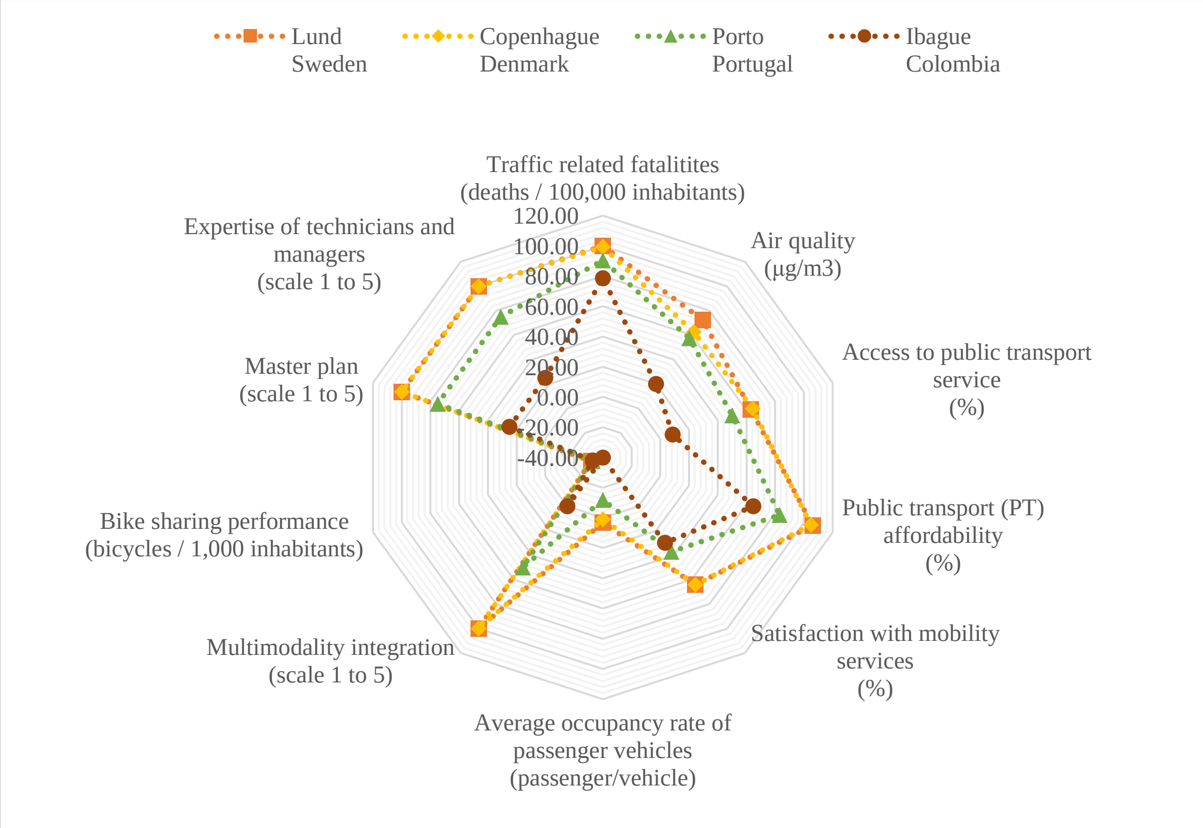


Figure 6.1 Performance of cities on the different selected indicators

In the case studies, the sustainability *measurement framework* (including the weights) was only partially applied, due to a limited access to data (this obstacle was overcome by the model described in chapter 7). Therefore, an index value was used with the indicators selected, with equal weights.

Therefore, a "sustainability index" was used to aggregate results, and allow a ranking of the cities. This index was calculated for each city, using the normalized values presented in the tables above (Table 6.2 to Table 6.5). This index is a kind of global performance measure that can be computed in different ways, in order to aggregate the values of the different indicators [21].

The basic options are to use either an arithmetic mean or a geometric mean. For the "assessment of urban transport systems", [21] have chosen to use the geometric mean, and based on their experience and positive judgements, we have taken the same approach in this work (Equation (6.2)). This "index" is then composed of n indicators $i_1 - i_n$

$$Index = \sqrt[n]{i_1 * i_2 * i_3 * \ldots * i_n} \quad (6.2)$$

Table 6.6 and Figure 6.2 show the ranking of the cities starting with the highest performer on top.

Table 6.6 Index ranking for the case studies

index score		*rank by score*
Lund	84.61	1
Copenhagen	82.89	2
Porto	64.23	3
Ibague	28.79	4

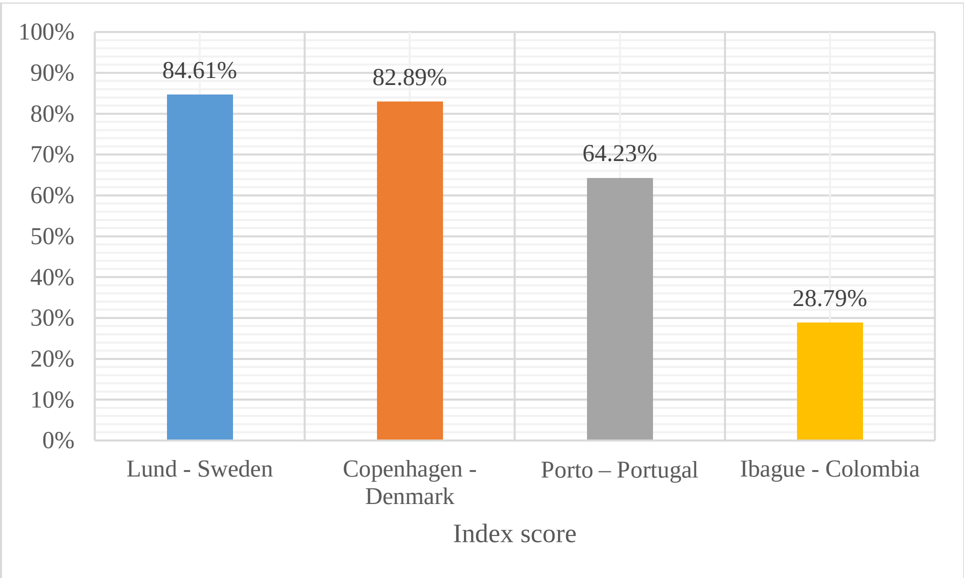


Figure 6.2 Index performance of cities

6.9. Summary

Applying our sustainability *measurement framework* to the case studies, resulted in having Lund on top of the ranking, while Copenhagen ranks second, but very close to Lund. These results are not surprising as Scandinavian cities, such as these, generally outperform other cities on most indicators regarding transport systems sustainability. Both cities have similar performance across most of the indicators.

The analysis also shows that Porto's transport system is on the way to "sustainability", and although it performs quite well in most of the evaluated items, still has aspects to improve, such as encouraging the use of the bicycle. In this sense, it is necessary that public authorities together with private companies, create incentive measures for people to start using non-motorized modes, as it is already the case of other European cities, such as Copenhagen.

Such measures would lead people to use the bicycle as a regular transport means to do normal daily activities such as going to work, and not just as a physical activity for the weekends. Therefore, it is very important to invest in secure infrastructure and ensure interconnections between modes of transport, especially with public transport (bus, metro, and train).

For Ibague, as expected, the results show the transport system still has a lot to improve regarding sustainability, with special attention to the "environment and human health" dimension, as well as in what concerns the "access to public transport" and "multimodality integration". The city should also improve its performance in the subjects related to the "fiscal and governance" dimension.

Although Ibague's transport system shows a better performance than Porto in what concerns the use of the bicycle (according to the data gathered from the transport surveys), the city should continue improving the conditions for movement in this mode of transport. It should also continue consolidating the public transport system as the main means of transport, unlike Porto, where the main means of transport is the car.

In what concerns "bike sharing" performance, we can conclude that today public bicycle-sharing systems do not have the expected positive impact on the people's mobility patterns, probably due to the high maintenance costs that are reflected into low rates of use. Therefore, in cities such as Ibague, where efforts are still being made to implement this type of systems, those efforts should probably be made in other directions, such as providing citizen and road safety to the main corridors, or articulating with private companies and local authorities, bicycle loans for employees to promote this transport in the city.

However, the more relevant contribution of this research is not really the actual performance of these or other cities, but to illustrate the developed concepts and show their potential of application. In this context, issues that require further attention include data availability, collection and processing. Therefore, consolidating reliable information systems and structuring data collection should be just as important as implementing policies to improve the sustainability of transport systems. And in fact, as observed throughout this research, measurement indicators play a fundamental role in the planning and decision-making processes.

In this line, the final research step of our approach was developed around the integration of the hierarchic sustainability *measurement framework* with the *decision-making processes* based on a *system dynamics* approach for policy design and assessment of sustainable mobility in emerging cities, as described in chapter 7.

7 A decision support system for policy design and assessment of sustainable mobility in emerging cities

7.1 Introduction

In order to overcome the weaknesses of conventional methods to study sustainability of the transportation, system dynamics has been applied recently [78]. Indeed, transport systems are complex systems with multiple variables and nonlinear feedback loops that are influenced by multiple factors, as described in chapter 3. In such context, conventional sustainability assessment approaches may be unsuitable to simulate and evaluate performance in transport systems [175].

Therefore, this research proposes a multi-layered model to analyze the *cause-and-effect* relationships in a system that integrates high-level policies, specific strategies and actions, and a sub-system to measure the impacts of those policies and actions, in terms of sustainability. For that purpose, the *analysis structure* (dimensions and indicators) defined in chapter 4 is used.

This evaluation helps in understanding how the SD modeling style can contribute to better understanding the relationships *policies/strategies/actions* and their impact in transport systems of emerging cities regarding sustainability performance. For this purpose, a general qualitative model was designed to apply the conceptual framework developed, and show its potential of application.

The model shows how policies impact the variables related to the indicators within the proposed *analysis structure*. The results are visualized using an *insight matrix*. It establishes the ease with which system dynamics can be applied to allow better planning, decision-making and communication. The implementation of this model can, therefore, be viewed as a real *decision support system* (DSS).

7.2 Sustainability policies

Each policy leads to an intervention set (strategies and actions/variables) which in turn have influence on the other factors of the model. These high-level policies are also based on an extensive literature review and in information collected about successful initiatives, implemented in sustainable transport systems of various cities (see [152]–[154]). The suggestions gathered at the semi-structured interviews were also an important contribution for this purpose.

In the next paragraphs, we briefly describe the main lines of a set of policies that are have designed hoping to contributing for enhancing sustainability in mobility systems.

Policy 1 – Green mobility

The city will encourage *green mobility* incorporating new fuels in light vehicles, by expanding infrastructure for both hydrogen-powered and electric vehicles, as well as enabling charging stations, reserved parking and hydrogen pumps. In particular, local authorities will incentive people to adopt electric and hydrogen-powered cars, through partnerships and pilot projects and by offering discounts for parking. The city will also invest in *e-mobility* (infrastructure and partnerships). If users do go by car, the aim is that as many as possible use electric, or hybrid and hydrogen cars, while heavier vehicles should run on new fuels such as biogas.

For this, the city will work to increase the use of electric vehicles, hydrogen-electric vehicles and heavy vehicles running on biofuels. Through demonstration projects, they will contribute to the development and wider use of new fuels in transport. The city will also implement electric charging points and hydrogen filing stations, and the possibilities for a secure infrastructure for biofuels will be explored. On the other hand, collaboration with industry and other public authorities will promote the purchase of vehicles operating with electricity, hydrogen and biofuels.

Policy 2 – Mobility for health and wellbeing

It will only be possible to improve the traffic flow where the potential is greatest to get people to drop the car and use bicycles and public transport instead, if analyses are conducted to ascertain exactly which car journeys are actually necessary [154]. Then, the city will be able to promote an integral mobility in the city – more walking, more cycling. The local authorities will offer alternatives for passengers that minimize the travel time for all, and recognizing walking, cycling (safety and sense of security for pedestrians and cyclists) and the public transport, as the structuring axis of the mobility system.

The public transport system will also be complemented with other initiatives that make it even easier for users to choose alternatives to the car. To help in this, a digital platform will help the users find, buy and pay for transport by different available modes of transport. Multimodal stations will also be built, i.e. public bicycles, car-sharing, bicycle parking and other services, e.g. toilets and online information systems. During the policy implementation period, the city will improve capacity on the bicycle network, and will develop partnerships supporting innovation of cyclist solutions. Bicycle tracks will be expanded, and cycle corridors and regional super cycle highways will be upgraded. Space will also be needed for parking the increased numbers of bicycles, e.g. by upgrading bicycle parking at traffic hubs and in shopping areas. Parking facilitates will also be located where they provide easy access to public transport. The city will also develop of a concept on improved conditions for cyclists, in order to promote the use of bicycles at workplaces.

The public transport system must be improved, which includes improving conditions at nodal points, as well as taking measures to make it easier for road users to get to their destination and to provide better traffic information. More and more, older buses will be replaced, by new models powered by electricity and biogas, so that city is able to achieve its target of a carbon neutral bus service by 2030. Some strategies and actions in this policy will implement carbon neutral bus services and "*Mobility as a Service*".

Policy 3 – Mobility for competitiveness and quality of life

This policy integrates actions and strategies to explicitly improve the system mobility regarding sustainability. Therefore, the city will implement multimodal stations, the integration of carsharing into urban spaces, ECO-driving for heavy traffic and municipal vehicles, optimization of traffic lights, efficient delivery of online purchases, and a freight network for large fleet owners, including the use of new fuels.

To illustrate the advantages of car-sharing over car ownership, the city will run a pilot project to integrate car-sharing vehicles into local streets and urban spaces. To ensure that the remaining car and lorry traffic runs as smoothly as possible, work will be done on traffic control and optimization on the main roads and at traffic lights, all over the city. This traffic control will include intelligent bus prioritization and green waves for cyclists. A special initiative encouraging ECO-driving for heavy vehicles on surrounding city roads will mean a smoother and more efficient movement of the vehicles.

Policy 4 – Integrating mobility and land use

Workplaces, schools, shops and sport associations are central destinations in cities today. Collaboration with these businesses can encourage journeys made on foot and by bicycle, to and from these destinations. Entrances may need to be reviewed to be linked with walkways and cycleways. This policy promotes the integration between urban planning and transport processes.

Mobility planning must increase the demand for green modes of transport. Large investments in public transport, cycle tracks and technologies for new vehicles, will in itself make carbon neutral transport more attractive to use, but the public´s knowledge of the various modes of transport need to be increased through information and campaigns.

Therefore, a business network will be set up to help companies develop transport plans. Collaboration with local groups should develop direct offers and provide information to citizens about transport opportunities. The travelling habits of users must be changed through campaigns to provide information and change behavior. City businesses must become involved spreading the use of electrical bikes for the city area.

Policy 5 – Modern governance for efficient and safe mobility

The city will promote an institutional framework to support and promote initiatives for the development of the transport system towards sustainability, encouraging a more humane infrastructure that ensures the safety of all users, privileging non-motorized modes, as well as guaranteeing accessibility for people with reduced mobility.

Safety is a crucial factor when it comes to encouraging more people to use their bicycles, regardless of whether they are children, young people, former commuters or newcomers to the city. This special focus on safety solutions will also included *green cycle routes* and safe routes to schools. These activities will be combined with information campaigns to influence behavior, e.g. campaigns such as “cycle to work” and cycling education for children, young people, newcomers and immigrants.

7.3 Characteristics of the system dynamics approach

The application of *system dynamics* (SD) to transportation is well documented in the literature [176]–[178]. Transport systems and policies are complex, involving multiple agents or stakeholders, with many feedbacks involved, with different time lags between responses of users, developers, operators and policy makers. SD not only offers a different perspective to transport planning but can also highlight the importance of these feedbacks and lagged responses. In addition, according to [78] the system dynamics approach recognizes that for long-run problems like sustainable transportation, methodologies based on data from the past such as econometric modelling and other statistical techniques are less reliable.

Accordingly, [179] describes system dynamics as a "*systems analysis approach that is used to study behavioral patterns of systems*". System dynamics is a discipline that emerged in the late 1950s, as an attempt to address dynamically complex long-term policy issues, in the public and private domain [180]. SD was developed by [181] to predict the behavior of dynamic systems and analyze the efficacy of decision-making by modelling and simulation [182]. The same author [182] states that SD is a broad concept that can be divided into two aspects: "system" represents the structure of the system and the concept of feedback effect, while "dynamics" reflects the changes in the behavior of the system components over time.

In such context, for [183] dynamic problems are characterized by variables that undergo significant changes in time. The defining property of a dynamic problem is not merely the variables being dynamic. More critically, in such problems, the dynamics of the variables must be closely associated with the operation of the internal structure of some identifiable system [180]. [183] concludes that the dynamics are essentially caused by the internal feedback structure of the system. The "structure" of a system is the totality of the relationships that exist between system variables. Over time the model will produce the dynamic behavior patterns of the system variables over time.

According to [184], the early applications of SD were in business management, but over the past few decades it has been applied to other areas, including government policy, the automobile industry and urban studies [180]. Since the complexity of urban areas and urban transportation is always increasing, applications of SD in regional policy have become more significant. [185] concludes that the "*SD approach fundamentally is able to formulate complex decision model systems in which:*

- *some components are abandoned due to the complexity and broadness of the system, amnesia of analyst, or causal relations of element;*
- *comparative approach is used for different scenarios;*
- *the system cannot be stopped and rerun from beginning;*
- *effect(s) of changes takes time for showing up in the system".*

Although there exist several methods for policy evaluation for sustainable development, SD is highlighted for its ability to analyze relations, among components, causes and effects, to determine key performance indicators, and to simulate the effects of changes in process design and policies [185], [186]. [175] concluded that SD is significantly different from conventional transportation modeling approaches which look specifically at the problem under analysis, and not from a broad perspective. The SD approach basically considers the system as a whole, and analyzes behavior of its component and the whole system for different scenarios over time [185].

According to [184], the qualitative models are better built with the input of the relevant stakeholders, and are generally communicated with *causal loop diagrams* (CLD). The qualitative model proposed here is developed based on the data obtained from the qualitative analysis in chapter 5, with the weights of the elements that make up the *analysis structure*.

The development of a CLD is a key part of the model building process and connects entities by causal relationships, and as the diagram develops the feedback loops become evident [184]. These loops are either positive (self-reinforcing) or negative (self-correcting or balancing) *feedback loops*. CLD help us visualize important elements of the system and conceptualize their relations [185].

The CLD developed by the proposed models (qualitative and quantitative) were designed by brainstorming among the sustainability experts interviewed, as described in chapter 5. [185] states that the "*feedback loops help us recognize how factors or variables affect each other. Variables which are located in more than one feedback loops in a system are source of influence or receive influence form other variables and need more attention*".

In such context, [184] concludes that CLD may be used to make the “mental models” (how people think a system works) of different stakeholders explicit, and therefore, help remove any barriers to implementation of a given policy.

System structure analysis includes defining system boundaries, modeling hypothesis, and constructing causalities and feedbacks [187]. Therefore, a simulation model was developed from a dynamic approach, that allowed to integrate the elements that make up the proposed sustainability measurement *analysis structure* and its simultaneous relationships with the proposed interventions set (high sustainability policies, strategies-actions and variables).

The structure of a real system is never completely known. For a “model” of the real system, the structure is a representation of those aspects of the real structure that we hypothesize to be important for the problem of interest. In our SD model, and to achieve the desired goal, we have established “*a more sustainable mobility system*” as level 0. This goal is achieved through vertical and horizontal links that connect the sustainability dimensions (defined in chapter 3), considered as level 1, with level 2 (sustainability indicators) (see the left branch of Figure 7.1). These indicators are, in turn, connected with high sustainability policies and strategies/actions through variables (see the right branch of Figure 7.1) defined by the decision makers. For this purpose, a *decision support system* (DSS) for policy design and assessment was designed, applying the *conceptual framework* recommended by our research.

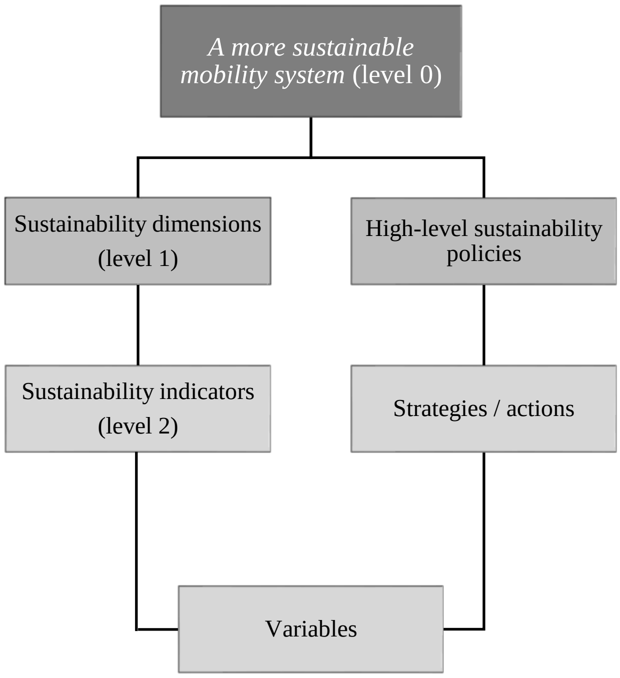


Figure 7.1 Conceptual structure of the *system dynamics model*

7.4 The iMODELER software

iMODELER is a tool for qualitative explorative cause and effect modeling. It also allows for quantitative (e.g. system dynamics) modeling of scenarios [75]. In such context with iMODELER it is possible to visualize complex systems and show interconnections between factors. The connections are shown with arrows between different factors, marked with pluses or minuses, to show a positive (self-reinforcing) or negative (self-correcting or balancing) feedback loop. Such a model helps to understand complexity and complex systems, with the advantage of relative simplicity compared to quantitative modeling.

In iMODELER, direct relations between factors have to be considered. This method is called the *know-why* method [188] and it is based on four questions:

- what leads directly to more of a factor?
- what leads directly to less of a factor?
- what might lead directly to more in the future?
- what might lead directly to less in the future?

iMODELER allows the identification and visualization of synergies and trade-offs among factors that make up the structure model. With the systemic consideration within iMODELER, these occurring synergies and trade-offs can be quickly identified and visualized [189].

7.5 A decision support system for policy design

This section presents the qualitative model developed to show the potential of a system dynamics approach, through causal diagram loops (CDL). The unit time frame of the model is "the year" and the model considers a typical implementation period of a 10-year public policy (from 2020 to 2030 — short term, to 2023, medium term, to 2026, and long term, to 2030).

The model runs in the iMODELER software, allowing a balance between qualitative and quantitative approaches. According to [190], qualitative *cause and effect* modelling allows a direct visual translation of relationships such as "*more of something leads directly to either more or less of something else*", This is depicted by an arrow between two factors, either denoted with a plus or a minus. The model shows how the influence of the factors (high-level policy set proposed) changes over time, because of feedback loops, visualizing the impact of those variables within the proposed model structure.

The inclusion of factors by participatory modeling, with experts and stakeholders, helps ensure a more robust and realistic model. Our model incorporated the contributions of sustainability experts and people with interest in sustainability topics. In proposing a set of high-level policies, that integrates strategies and actions, and is based on the analysis of successful cases implemented in sustainable urban transport systems.

The connections between the factors of the model are qualitatively weighted, and for this purpose, the model uses the defined prioritized measurement *analysis structure* defined in chapter 5. Qualitative weighting allows the user to define whether one factor's impact onto another is weak or strong when compared to the impact of other factors, and whether this impact changes from short term to medium term or long term. The weights of the connections between this *analysis structure* and the other model factors are defined based on the feedback gathered by the semi-structured interviews, and on available policy reports.

The connections in the qualitative model represent relations and arguments based on the authors' knowledge. Therefore, we provide a *template* (qualitative model) which requires adjustments for each specific context, as well as a *conceptual framework* to evaluate sustainability in mobility systems of emerging cities (prioritized sustainability measurement *analysis structure*) that constitutes the basis of the qualitative model.

According to [190] "*one method for weighting is to first determine the strongest impact, then the second strongest, and to continue with the third strongest and all following subsequent factors in this manner. To keep the sum of weights below or equal to 100 is also advisable as this helps maintain consistency and can be more easily interpreted as percentage values for the impacts of each factor*". Only after all the connections are weighted should one successively analyze insight matrices. This matrices reveals which factors are synergistic (serving several targets) and which have trade-offs or are ambivalent (positive to one goal, negative to another) [190]. In such context, [190] concluded that "*qualitative models as a visualization of argument form stakeholders and experts allow for inclusion of potentially relevant factors in order to gain a better understanding of a complex system*".

The overall model[1] (see Figure 7.2) cannot be read as a single picture, as it already contains more than 100 factors with over 300 connections, leading to more than 500 feedback loops. Consequently, the model is best read by changing the viewing perspective, placing specific factors as center points. As a starting point and central target of the model we considered the factor named "*a more sustainable mobility system*". The central target is necessary as it allows for the analysis of the model with its "*insight matrix*" as a way to identify and evaluate potential measures potentially leading to an increase or decrease in the target over time.

All the elements that make up the sustainability measurement *analysis structure* (dimensions at level 1, and indicators at level 2) are directly connected to the overall target. Although subjective, this selection is widely in line with the factors that can affect the sustainability performance in mobility systems of emerging cites, being the result of applying the comprehensive methodology described throughout this research.

---

[1] The model is available on the iModeler platform upon request to the author via email <juancmedina17@hotmail.com>

The proposed interventions are defined in two sets: i) strategies and actions connected each other, and connected with the level 2 (sustainability indicators) through variables; ii) high-level policy set, considered as contributing factors and connected with strategies and actions. The influence of these factors on "*a more sustainable mobility system*" is thus also visualized in an insight matrix for this overall target.

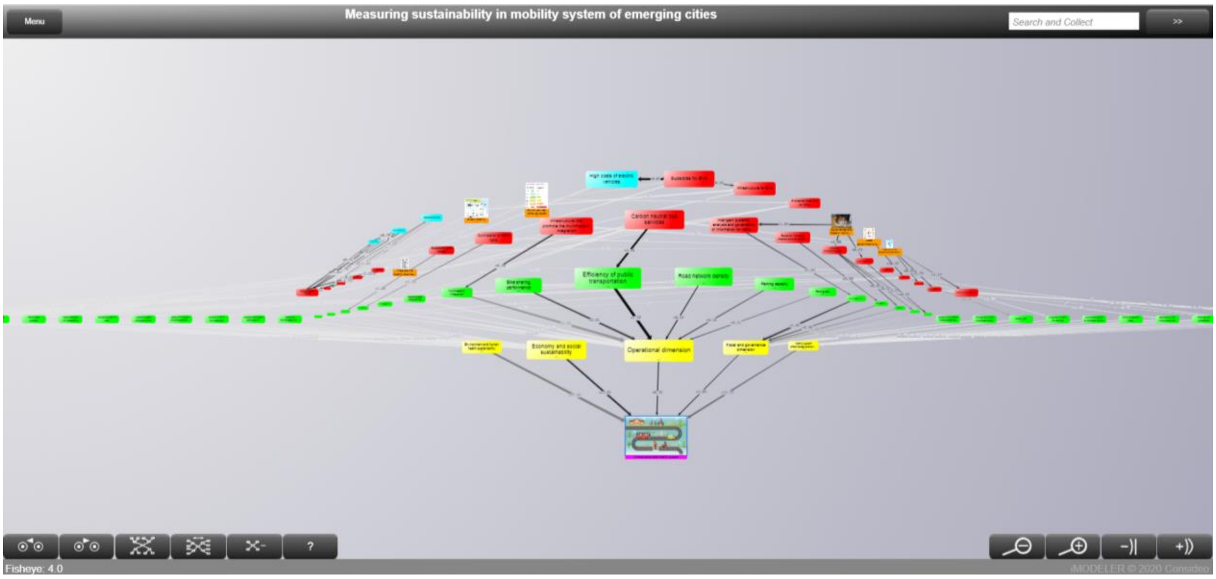


Figure 7.2 Model overview

With a small set of screenshots, we try now to illustrate how the DSS operates. Figure 7.3 shows the model from the point of view of "*a more sustainable mobility system*" at level 0 (in purple), with the first level of connections, considered as "*sustainability dimensions*" at level 1 (in yellow). The proposed model considers that an increase of the five dimesions leads directly to a more sustainable mobility system (e.g., more "*environment and human health*" results in "*more sustainable mobility system*"). This is represented by (+) for each connection between level 1 and level 0, with the associated weights (obtained as described in chapter 5) (see Figure 7.4).

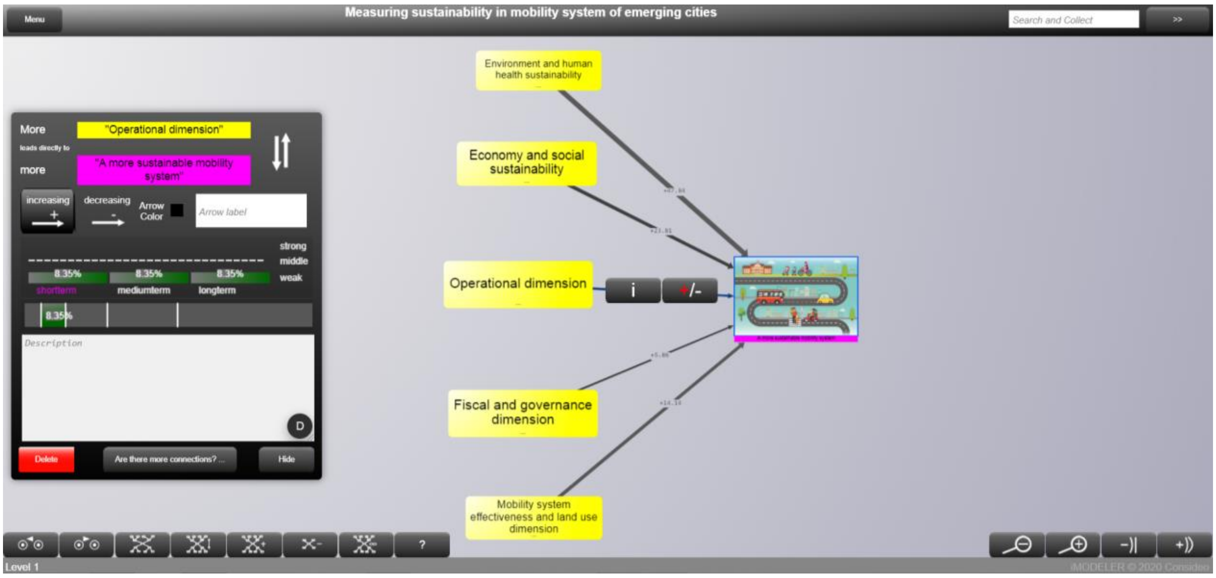


Figure 7.3 Model view from level 0 to the *dimensions* level

Figure 7.4 Weighting matrix of level 0

Then, the next view shows the connection between level 2 (in green) and level 1 (see Figure 7.5), with the associated weights (see Figure 7.6). As the model generates numerous connections between levels, we just show the connections between factors of a single model *branch*.

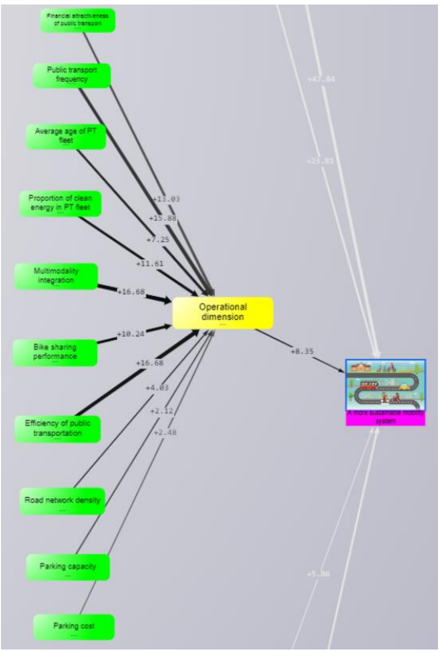


Figure 7.5 Model view from the *dimensions* level (*operational* dimension)

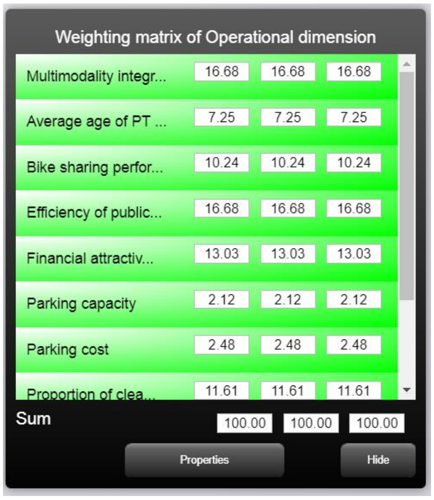


Figure 7.6 Example of a weighting matrix of the dimensions level

As shown in Figure 7.7, concrete strategies and actions (in red) were linked to subject areas in level 2 (sustainability indicators) through variables (in light blue). These concrete interventions may influence the subject areas in positive or negative ways. This set and their possible influences were defined based on an extensive literature review and in information about successful policies and strategies, implemented in sustainable transport systems of various cities, as well as from the feedback gathered of the semi-structured interviews (as described in chapter 5).

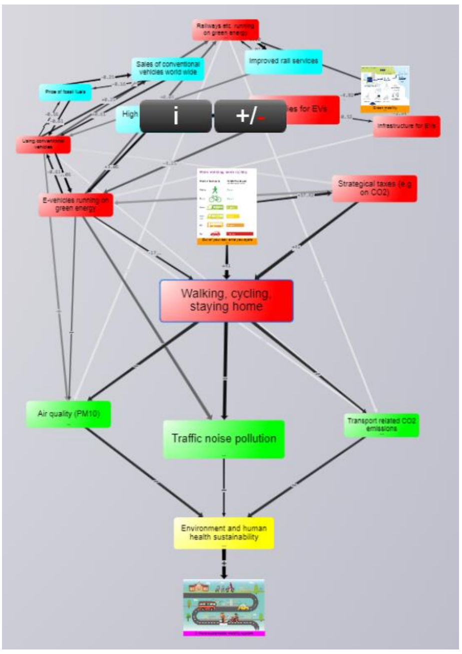


Figure 7.7 Model view from the *strategies and actions* level

Then, the system shows a concrete policy set (five sustainability policies) that is directly linked with the strategies and actions, and indirectly with the other levels of the model (see Figure 7.8).

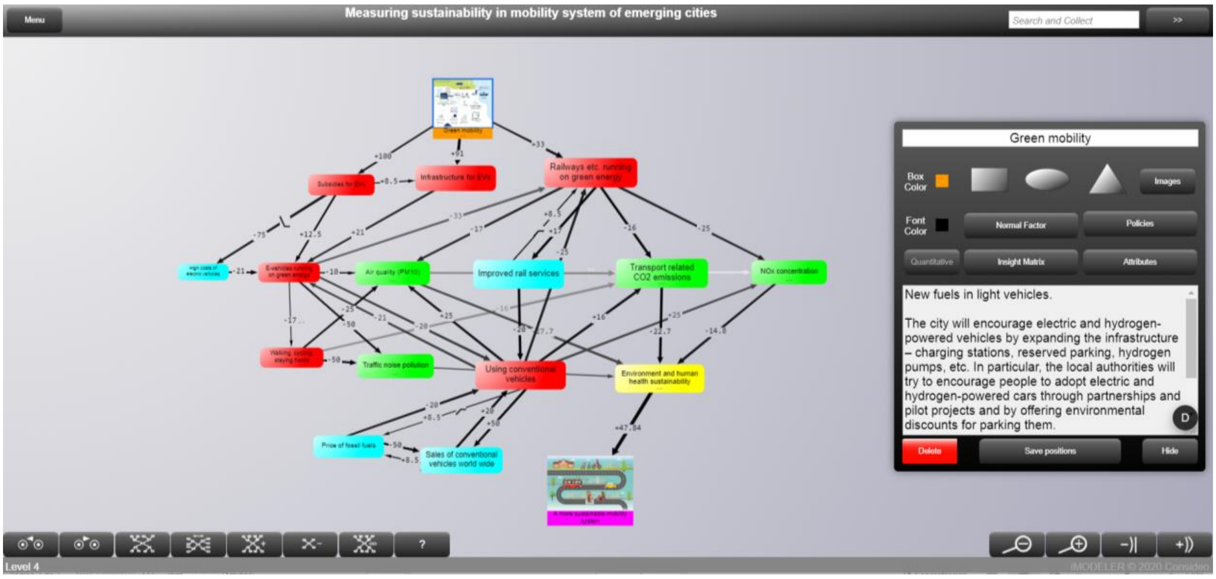


Figure 7.8 Model view from the *high policies* level (*green mobility*)

Finally, the model runs based on the relations defined by the links, and generates the feedback loops according to the inputs by the modeler. The software evaluates the effects of the *feedback loops* built into the model, and shows the results in the *insight matrix*, as described in Figure

7.9. The “*insight matrix*” (from the factor “*a more sustainable mobility system*”) shows on this horizontal axis, the effectiveness of other factors either as increasing “*a more sustainable mobility system*” or decreasing it. The vertical axis indicates the change of impact over time from short to medium and to long term. The diameter of the factors indicates a further attribute, e.g. the current state of a measure, a target, or an obstacle [190].

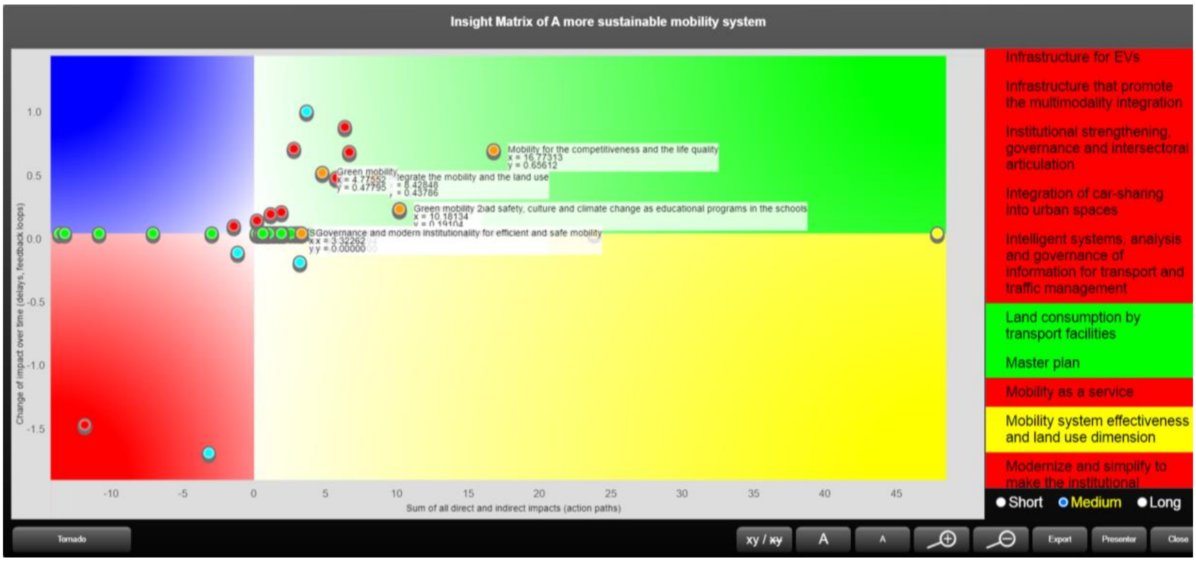


Figure 7.9 Insight matrix of “*a more sustainable mobility system*”

The effects of concrete sustainability policies are represented in the chart of Figure 7.10. In order to analyze the effects of every policy in the target factor (“*a more sustainable mobility system*”), the target factor must be “graphically” placed at the center of the process model. Figure 7.10 shows the positive and negative influences between the respective actions, as well as the associated synergies and trade-offs. Helping to interpret the *insight matrix* of the target factor. It shows the influences of the five proposed high-level sustainability policies onto “*a more sustainable mobility system”* by their position on the vertical axis. By changing between short, medium and long terms, the model shows how the influence of the proposed policies change over time because of feedback loops or delays [189].

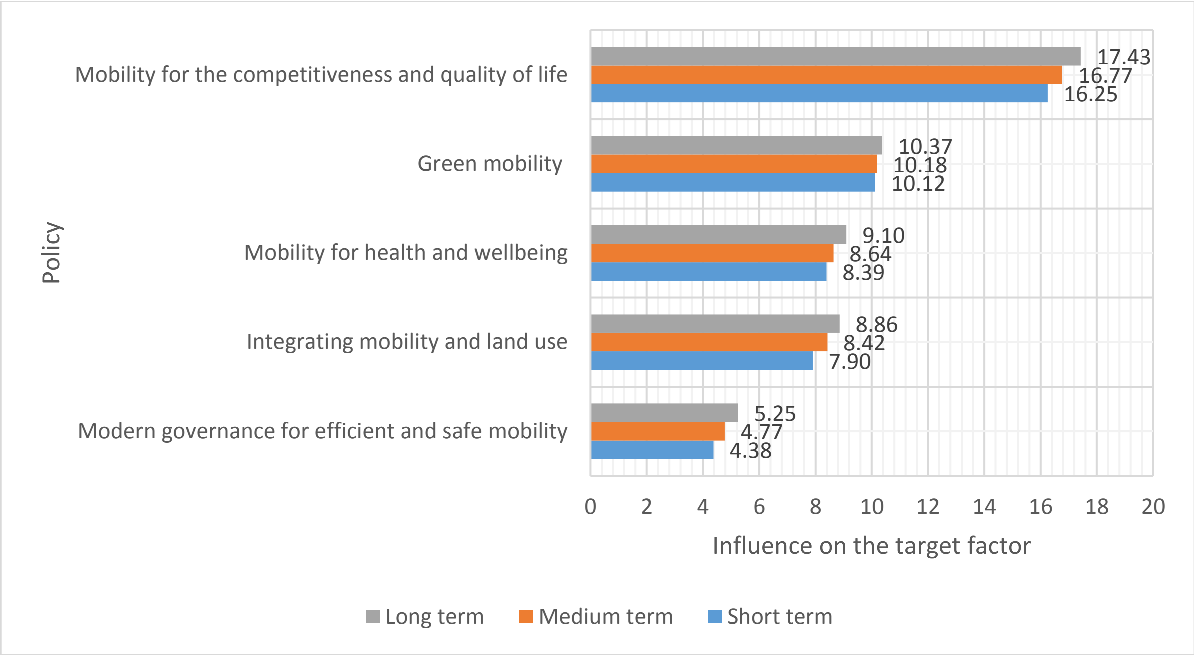


Figure 7.10 Influence of the proposed *high-level sustainability policies*

7.5.1 Discussion of the results

The insights from qualitative models like the one presented here are, in general, logically sound (based on abductive logic) and yet they depend on the accuracy of the single pairwise arguments and on the inclusion of all relevant factors [190]. Therefore, considering that the basis of our model follows a comprehensive *conceptual framework* as defined, the results obtained from this qualitative model can be considered valid. Moreover, these results are consistent with the analysis of similar sustainability policies implemented in different contexts, where encouraging non-motorized modes has improved the sustainability performance of the mobility systems (as proposed in the policies with the first and third highest impacts).

The influence of the "*green mobility*" policy is coherent with the findings of this research, that concluded that environmental integrity is a condition *sine qua non* of the nested model of sustainability. In relation to the "*integrating mobility and land use*" and "*modern governance for efficient and safe mobility*", their influence in the sustainability performance within the model structure is lower. However, these initiatives are a good starting point to solve some current governance inefficiencies that can generate cost overruns for the municipalities.

Consequently, for decision makers, this implies that the “*green mobility”* and the “*mobility for health and wellbeing*” policies should have higher priority and be executed first. These policies have no negative effects on the target factor. The “*mobility for competitiveness and quality of life*” and the “*integrating mobility and land use*” policies have also a positive but smaller impact on the entire target factor. Decision makers should, therefore, evaluate their implementation analyzing the available budget, giving priority to the policies suggested by the model. The “*modern governance for efficient and safe mobility*” policy despite having the lowest influence to achieve the target factor (desired goal) “*a more sustainable mobility system”*, can be taken into account if the context requires it, since it showed no negative values (negative influence within the system).

7.6 Summary

The qualitative model presented in this chapter is a tool that can be usefully used as a *decision support system* (DSS) for policy design and assessment of sustainable mobility in emerging cities, yet adaptable to different contexts. It can help transportation and planning managers in the formulation of sustainability policies to better prioritize alternatives and choose those with the highest synergies with other factors.

This tool is only a good example of modeling a complex problematic situation and should be viewed as subjective, simplified and of abductive logic [190], with a performance that depends on the input from experts and stakeholders, and with results that need to be revised over time. However, such an endeavor is surely useful for gaining a better understanding of possible future developments.

Our DSS will provide planning and transportation decision-makers with the ability to look into the future and to decide based on past and present information and also in available forecasts. In particular, it will help analyze the influence and impacts of the proposed sustainability policies, and provide criteria to make a better assessment and management of public spending, in order to achieve sustainable mobility systems.

The developed qualitative model for policy design and assessment is easily adaptable to quite different contexts. Moreover, this research shows the benefits of having a systemic approach towards more sustainability mobility systems. Furthermore, users of the model may easily change the considered factors and relationships, to capture the specific aspects of each particular context. The major benefit of this "*open source*" modelling is its potential to continue reflecting on important factors that contribute to the achievement of the different sustainability targets.

While qualitative models are useful in describing the structure and dynamics of a system, decision makers expect these analyses to be supported by some quantitative results. Therefore, a possible line of future work can be to develop a quantitative model based on our *conceptual framework*, to further explore the influences of implementing a sustainability policy (mathematically defining the different element of the model).

8 Conclusions

The research presented in this dissertation aimed at developing a conceptual *framework* for supporting the design and assessment of sustainable urban mobility policies, with a particular focus on emerging cities. We have, therefore, addressed several subjects regarding sustainability evaluation and measurement in transport systems, as a structural element of decision support processes in policy design.

The proposed *framework* focused on three structural elements: i) a measurement *analysis structure* for sustainability in urban mobility systems, based on a set of dimensions and indicators; ii) a prioritization of this analysis structure, with the assignment of weights for each of its elements; and iii) the integration of the prioritized analysis structure with possible interventions (policies/strategies/actions), through a *system dynamics* approach.

A concept was proposed for a *decision support system* providing the tools for: i) representing the structure of the mobility system, showing the connections of its components (causal loop diagrams); and ii) providing a formal visual representation of the changes in behavior (effects) of the system components over time. We also demonstrated how this model can be applied in a real case, and how it can be used to support the formulation processes of sustainable urban mobility policies, for the particular case of emerging cities.

8.1 Thesis contributions

This thesis is based on the assumption that a sustainability evaluation of urban mobility systems based solely on the three traditional dimensions (environmental, economic and social) does not provide an integral and useful assessment of such systems, and that there is a need for a more comprehensive *analysis structure.* Such tool should be able to assess the performance of mobility systems with regard to sustainability in an integrated way, and should be based on an appropriate set of *indicators*, grouped in several key *dimensions*, as proposed in this research. Then, building upon our findings regarding the validity and adequacy of this new set of (qualitative and quantitative) indicators, we propose a conceptual *framework* that hierarchizes those dimensions and indicators, and is used as a basis for a *decision support system* for policy design and assessment of sustainable mobility in emerging cities.

8.1.1 Contributions to research

The main contributions of this dissertation were the development of a conceptual *framework* for the design and assessment of sustainable urban mobility policies, in the case of emerging cities. This framework served as the basis for a decision support system to aid the construction of interventions promoting sustainable mobility and their assessment processes.

A theoretical framework (chapter 2), based on the concepts of sustainability, sustainable development and sustainable transport, was developed for evaluating sustainability in urban mobility systems, through a multidimensional approach. Chapter 3 presents the process followed to define the level 1 (dimensions) of the measurement *analysis structure* for sustainability. This chapter highlights the importance of expanding the basic framework supported on the traditional dimensions of sustainability (environmental, economic and social) by incorporating three additional, more encompassing aspects. In chapter 4, a novel framework to measure sustainability is proposed, structured in three analysis levels: at level 0, the global desired goal, defined as *measuring sustainability in mobility systems of emerging cities*; at level 1, five dimensions of sustainability; and at level 2, 42 sustainability indicators. Chapter 5 presents the multicriteria approaches we have used for the hierarchization of dimensions and indicators, and chapter 6 describes the application of the proposed conceptual framework to the case studies. Finally, chapter 7 describes the *system dynamics* approach to link qualitative and quantitative models, creating a decision support system.

8.1.2 Contributions to practice

The results and deliverables of this research can help local authorities and transportation planners, and possibly other decision-makers, to improve the formulation of more sustainable urban mobility policies. This contribution will hopefully be quite relevant in the case of emerging cities.

Moreover, we have compiled recommendations from a significant number of sustainability experts, with different functions and areas, and from different regions of the world.

In practical terms, this research proposes a clear, structured methodology for addressing sustainability in urban mobility, and delivers a conceptual framework (along with decision support tools) for application in real situations.

These results aim at facilitating the generation of bottom-up (rather than top-down) sustainable mobility policies, and at determining which interventions would have the greatest impact. The project results should be easily adaptable to different city situations, even for quite different geo-spatial contexts, as it is the case of Europe, where top-down policies can be designed taking into account the specific features of each transportation system. In addition, we have designed some case studies that demonstrate the applicability of the framework and decision support system, and show their potential for replication.

8.2 Research questions revisited

This dissertation was developed around three main research questions, about the sustainability evaluation processes in mobility systems of emerging cities, and on the impacts of sustainable interventions (policies/strategies/actions), as a planning element in policy design. In order to summarize the main outcomes of the research, this section provides concise answers to those questions, obviously not replacing the detailed analysis presented along the dissertation (see Table 8.1).

Table 8.1 Sections of the dissertation where research questions are addressed in detail

Research question	*addressed in detail in chapters*
Question 1	2, 3, 4, 5
Question 2	2, 3, 4
Question 3	7

8.2.1 Research question 1

How to assess, in an integrated manner, the performance of the mobility systems of emerging cities, in terms of sustainability?

Based on the theoretical framework proposed in chapter 2, as well as on a comprehensive literature review in chapter 3, a first research gap was identified on how urban transportation systems are being evaluated regarding sustainability. In order to overcome this gap, this research has developed an integrated multidimensional *framework* for sustainability assessment in mobility systems. This research incorporates three novel dimensions (technical attributes in the operational issues, fiscal and governance, and effectiveness and land use) beyond the traditional dimensions – *the triple bottom line* (environmental, social and economic).

In chapter 4 we have shown that indicators are a relevant component in the decision-making processes, as they are capable of generating information for those processes. Measurement indicators serve to define goals and objectives, as well as help to support policy design, planning and management. In such context, we have proposed an integrated methodology to select appropriate indicators, and in chapter 5 we present a hierarchical framework to determine the weights of the dimensions and indicators, for the associated interest groups (users, experts, decision makers and other stakeholders). Finally, in chapter 6, this hierarchical framework was applied to four cities as case studies, showing how it can be applied in practice.

8.2.2 Research question 2

What are the most suitable factors to measure sustainability in the mobility systems of emerging cities?

To respond to this question, we have identified a set of factors to measure sustainability. Chapter 4 summarizes our contributions in this area (considering the findings from chapters 2 and 3). The traditional approach to evaluate sustainability in mobility systems was expanded, following a nested model of sustainability, where environmental integrity is considered a condition *sine qua non*.

We have, therefore, developed a methodology designed in two phases (*preliminary and exploratory phases*) supported mainly in qualitative approaches, with the main purpose to provide guidance about the choice of sustainability measurement tools. Therefore, the answer to this question is not to provide a definitive list of indicators or factors, but rather provide a comprehensive analysis structure, easy to adapt to different contexts.

The developed measurement framework contains new sustainability dimensions, such as *fiscal and governance*, and presents a set of novel indicators, of a qualitative nature, such as *expertise of technicians and managers.*

8.2.3 Research question 3

How do the measuring tools impact policy design to improve the sustainability of the mobility systems of emerging cities?

Based on the multidimensional *framework* developed in the previous stages of our research, a *decision support system* was deployed for policy design and assessment of sustainable mobility in emerging cities (see chapter 7). This system was developed around a *system dynamics* approach for modeling the relationships between the different system components (using causal loop diagrams) and for studying their behavior over time.

The "qualitative" part of this model was developed, using the *confirmatory* sustainability measurement *framework* (chapter 5), to represent and study the relationships between system components. This development indirectly responds to research question 3, and demonstrates the potential of the developed framework as a key element in the design and assessment of sustainability policies for urban mobility.

8.3 Limitation of the research and future developments

As the geo-spatial scope of this research is bound to *emerging cities*, the obtained results may not be entirely generalizable to other contexts, However, we believe that the contributions of this research go beyond the direct methodological outcomes especially directed for emerging cities (as the adopted case studies were of a more general nature).

Nevertheless, the approach proposed by this research should not be viewed as a strict and unique path to follow, but rather as a structured guide for supporting planners and managers, and as a way to deal with the inherent complexity of determining the factors affecting the sustainability of mobility systems. In fact, the outcomes of this research seem to have a considerable potential for adaptation to different city contexts, as our framework includes a wide variety of specific and general features. But the concrete way this adaptation is performed may, in some aspects and situations, be a complex issue.

On the other hand, another general limitation of the approach may be the large quantity of information required, along with the difficulty in dealing with uncertainty and conflicts.

There are, therefore, some interesting topics for future research, and these topics can be viewed in three perspectives. First, in a conceptual perspective, and due to the inherent complexity and uncertainty in the factors that affect the sustainability of mobility systems, other variables may become relevant, thus requiring further analysis. A second, interesting future development, of a mainly technical nature, would be the design of a “smart” software application to compute the weights of dimensions and indicators, automatically.

Finally, a third topic for further research is naturally the application of the proposed framework to urban mobility in other regions of the world, and in other social and cultural contexts. Therefore, more work is required to test our framework for the design and assessment of sustainable mobility policies in emerging cities. Then, the application to other different cases would nurture the framework and enhance its practical utility.

On the other hand, while qualitative models are useful in describing the structure of a system and its dynamics, most decision makers wish to see some quantitative results. Therefore, another possible line of future work is the development of a quantitative model taking as a basis the conceptual framework developed by this research.

Appendix

A E-mail example: survey

An example of the e-mail sent to the people (105) with interest in sustainability topics.

Dimensions and indicators to measure sustainability of mobility systems in emerging cities

Español abajo

--

Dear colleagues,

This survey is part of my PhD research "*a decision support system for policy design and assessment of sustainable mobility in emerging cities*" of the doctoral program in transportation systems from Universidade do Porto.

It is a consultation to experts in sustainable mobility like you, with the aim to consolidate, validate and rank the dimensions and indicators proposed to measure the sustainability of mobility systems in the specific context of emerging cities.

The dimensions and indicators presented in the survey come from a comprehensive review of relevant literature and documents, adapted as necessary for the purpose of this research. Original sources are properly attributed in the thesis. Feel free to contact me for more details.

No personal information will be collected. Your answers will be analysed in an aggregated form and solely for the purpose of my research.

Your contribution is greatly appreciated and it will certainly aid in developing sustainable initiatives for often overlooked emerging cities.

Thank you for your time and for your valuable contributions to my research!

Kind regards,

Juan Arguello, PhD student
Doctoral Program in Transport System / MIT Portugal
Faculdade de Engenharia da Universidade do Porto
up201610839@fe.up.pt

B Survey example

An example of the survey used in the *exploratory phase*.

U.PORTO

FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Doctoral Program in Transport Systems

Dimensions and indicators to measure sustainability of mobility systems in emerging cities

1. General demographic information

This survey is part of my PhD research on **a decision support system for policy design and assessment of sustainable mobility in emerging cities.** It is a consultation to experts like you, with the aim to consolidate, validate and rank the dimensions and indicators proposed to measure the sustainability of mobility systems in the specific context of emerging cities.

The dimensions and indicators presented in the survey come from a comprehensive review of relevant literature and documents, adapted as necessary for the purpose of this research. Original sources are properly attributed in the PhD thesis. Feel free to contact me for more details.

No personal information will be collected. Your answers will be analysed in an aggregated form and solely for the purpose of my research.

Your participation is absolutely voluntary and anonymous. You can withdraw at any time by not completing the survey. As no personal information is collected, it won't be possible to delete your responses once they are submitted.

Your contribution is greatly appreciated and it will certainly aid in developing sustainable initiatives for often overlooked emerging cities.

Juan Arguello, PhD student
Doctoral Program in Transport Systems / MIT Portugal
Faculdade de Engenharia da Universidade do Porto
up201610839@fe.up.pt

1. Gender

- ◯ Female
- ◯ Male
- ◯ Prefer not to say
- ◯ Other

2. Age range

- ◯ 18 to 24
- ◯ 25 to 34
- ◯ 35 to 44
- ◯ 45 to 54
- ◯ 55 to 64
- ◯ 65 and over

3. Location

- ◯ Africa
- ◯ Asia
- ◯ Central America and the Caribbean
- ◯ Europe
- ◯ Middle East
- ◯ North America
- ◯ Oceania
- ◯ South America

* 4. What of the following options better describe your current position or role?

- [ ] Academic/Researcher
- [ ] Activist/Citizen
- [ ] Consultant
- [ ] Decision maker
- [ ] Policy maker
- [ ] Other (please specify)

2. Dimensions related to sustainability

* 5. To what extent do you consider the following *dimensions* to be important to assess th
performance of a mobility system in emerging cities in terms of sustainability?

- Environment and human health: the impact of activities related to urban transport on the environment and the population.
- Economy and social: potential economic vulnerabilities due to the mobility system, and the ability of the system to promote equality and social inclusion.
- Operational: technical attributes to evaluate the operation of urban mobility systems.
- Fiscal and governance: management of public spending by transport-related authorities and degree of independence of those entities.
- Efficiency of the mobility system: transport policies that can reduce externalities of the mobility system, such as fatalities and congestion.

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Environment and human health	○	○	○	○	○
Economy and social	○	○	○	○	○
Operational	○	○	○	○	○
Fiscal and governance	○	○	○	○	○
Efficiency of the mobility system	○	○	○	○	○

Additional comments (optional)

6. Do you consider any other *dimension* **should be** included in the study?

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other (1)	○	○	○	○	○
please specify					
Other (2)	○	○	○	○	○
please specify					
Other (3)	○	○	○	○	○
please specify					

3. Indicators to measure the *environment and human health dimension*

* **7. To what extent do you consider the following indicators to be important to assess the performance of a mobility system in emerging cities in terms of *environment and human health*?**

Indicator	Measurement	Reference values	
		Worst	Best
Air quality (PM10) µg/m3	Annual average daily concentrations of PM10	40	0
NO2 concentration µg/m3	Annual average daily concentration of NO2	40	0
Transport related CO2 emissions T/person/year	Average carbon dioxide (equivalent) emitted per person from transport activities	3	0
Traffic noise pollution dBA	Annual average sound pressure level	53	10
Traffic related fatalities *Deaths/100.000 inhabitants*	Road fatalities per 100.000 inhabitants	35	0

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Air quality (PM10)	○	○	○	○	○
NO2 concentration	○	○	○	○	○
Transport related CO2 emissions	○	○	○	○	○
Traffic noise pollution	○	○	○	○	○
Traffic related fatalities	○	○	○	○	○

Additional comments (optional)

8. What other indicator related to *environment and human health* should be included in this study?

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other (1)	○	○	○	○	○

please specify

Other (2)	○	○	○	○	○

please specify

Other (3)	○	○	○	○	○

please specify

4. Indicators to measure the *economic and social dimension*

* 9. To what extent do you consider the following indicators to be important to assess the performance of a mobility system in emerging cities in terms of *economic and social sustainability*?

Indicator	Measurement	Reference values	
		Worst	Best
Direct trip cost for user %	Average monthly cost of an urban trip in public transport, compared to minimum wage	20	3.5
Indirect trip cost for user *min*	Average time spent of a trip for work in public transport during the typical week	62.1	18.4
Population density Inhabitants/Km^2	Ratio between the population and the urban area	0.7	17.8

Variation of public transport in the modal split *%*	Variation of the percentage of the trips made by public transport compared to its share in the last but one measurement	0	+100
Variation of non-motorized in the modal split *%*	Variation of the percent of the trips made by non-motorized compared to its share in the last but one measurement	0	+100
Transport security *Users/100.000 passengers*	Proportion of transport users that have been subject of petty crime and other security related incidents	-	0

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Direct trip cost for user					
Indirect trip cost for user					
Population density					
Variation of public transport in the modal split					
Variation of non-motorized in the modal split					
Transport security					

Additional comments (optional)

10. What other indicator related to *economic and social sustainability* should be included in this study?

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other					

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other					

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other					

Other (please specify)

5. Indicators to measure the *operational dimension*

* 11. To what extent do you consider the following indicators to be important to assess the performance of a mobility system in emerging cities in terms of *operational sustainability*?

Indicator	Measurement	Reference values	
		Worst	Best
Public transport frequency *veh/day*	Frequency of the public transport route with the highest load	32	515
Bike sharing performance *Bicycles /100.000 habitants*	Ratio between the total quantity of bicycles in public shared system and the population	0	238
Road network density *Km/Km²*	Ratio between the total length of the urban road network and the urban area	3.7	11
Efficiency of public transportation *MJ/pas.km*	Energy consumption of public transport per passenger kilometre	18.46	0.54
Parking capacity *Number of parking spaces*	Number of parking spaces (on and off-street) available in the central area	-	-
Parking cost *%*	Average cost of short term parking (up to 2 hours) as a proportion of daily minimum wage	-	-

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Public transport frequency	○	○	○	○	○
Bike sharing performance	○	○	○	○	○
Road network density	○	○	○	○	○
Efficiency of public transportation	○	○	○	○	○
Parking capacity	○	○	○	○	○
Parking cost	○	○	○	○	○

Additional comments (optional)

12. What other indicator related to *operational sustainability* should be included in this study?

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

6. Indicators to measure the *fiscal and governance dimension*

* 13. To what extent do you consider the following indicators to be important to assess the performance of a mobility system in emerging cities in terms of *fiscal sustainability and governance dimension*?

Indicator	Measurement	Reference values	
		Worst	Best
Financial attractiveness of public transport *Cost public transport/cost private car*	Ratio between the price of a 5km journey with public transport and the cost of a 5km journey with own private car	6.7	0.2
Public expenditures and investment in transport system *%*	Share of local authority's financing devoted to transport; running five-year average	10	50
Financial autonomy *Score between 0 (Not - 1 (Yes)*	Financial autonomy for investments in mobility projects	0	1
Master plan *Score between 0 (Not) - 1 (Yes)*	Existence of a master plan of mobility and sustainability for development of the city	0	1
Debt ratio *%*	Ratio between the average annual debt derived from mobility projects and the annual budget allocated to the mobility sector	-	-

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Financial attractiveness of public transport	○	○	○	○	○
Public expenditures and investment in transport system	○	○	○	○	○
Financial Autonomy	○	○	○	○	○
Master plan	○	○	○	○	○
Debt ratio	○	○	○	○	○

Additional comments (optional)

14. What other indicator related to *fiscal sustainability and governance dimension* should be included in this study?

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

7. Indicators to measure the *efficiency of the mobility system dimension*

* 15. **To what extent do you consider the following indicators to be important to assess the performance of a mobility system in emerging cities in terms of *efficiency of the mobility system*?**

Indicator	Measurement	Reference values	
		Worst	Best
Impact of transport public policy *Scale 0 - 10*	Qualitative assessment of public policies in mobility	0	10
Satisfaction with the mobility services *%*	Percent of users satisfied with urban mobility services	30	95
Pathways for pedestrians *m^2/habitant*	Ratio between the total length of protected pedestrian infrastructure and the total inhabitants in the urban area	3.5	10
Cycle path network density *Bikes/ Habitant*	Ratio between the total length of cycle infrastructure and the total inhabitants	0	-
Motori-zation rate veh/ 1.000 inhab	Ratio between the quantity of motorized vehicles and the population	750	0

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Impact of transport public policy	○	○	○	○	○
Satisfaction with the mobility services	○	○	○	○	○
Pathways for pedestrians	○	○	○	○	○
Cycle path network density	○	○	○	○	○
Motorization rate	○	○	○	○	○

Additional comments (optional)

16. What other indicator related to *efficiency of the mobility system* should be included in this study?

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

	Absolutely unimportant	Somewhat unimportant	Neither important nor unimportant	Very important	Absolutely important
Other	○	○	○	○	○

Other (please specify)

Thank you for your time and for your valuables contributions to my research!

C List of sustainability experts

The list of experts who answered the AHP-based questionnaire.

Name *[country]*	*Sector* *[topics]*	*Current institutions* *[position]*	*Interview place* *[date]*
Henrik Gudmunsson [Denmark]	Academia/consultancy [Sustainability indicators]	CONCITO [Senior consultant]	Aalborg University [November 2019]
Sidsel Kjems [Denmark]	Academia/Government [Sustainable public policies]	Københavns Kommune [Chief consultant]	Københavns Kommune [November 2019]
Thomas Nielsen [Denmark]	Academia/Government [Sustainability indicators]	The Danish Road Directorate [Senior consultant]	The Danish Road Directorate [November 2019]
Jens Stissing Jensen [Denmark]	Academia [Sustainability indicators]	Aalborg University [Associate professor]	Aalborg University [November 2019]
Andres Valderrama [Denmark]	Academia [Sustainable public policies]	Aalborg University [Associate professor]	Aalborg University [November 2019]
Per Eneroth [Sweden]	Government [Sustainable public policies]	Lunds kommun [head of the road and traffic division]	Lunds kommun [November 2019]
Anna Karlsson [Sweden]	Government [Sustainable public policies]	Lunds kommun [head of the traffic and mobility department]	Lunds kommun [November 2019]
Todd Litman [Canada]	Academia/consultancy [Sustainability indicators]	Victoria Transport Policy Institute [Executive director]	Skype [November 2019]
Yannick Cornet [Slovakia]	Academia [Sustainability indicators]	University of Žilina [Senior researcher]	Skype [November 2019]
Luis Felipe Lota [Colombia]	Academia/Government [Sustainability indicators]	Agencia Nacional de Seguridad Vial [Director]	Skype [December 2019]
Jonathan Bernal [Colombia]	Academia/Government [Sustainable public policies]	Departamento Nacional de Planeación [Director]	Skype [December 2019]
Sonia Mangones [Colombia]	Academia [Sustainability indicators]	Universidad Nacional de Colombia [Associate professor]	Skype [November 2019]
Lenin Bulla [Colombia]	Academia/Consultancy [Sustainability indicators]	Universidad Nacional de Colombia [Associate professor]	Skype [November 2019]
Diego Cabrera [Colombia]	Academia [Sustainability indicators]	Universidad de Bogotá Jorge Tadeo [Associate professor]	Skype [November 2019]

Name *[country]*	*Sector* *[topics]*	*Current institutions* *[position]*	*Interview place* *[date]*
Carmen Rosales [Colombia]	Consultancy [Sustainable public policies]	Steer Davies Gleave [Associate and planning market leader]	Skype [November 2019]
Daniel Perez [Colombia]	Academia/Government [Sustainable public policies]	Ministerio de Transporte [Adviser]	Skype [November 2019]
Ximena Cantor [Colombia]	Government [Sustainable public policies]	Departamento Nacional de Planeacion [Adviser]	Skype [December 2019]
Oscar Andres Patiño [Colombia]	Government [Sustainable public policies]	Departamento Nacional de Planeacion [Adviser]	Skype [December 2019]
Jorge Riveros [Colombia]	Government [Sustainable public policies]	Agencia Nacional de Seguridad Vial [Adviser]	Skype [December 2019]

D E-mail example: AHP-based questionnaire

An example of the e-mail sent to the 19 sustainability experts.

Assunto **Measuring sustainability in mobility in emerging cities - second iteration**
Remetente up201610839
Para
Data 2019-12-02 20:20

Sustainability dimensio... indicators proposal.pdf

Dear colleague,

As I had the chance to comment, I'm sending the second iteration of my research on the dimensions and indicators to evaluate the sustainability of mobility systems in emerging cities. This has been consolidated from the results of the first survey that you kindly completed. This second version is designed for experts like you and aims at weighting the dimensions and indicators by using Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process (FAHP)- Using Geometric Mean.

I kindly ask you to complete the information in the following tool:

https://bpmsg.com/ahp/ahp-hiergini.php?sc=zudutA

The tool is easy to use and should take between 25 and 45 minutes depending on your familiarity with the dimensions and indicators.

You should follow these steps:

1. Click the link above, verify the session code (zudutA) and insert your name. Then click the "Check input" button and afterwards the "Go" button.

2. The decision hierarchy table summarises the pairwise comparisons needed at every level. Click the "AHP" button next to "Measuring sustainability of mobility systems" at Level 0 to compare the dimensions.

3. A pairwise comparison table will show the different options and the level of relative importance between each two of them. Please select column A or B depending on which factor (dimension or indicator) you consider more important than the other. Then use the numbers to the right to select the level of importance of the selected factor over the other, according to the following scale:
AHP Scale: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between)

4. After selecting your options, click "Calculate" to check the consistency of the answers. If there is any potentially inconsistent selection, the tool will suggest plausible changes. Once you are happy with your selections, click the "Submit" button.

5. Now click the "AHP" button next to each dimension at Level 1 to compare the indicators for each dimension. Repeat the process for all dimensions.

6. Finally, press the "Save judgements" button when you are done with both levels (0 and 1).

The definitions of the dimensions and indicators presented in the attach come from a comprehensive review of relevant literature and documents, adapted as necessary for the purpose of this research. Original sources are properly attributed in the PhD thesis. Feel free to contact me for more details.

GDPR note: Your participation is absolutely voluntary and the purpose of this data collection is absolutely academic. By clicking the link above you consent your information to be processed for the purpose of this research. Your answers will be anonymised and analysed in an aggregated way. The name you use in the first step will be recorded along with your email, after processing this information, I will delete it after 6 months. You can use any alphanumeric combination for the name field. This information will be collected and processed by myself as the main researcher and will not be shared with anyone inside or outside the context of the research. You can withdraw at anytime by not saving your results. If, after submitting, you want me to delete your information at anytime please contact me indicating the name you used in the first step.

Your contribution is greatly appreciated and it will certainly aid in developing sustainable initiatives for often overlooked emerging cities.

Thank you for your time and for your valuable contributions to my research!

Kind regards,

Juan Arguello, PhD student
Doctoral Program in Transport System / MIT Portugal
Faculdade de Engenharia da Universidade do Porto
up201610839@fe.up.pt

E AHP-based questionnaire example

An example of the AHP-based questionnaire used in the *confirmatory phase*.

Project: **Measuring sustainability of mobility systems**

Project description

This is the second part of my PhD research on a decision support system for policy design and evaluation of sustainable mobility in emerging cities, that present a new proposal of dimensions and indicators consolidated starting of the results from the first survey. This part is diriged to experts like you, with the aim to rank the dimensions and indicators proposed.

Decision Hierarchy

Level 0	Level 1	Level 2	Glb Prio.
	Environment and human health 0.200 AHP	Air quality PM10 (μg/m3) 0.200	4.0%
		NOx concentration (μg/m3) 0.200	4.0%
		Transport relatedCO2emissions (T/person/year) 0.200	4.0%
		Traffic related fatalities (D/100K inhab) 0.200	4.0%
		Traffic noise pollution (dBA) 0.200	4.0%
	Economy and social 0.200 AHP	PT affordability (%) 0.111	2.2%
		Indirect trip user (min) 0.111	2.2%
		Access to public transport service (%) 0.111	2.2%
		Share PT which are wheelchair accessible (%) 0.111	2.2%
		Variation PT in the modal split (%) 0.111	2.2%
		Variation of the female users in the PT (%) 0.111	2.2%
		Variation non-motorized in modal split (%) 0.111	2.2%
		Population density (Inhab/Km2) 0.111	2.2%
		Transport security (Users/100K pass) 0.111	2.2%
		Attractiveness of public transport ($PT/$PC) 0.100	2.0%
		Public transport frequency (Veh/day) 0.100	2.0%
		Average age of PT fleet (Age) 0.100	2.0%

Measuring sustainability of mobility systems AHP	Operational 0.200 AHP	Proportion of clean energy in PT fleet (%) 0.100	2.0%
		Multimodality integration (Scale 1to5) 0.100	2.0%
		Bike sharing performance (Bicy/100K inhab) 0.100	2.0%
		Efficiency public transportation (MJ/pas.km) 0.100	2.0%
		Road network density (Km/Km2) 0.100	2.0%
		Parking capacity (#park spaces/inhabitant) 0.100	2.0%
		Parking cost (%) 0.100	2.0%
	Fiscal and governance 0.200 AHP	Public expenditures in transport system (%) 0.125	2.5%
		Operational cost PT system (%) 0.125	2.5%
		Expertise technicians-managers (Scale 1to5) 0.125	2.5%
		Stakeholders engagement (Scale 1to5) 0.125	2.5%
		Financial autonomy (Scale 1to5) 0.125	2.5%
		Variation informal transport modal split (%) 0.125	2.5%
		Participation of the multilateral banks (%) 0.125	2.5%
		Master plan (Scale 1to5) 0.125	2.5%
		Proportion of land with mix use (%) 0.100	2.0%
		Land consumption by transport facilities (%) 0.100	2.0%
		Traffic congestion delay (min) 0.100	2.0%
		Satisfaction with mobility services (%) 0.100	2.0%

	Mobility system effectiveness and land use 0.200 AHP	Pathways for pedestrians (m2/inhab) 0.100	2.0%
		Cycle path network density (Bike/hab) 0.100	2.0%
		PT fleet size (Buses/million people) 0.100	2.0%
		Average occupancy rate of pass-veh (%) 0.100	2.0%
		Motorcycle rate (Moto/1k inhab) 0.100	2.0%
		Motorization rate (Veh/1K inhab) 0.100	2.0%
			1.0

Pairwise Comparison AHP-OS

Evaluation of Criteria for Measuring sustainability of mobility systems

Pairwise Comparison Measuring sustainability of mobility systems

10 pairwise comparison(s). Please do the pairwise comparison of all criteria. When completed, click *Check Consistency* to get the priorities.

AHP Scale: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between).

With respect to *Measuring sustainability of mobility systems*, which criterion is more important, and how much more on a scale 1 to 9?

	A - wrt Measuring sustainability of mobility systems - or B?		Equal	How much more?
1	◉ Environment and human health	○ Economy and social	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
2	◉ Environment and human health	○ Operational	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
3	◉ Environment and human health	○ Fiscal and governance	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
4	◉ Environment and human health	○ Mobility system effectiveness and land use	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
5	◉ Economy and social	○ Operational	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
6	◉ Economy and social	○ Fiscal and governance	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
7	◉ Economy and social	○ Mobility system effectiveness and land use	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9

8	◉ Operational	○ Fiscal and governance	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
9	◉ Operational	○ Mobility system effectiveness and land use	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
10	◉ Fiscal and governance	○ Mobility system effectiveness and land use	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9

CR = 0% Please start pairwise comparison

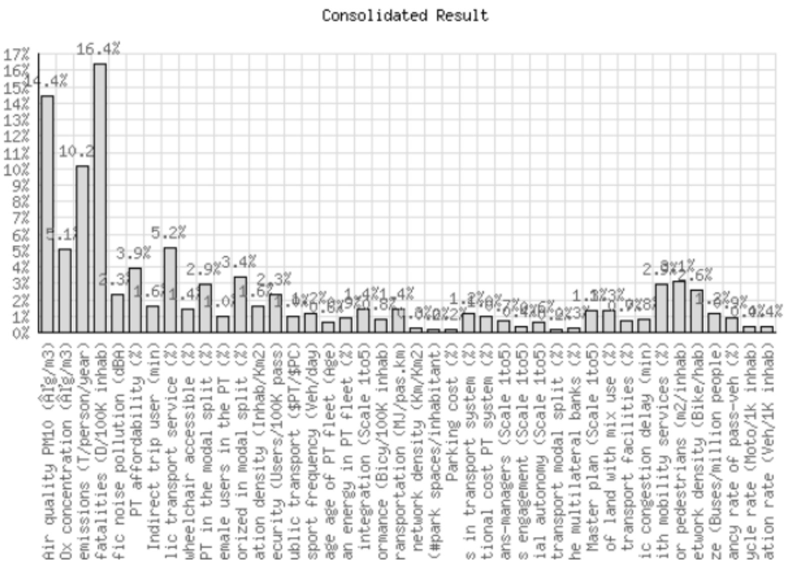
Calculate

AHP-OS author: Klaus D. Goepel, BPMSG. Contact . Last update: Sep 20, 2019 Rev: 50

F AHP-based questionnaire responses: AHP method

The AHP-based questionnaire responses were calculated via an on-line in www.bpmsg.com [191].

Consolidated Global Priorities



Breakdown by Nodes

Details Node: Measuring sustainability of mobility systems - CR: 2.4% - AHP group consensus: 76.6% high

Details Node: Environment and human health - CR: 1.9% - AHP group consensus: 71.9% moderate

Details Node: Economy and social - CR: 1.2% - AHP group consensus: 71.4% moderate

Details Node: Operational - CR: 1.3% - AHP group consensus: 67.0% moderate

Details Node: Fiscal and governance - CR: 2% - AHP group consensus: 69.3% moderate

Details Node: Mobility system effectiveness and land use - CR: 1.7% - AHP group consensus: 73.9% moderate

Breakdown by Nodes

Hide Node: Measuring sustainability of mobility systems - CR: 2.4% - AHP group consensus: 76.6% high

Consolidated Priorities

Consistency Ratio CR: 2.4%

Cat		Priority	Rank
1	Environment and human health	48.3%	1
2	Economy and social	23.4%	2
3	Operational	8.2%	4
4	Fiscal and governance	5.7%	5
5	Mobility system effectiveness and land use	14.3%	3

Consolidated Decision Matrix

Aggregation of individual judgments for 19 Participant(s)

	1	2	3	4	5
1	1	2.87	5.40	5.65	3.83
2	0.35	1	3.51	3.96	1.94
3	0.19	0.28	1	1.96	0.48
4	0.18	0.25	0.51	1	0.34
5	0.26	0.51	2.10	2.92	1

G AHP-based questionnaire responses: FAHP method

The AHP-based questionnaire responses were calculated in a worksheet proposed by this research.

Expert 1

	1			2			3			4			5			Normalized weights
1	1	1	1	4	5	6	6	7	8	8	9	9	6	7	8	0,571
2	1/6	1/5	1/4	1	1	1	4	5	6	4	5	6	2	3	4	0,214
3	1/6	1/7	1/8	1/6	1/5	1/4	1	1	1	2	3	4	1/4	1/3	1/2	0,062
4	1/9	1/9	1/8	1/6	1/5	1/4	1/4	1/3	1/2	1	1	1	1/6	1/5	1/4	0,035
5	1/8	1/7	1/6	1/4	1/3	1/2	2	3	4	4	5	6	1	1	1	0,118

	ri		
1	4,095	4,663	5,102
2	1,398	1,719	2,048
3	0,425	0,491	0,574
4	0,238	0,272	0,330
5	0,758	0,935	1,149
total	6,914	8,080	9,202
reverse	0,145	0,124	0,109
Ascending order	0,109	0,124	0,145

	wi		
1	0,445	0,577	0,738
2	0,152	0,213	0,296
3	0,046	0,061	0,083
4	0,026	0,034	0,048
5	0,082	0,116	0,166

	Mi	Ni
1	0,587	0,571
2	0,220	0,214
3	0,063	0,062
4	0,036	0,035
5	0,121	0,118
		1,000

Expert 2

	1			2			3			4			5			Normalized weights
1	1	1	1	1	2	3	6	7	8	8	9	9	6	7	8	0,471
2	1/3	1/2	1	1	1	1	6	7	8	6	7	8	6	7	8	0,357
3	1/6	1/7	1/8	1/8	1/7	1/6	1	1	1	1	2	3	1	1	2	0,068
4	1/9	1/9	1/8	1/8	1/7	1/6	1/3	1/2	1	1	1	1	1	1	2	0,052
5	1/8	1/7	1/6	1/8	1/7	1/6	1/2	1	1	1/2	1	1	1	1	1	0,053

	ri		
1	3,104	3,882	4,441
2	2,352	2,798	3,482
3	0,461	0,527	0,660
4	0,341	0,380	0,530
5	0,330	0,459	0,488
total	6,588	8,047	9,601
reverse	0,152	0,124	0,104
Ascending order	0,104	0,124	0,152

	wi		
1	0,323	0,482	0,674
2	0,245	0,348	0,529
3	0,048	0,066	0,100
4	0,036	0,047	0,080
5	0,034	0,057	0,074

	Mi	Ni
1	0,493	0,471
2	0,374	0,357
3	0,071	0,068
4	0,054	0,052
5	0,055	0,053
		1,000

References

[1] S. Amoroso, L. Caruso, and F. Castelluccio, ‘Indicators for sustainable mobility in the cities’, *WIT Trans. Ecol. Environ.*, vol. 148, pp. 253–262, 2011.

[2] J. Zheng, N. W. Garrick, C. Atkinson-Palombo, C. McCahill, and W. Marshall, ‘Guidelines on developing performance metrics for evaluating transportation sustainability’, *Res. Transp. Bus. Manag.*, vol. 7, pp. 4–13, 2013, doi: 10.1016/j.rtbm.2013.02.001.

[3] M. K. Ibadi, ‘Developing a Standardized Sustainable Transportation Indicators Set’, *J. Univ. Babylon*, vol. 25, no. 5, pp. 1779–1786, 2017.

[4] T. Litman, ‘Well measured: Developing indicators for comprehensive and sustainable transport planning’, *Transp. Res. Rec.*, no. 1, 2005, doi: 10.3141/2017-02.

[5] T. Litman, ‘Developing indicators for comprehensive and sustainable transport planning’, *Transp. Res. Rec.*, vol. 2017, no. 1, pp. 10–15, 2007, doi: 10.3141/2017-02.

[6] ECMT, *Assessment and Decision Making for Sustainable Transport, European Conference of Ministers of Transportation and the OECD (www.oecd.org)*. OECD Publishing, 2004.

[7] A. Sdoukopoulos, M. Pitsiava-Latinopoulou, S. Basbas, and P. Papaioannou, ‘Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives’, *Transp. Res. Part Transp. Environ.*, vol. 67, pp. 316–333, 2019, doi: https://doi.org/10.1016/j.trd.2018.11.020.

[8] Banco Interamericano de Desarrollo, ‘Guía Metodológica Programa de Ciudades Emergentes y Sostenibles: Tercera edición’. 2016.

[9] M. Burinskienė, K. Gaučė, and J. Damidavičius, *Successful Sustainable Mobility Measures Selection*. 2017.

[10] J. Damidavičius, V. Palevičius, and G. Jakubauskas, ‘Analysis of Innovative and Modern Technology of Parking Lots’, *Moksl. - Liet. Ateitis*, vol. 8, pp. 131–138, 2016, doi: 10.3846/mla.2016.922.

[11] J. A. Black, A. Paez, and P. A. Suthanaya, ‘Sustainable urban transportation: performance indicators and some analytical approaches’, *J. Urban Plan. Dev.*, vol. 128, no. 4, pp. 184–209, 2002.

[12] J. Borken, ‘Indicators for sustainable mobility: a policy oriented approach’, 2003, pp. 19–20.

[13] P. Jones, K. Lucas, and M. Whittles, ‘Evaluating and implementing transport measures in a wider policy context: the “Civilising Cities” initiative’, *Transp. Policy*, vol. 10, no. 3, pp. 209–221, 2003.

[14] J. P. Lima, R. da S. Lima, and A. N. R. da Silva, ‘Evaluation and Selection of Alternatives for the Promotion of Sustainable Urban Mobility’, *Procedia - Soc. Behav. Sci.*, vol. 162, pp. 408–418, 2014, doi: https://doi.org/10.1016/j.sbspro.2014.12.222.

[15] H. Gudmundsson, G. Marsden, and Z. Josias, ‘Sustainable transportation: Indicators, frameworks, and performance management’, *Springer*, 2016.

[16] A. Buzási and M. Csete, ‘Sustainability indicators in assessing urban transport systems’, *Period. Polytech. Transp. Eng.*, vol. 43, no. 3, pp. 138–145, 2015.

[17] P. Zito and G. Salvo, ‘Toward an urban transport sustainability index: an European comparison’, *Eur. Transp. Res. Rev.*, vol. 3, no. 4, pp. 179–195, 2011.

[18] J. Damidavičius, M. Burinskienė, and R. Ušpalytė-Vitkūnienė, ‘A Monitoring System for Sustainable Urban Mobility Plans’, *Balt. J. Road Bridge Eng.*, vol. 14, pp. 158–177, Jun. 2019, doi: 10.7250/bjrbe.2019-14.438.

[19] L. Persia, E. Cipriani, V. Sgarra, and E. Meta, ‘Strategies and Measures for Sustainable Urban Transport Systems’, *Transp. Res. Procedia*, vol. 14, pp. 955–964, 2016, doi: https://doi.org/10.1016/j.trpro.2016.05.075.

[20] M. Hart, *Guide to sustainable community indicators*. North Andover, MA: Hart Environmental Data, 2006.

[21] M. Regmi and H. Gudmunsson, *Monograph Series on Sustainable and Inclusive Transport: Assessment of Urban Transport Systems, UNESCAP, Bangkok, ()*. 2017.

[22] V.-M. Perra, A. Sdoukopoulos, and M. Pitsiava-Latinopoulou, ‘Evaluation of sustainable urban mobility in the city of Thessaloniki’, *Transp. Res. Procedia*, vol. 24, no. 1, pp. 329–36, 2017.

[23] G. Marsden and C. Snell, ‘The role of indicators, targets and monitoring in decision-support for transport’, *Eur. J. Transp. Infrastruct. Res.*, vol. 9, no. 3, 2009.

[24] T. A. Litman, ‘Sustainable transportation indicators: a recommended research program for developing sustainable transportation indicators and data’, 2009.

[25] T. Litman and D. Burwell, ‘Issues in sustainable transportation’, *Int. J. Glob. Environ. Issues*, vol. 6, no. 4, pp. 331–347, 2006.

[26] T. Beatley, ‘The Many Meanings of Sustainability: Introduction to a Special Issue of JPL’, *J. Plan. Lit.*, vol. 9, no. 4, pp. 339–342, 1995, doi: 10.1177/088541229500900401.

[27] Transportation Research Board, ‘Toward A Sustainable Future: Addressing the Long-Term Effects of Motor Vehicle Transportation on Climate and Ecology -- Special Report 251’. The National Academies Press, Washington, DC, p. 261, 1997, [Online]. Available: https://www.nap.edu/catalog/11390/toward-a-sustainable-future-addressing-the-long-term-effects-of.

[28] Centre for Sustainable Transportation, ‘Sustainable Transportation Performance Indicators’. Centre for Sustainable Transportation (www.cstctd.org), 2005, [Online]. Available: http://cst.uwinnipeg.ca/completed.html.

[29] United Nations, *Monograph Series on Sustainable and Inclusive Transport*. 2017.

[30] J. Okata, *Sustainable urban transport in an Asian context*, vol. 9. Springer Science & Business Media, 2010.

[31] Rand Europe et al, 'Operationalizing Sustainable Transport and Mobility: System Diagram and Indicators. SUMMA'. Deliverable 3 of Work package. 2 May 2004, 2004, [Online]. Available: http://www.tmleuven.be/project/summa/summa-d3.pdf.

[32] D. Banister, 'The sustainable mobility paradigm', *Transp. Policy*, vol. 15, no. 2, pp. 73–80, 2008.

[33] World Commission on Environment and Development., *Our common future*. Oxford; New York: Oxford University Press, 1987.

[34] EC European Commission, 'WHITE PAPER roadmap to a single European transport area towards a competitive and resource efficient transport system', *COM 2011*, vol. 144, 2011.

[35] T. Pálvölgyi and G. Szendrő, 'Trends and indicators for sustainable mobility in Hungary', *Acta Acad. Paedagog. Agriensis Nova Ser. Acta Oeconomica*, vol. 1, pp. 125–132, 2012.

[36] G. Szendrő and Á. Török, 'Theoretical investigation of environmental development pathways in the road transport sector in the European Region', *Transport*, vol. 29, no. 1, pp. 12–17, 2014.

[37] C. Zegras, 'Sustainable transport indicators and assessment methodologies', 2006, vol. 1, pp. 25–27.

[38] T.-A. Shiau and J.-S. Liu, 'Developing an indicator system for local governments to evaluate transport sustainability strategies', *Ecol. Indic.*, vol. 34, pp. 361–371, 2013.

[39] A. Alonso, A. Monzón, and R. Cascajo, 'Comparative analysis of passenger transport sustainability in European cities', *Ecol. Indic.*, vol. 48, pp. 578–592, 2015.

[40] MOST, 'Moving on Sustainable Transportation'. Transport Canada (www.tc.gc.ca/envaffairs/most), 1999.

[41] M. Kiba-Janiak and J. Witkowski, 'Sustainable Urban Mobility Plans: How Do They Work?', *Sustainability*, vol. 11, no. 17, p. 4605, 2019.

[42] Sustainable Mobility for All, 'Global Mobility Report 2017: Tracking Sector Performance. 2017', *World Bank*.

[43] A. P. T. UITP, 'Mobility in cities database', *Synth. Rep.*, 2015.

[44] M. Palme, 'La ciudad emergente: complejidad, organización y crecimiento energético en el metabolismo urbano', 2017.

[45] H. Terraza, D. Rubio Blanco, and F. Vera, 'De ciudades emergentes a ciudades sostenibles', 2016.

[46] R. Hernádez Sampieri, C. Fernádez Collado, and M. Baptista Lucio, ‘Metodología de la Investigación (Sexta edición ed.)’, *Mex. Ill Interam. Mex. SA*, 2014.

[47] R. K. Yin, ‘Case study research: Design and methods. Sage publications’, *Thousand Oaks*, 2009.

[48] Maureen. Hart and Hart Environmental Data., *Guide to sustainable community indicators*. North Andover, MA: Hart Environmental Data, 2006.

[49] R. A. MacDonald, *Sustainable transportation and land use planning at Simon Fraser University: A case study of the Burnaby Mountain Campus*. Simon Fraser University, 2000.

[50] P. Newman and J. Kenworthy, *Sustainability and cities: overcoming automobile dependence*. Island press, 1999.

[51] J. Nichols, N. Garrick, and C. Atkinson-Palombo, ‘Framework for Developing Indicators of Sustainability for Transportation Planning’, 2009.

[52] R. J. Patrick, *Developing sustainability indicators for rural residential areas: The public transit connection*. 2004.

[53] H. Haghshenas and M. Vaziri, ‘Urban sustainable transportation indicators for global comparison’, *Ecol. Indic.*, vol. 15, no. 1, pp. 115–121, 2012, doi: https://doi.org/10.1016/j.ecolind.2011.09.010.

[54] X. Gan *et al.*, ‘When to use what: Methods for weighting and aggregating sustainability indicators’, *Ecol. Indic.*, vol. 81, pp. 491–502, 2017.

[55] E. R. Jimenez Perez, ‘Airport strategic planning in the context of low-cost carriers ascendency: insights from the European experience’, 2015.

[56] P. M. Brewerton and L. J. Millward, *Organizational research methods: A guide for students and researchers*. Sage, 2001.

[57] A. Bryman, *Research methods and organization studies*, vol. 20. Routledge, 2003.

[58] O. Ghorbanzadeh, S. Moslem, T. Blaschke, and S. Duleba, ‘Sustainable urban transport planning considering different stakeholder groups by an interval-AHP decision support model’, *Sustainability*, vol. 11, no. 1, p. 9, 2019.

[59] S. Moslem and S. Duleba, ‘Application of AHP for evaluating passenger demand for public transport improvements in Mersin, Turkey’, *Pollack Period.*, vol. 13, no. 2, pp. 67–76, 2018.

[60] T. L. Saaty, ‘Transport planning with multiple criteria: the analytic hierarchy process applications and progress review’, *J. Adv. Transp.*, vol. 29, no. 1, pp. 81–126, 1995.

[61] S. Chowdhury, Y. Hadas, V. Gonzalez, and B. Schot, ‘Public transport users’ and policy makers’ perceptions of integrated public transport systems’, *Transp. Policy*, vol. 61, pp. 75–83, Jan. 2018, doi: 10.1016/j.tranpol.2017.10.001.

[62] S. Moslem and S. Duleba, ‘Sustainable Urban Transport Development by Applying a Fuzzy-AHP Model: A Case Study from Mersin, Turkey’, *Urban Sci.*, vol. 3, May 2019, doi: 10.3390/urbansci3020055.

[63] R. W. Saaty, ‘Decision making in complex environment: The analytic hierarchy process (AHP) for decision making and the analytic network process (ANP) for decision making with dependence and feedback’, *Pittsburgh Super Decis.*, 2003.

[64] T. Saaty, *The analytical Hierarchical Process (Vol. 1)*. New York: J Wiley, 1980.

[65] T. L. Saaty and L. G. Vargas, ‘The analytic hierarchy process series’, *Univ. Pittsbg.*, 1990.

[66] C. Kahraman, *Fuzzy multi-criteria decision making: theory and applications with recent developments*, vol. 16. Springer Science & Business Media, 2008.

[67] D. O. Aikhuele and F. S. Souleman, ‘AA (2014). Application of Fuzzy AHP for Ranking Critical Success Factors for the Successful Implementation of Lean Production Technique’, *Aust. J. Basic Appl. Sci.*, vol. 8, pp. 399–407.

[68] P. Grošelj and L. Zadnik Stirn, ‘Evaluation of several approaches for deriving weights in fuzzy group analytic hierarchy process’, *J. Decis. Syst.*, vol. 27, no. sup1, pp. 217–226, May 2018, doi: 10.1080/12460125.2018.1460160.

[69] L. Abdullah and N. Zulkifli, ‘Integration of fuzzy AHP and interval type-2 fuzzy DEMATEL: An application to human resource management’, *Expert Syst. Appl.*, vol. 42, no. 9, pp. 4397–4409, 2015, doi: https://doi.org/10.1016/j.eswa.2015.01.021.

[70] Y. Chen, S. Wang, J. Yao, Y. Li, and S. Yang, ‘Socially responsible supplier selection and sustainable supply chain development: A combined approach of total interpretive structural modeling and fuzzy analytic network process’, *Bus. Strategy Environ.*, vol. 27, pp. 1708–1719, Dec. 2018, doi: 10.1002/bse.2236.

[71] G. Fan, D. Zhong, F. Yan, and P. Yue, ‘A hybrid fuzzy evaluation method for curtain grouting efficiency assessment based on an AHP method extended by D numbers’, *Expert Syst. Appl.*, vol. 44, pp. 289–303, 2016, doi: https://doi.org/10.1016/j.eswa.2015.09.006.

[72] S. Moslem, O. Ghorbanzadeh, T. Blaschke, and S. Duleba, ‘Analysing Stakeholder Consensus for a Sustainable Transport Development Decision by the Fuzzy AHP and Interval AHP’, *Sustainability*, vol. 11, p. 3271, Jun. 2019, doi: 10.3390/su11123271.

[73] K.-S. Park, Y.-J. Seo, A. Kim, and M.-H. Ha, ‘Ship acquisition of shipping companies by sale & purchase activities for sustainable growth: Exploratory fuzzy-AHP application’, *Sustainability*, vol. 10, no. 6, p. 1763, 2018.

[74] R. Joumard and H. Gudmundsson, *Indicators of environmental sustainability in transport: an interdisciplinary approach to methods*. European Commission, 2010.

[75] K. Neumann, *CONSIDEO MODELER: So einfach wie Mind Mapping: Vernetztes Denken und Simulation*. BoD–Books on Demand, 2010.

[76] K. Neumann, ‘Know-why’, *Syst. Think. Model. Norderstedt Books Demand*, 2012.

[77] K. Neumann, ‘Reflecting on complex challenges through qualitative modeling using the iMODELER’, *Emergence Complex. Organ.*, vol. 16, no. 2, pp. 29–43, 2014.

[78] Y. Yevdokimov, ‘Sustainable Transportation System: A System Dynamics Approach’, presented at the 3rd International Conference on Public Economics, Paris, 2002.

[79] Á. Török, ‘Environmental comparism of road and railway transport: a case study in Hungary’, *Int. J. Traffic Transp. Eng.*, vol. 4, no. 2, pp. 210–219, 2014.

[80] Z. Toth-Szabo and A. Várhelyi, ‘Indicator Framework for Measuring Sustainability of Transport in the City’, *Transp. Res. Arena 2012*, vol. 48, pp. 2035–2047, Jan. 2012, doi: 10.1016/j.sbspro.2012.06.1177.

[81] A. Maxim, ‘Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis’, *Energy Policy*, vol. 65, pp. 284–297, 2014, doi: https://doi.org/10.1016/j.enpol.2013.09.059.

[82] H. Kan, R. Chen, and S. Tong, ‘Ambient air pollution, climate change, and population health in China’, *Environ. Int.*, vol. 42, pp. 10–19, 2012.

[83] J. S. Pandey, R. Kumar, and S. Devotta, ‘Health risks of NO2, SPM and SO2 in Delhi (India)’, *Atmos. Environ.*, vol. 39, no. 36, pp. 6868–6874, 2005.

[84] B. Puri26, ‘SUSTAINABLE TRANSPORT AND INTER MODAL MIX’, *Transp. Sustain. Dev. Goals*, p. 54.

[85] J. Zheng, C. Atkinson-Palombo, C. McCahill, R. O’Hara, and N. W. Garrick, ‘Quantifying the economic domain of transportation sustainability’, *Transp. Res. Rec.*, vol. 2242, no. 1, pp. 19–28, 2011.

[86] T. Litman, ‘Are Vehicle Travel Reduction Targets Justified? Evaluating Mobility’, presented at the Management Policy Objectives Such As Targets To Reduce VMT And Increase Use Of Alternative Modes, VTPI (www. vtpi. org); at www. vtpi. org/vmt_red. pdf, 2010, doi: 10.3141/2017-02.

[87] T. Litman, ‘Evaluating transportation equity’, *World Transp. Policy Pract.*, vol. 8, no. 2, pp. 50–65, 2002.

[88] N. Low and B. Gleeson, *Making urban transport sustainable*. Springer, 2002.

[89] A. Dobranskyte-Niskota, A. Perujo, and M. Pregl, ‘Indicators to assess sustainability of transport activities’, *Eur. Com. Jt. Res. Cent.*, 2007.

[90] D. Bongardt, D. Schmid, C. Huizenga, and T. Litman, ‘Sustainable transport evaluation: Developing practical tools for evaluation in the context of the CSD process’, *Partnersh. Sustain. Low Carbon Transp. Eschborn Ger.*, 2011.

[91] T. de A. Villela, M. Magalhães, H. Gomes, B. Arruda, and L. Silveira, ‘Metodologia para desenvolvimento e Seleção de Indicadores para planejamento de transportes’, presented at the 21st Annual Meeting of Brazilian National Association for Transport Research & Education; ANPET: Rio de Janeiro, Brazil, 2007.

[92] R. Eckersley, ‘Perspectives on progress: is life getting better?’, 1997.

[93] European Environment Agency, *EEA core set of indicators: Guide*. European Environment Agency, 2005.

[94] E. K. Tam, ‘Challenges in using environmental indicators for measuring sustainability practices’, *J. Environ. Eng. Sci.*, vol. 1, no. 6, pp. 417–425, 2002.

[95] J. Gil, *Urban Modality - Integrated approaches for sustainable urban mobility*. 2017.

[96] U. Habitat, ‘Sustainable cities and communities: SDG goal 11 monitoring framework’, 2016.

[97] W. Steffen *et al.*, ‘Planetary boundaries: Guiding human development on a changing planet’, *Science*, vol. 347, no. 6223, p. 1259855, 2015.

[98] M. Trompet, X. Liu, and D. J. Graham, ‘Development of key performance indicator to compare regularity of service between urban bus operators’, *Transp. Res. Rec.*, vol. 2216, no. 1, pp. 33–41, 2011.

[99] R. Liu and S. Sinha, ‘Modelling urban bus service and passenger reliability.’, 2007.

[100] R. Cervero and A. Golub, ‘Informal public transport: A global perspective’, *Urban Transp. Dev. World Handb. Policy Pract.*, pp. 488–518, Jan. 2011.

[101] G. Beirão and J. S. Cabral, ‘Understanding attitudes towards public transport and private car: A qualitative study’, *Transp. Policy*, vol. 14, no. 6, pp. 478–489, 2007.

[102] J. Wu, ‘Landscape sustainability science: ecosystem services and human well-being in changing landscapes’, *Landsc. Ecol.*, vol. 28, no. 6, pp. 999–1023, 2013.

[103] C. Böhringer and P. E. Jochem, ‘Measuring the immeasurable—A survey of sustainability indices’, *Ecol. Econ.*, vol. 63, no. 1, pp. 1–8, 2007.

[104] E. D. Özdemir, M. Härdtlein, T. Jenssen, D. Zech, and L. Eltrop, ‘A confusion of tongues or the art of aggregating indicators—Reflections on four projective methodologies on sustainability measurement’, *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2385–2396, 2011.

[105] J. Wu and T. Wu, ‘Sustainability indicators and indices: an overview’, in *Handbook of sustainability management*, World Scientific, 2012, pp. 65–86.

[106] R. K. Singh, H. R. Murty, S. K. Gupta, and A. K. Dikshit, 'An overview of sustainability assessment methodologies', *Ecol. Indic.*, vol. 9, no. 2, pp. 189–212, 2009.

[107] M. C. Wilson and J. Wu, 'The problems of weak sustainability and associated indicators', *Int. J. Sustain. Dev. World Ecol.*, vol. 24, no. 1, pp. 44–51, 2017.

[108] S. Morse, N. McNamara, M. Acholo, and B. Okwoli, 'Sustainability indicators: the problem of integration', *Sustain. Dev.*, vol. 9, no. 1, pp. 1–15, 2001.

[109] H. V. Rowley, G. M. Peters, S. Lundie, and S. J. Moore, 'Aggregating sustainability indicators: beyond the weighted sum', *J. Environ. Manage.*, vol. 111, pp. 24–33, 2012.

[110] V.-A. Cloquell-Ballester, R. Monterde-Díaz, V.-A. Cloquell-Ballester, and M.-C. Santamarina-Siurana, 'Systematic comparative and sensitivity analyses of additive and outranking techniques for supporting impact significance assessments', *Environ. Impact Assess. Rev.*, vol. 27, no. 1, pp. 62–83, 2007.

[111] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, and J.-H. Zhao, 'Review on multi-criteria decision analysis aid in sustainable energy decision-making', *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2263–2278, 2009.

[112] S. K. Sehra, Y. S. Brar, and N. Kaur, 'Applying fuzzy-AHP for software effort estimation in data scarcity', *IJETT*, vol. 45, pp. 4–9, 2017.

[113] M. Jørgensen, 'A review of studies on expert estimation of software development effort', *J. Syst. Softw.*, vol. 70, no. 1–2, pp. 37–60, 2004.

[114] M. Jørgensen, 'Forecasting of software development work effort: Evidence on expert judgement and formal models', *Int. J. Forecast.*, vol. 23, no. 3, pp. 449–462, 2007.

[115] M. Jørgensen, B. Boehm, and S. Rifkin, 'Software development effort estimation: Formal models or expert judgment?', *IEEE Softw.*, vol. 26, no. 2, pp. 14–19, 2009.

[116] M. Jørgensen and T. Halkjelsvik, 'The effects of request formats on judgment-based effort estimation', *J. Syst. Softw.*, vol. 83, no. 1, pp. 29–36, 2010.

[117] R. M. Dawes and B. Corrigan, 'Linear models in decision making.', *Psychol. Bull.*, vol. 81, no. 2, p. 95, 1974.

[118] G. Munda and M. Nardo, 'Non-compensatory composite indicators for ranking countries: A defensible setting', *EUR Rep. EUR*, vol. 21833, 2005.

[119] O. S. Vaidya and S. Kumar, 'Analytic hierarchy process: An overview of applications', *Eur. J. Oper. Res.*, vol. 169, no. 1, pp. 1–29, 2006.

[120] A. Arranz-López, J. A. Soria-Lara, C. López-Escolano, and Á. P. Campos, 'Retail mobility environments: a methodological framework for integrating retail activity and non-motorised accessibility in Zaragoza, Spain', *J. Transp. Geogr.*, vol. 58, pp. 92–103, 2017.

[121] R. K. Singh, H. R. Murty, S. K. Gupta, and A. K. Dikshit, ‘Development of composite sustainability performance index for steel industry’, *Ecol. Indic.*, vol. 7, no. 3, pp. 565–588, 2007, doi: https://doi.org/10.1016/j.ecolind.2006.06.004.

[122] E. Hermans, F. Van den Bossche, and G. Wets, ‘Combining road safety information in a performance index’, *Accid. Anal. Prev.*, vol. 40, no. 4, pp. 1337–1344, 2008.

[123] G. Graham, J. Freeman, and T. Chen, ‘Green supplier selection using an AHP-Entropy-TOPSIS framework’, *Supply Chain Manag. Int. J.*, 2015.

[124] W. Ho, X. Xu, and P. K. Dey, ‘Multi-criteria decision making approaches for supplier evaluation and selection: A literature review’, *Eur. J. Oper. Res.*, vol. 202, no. 1, pp. 16–24, 2010.

[125] M. Nardo, M. Saisana, A. Saltelli, and S. Tarantola, ‘Tools for composite indicators building’, *Eur. Com. Ispra*, vol. 15, no. 1, pp. 19–20, 2005.

[126] J. S. Challa, A. Paul, Y. Dada, V. Nerella, P. R. Srivastava, and A. P. Singh, ‘Integrated software quality evaluation: a fuzzy multi-criteria approach’, *J. Inf. Process. Syst.*, vol. 7, no. 3, pp. 473–518, 2011.

[127] M.-C. Lee, ‘Information security risk analysis methods and research trends: AHP and fuzzy comprehensive method’, *Int. J. Comput. Sci. Inf. Technol.*, vol. 6, no. 1, p. 29, 2014.

[128] Y.-M. Wang, Y. Luo, and Z. Hua, ‘On the extent analysis method for fuzzy AHP and its applications’, *Eur. J. Oper. Res.*, vol. 186, no. 2, pp. 735–747, 2008.

[129] A. Sarfaraz, P. Mukerjee, and K. Jenab, ‘Using fuzzy analytical hierarchy process (AHP) to evaluate web development platform’, *Manag. Sci. Lett.*, vol. 2, no. 1, pp. 253–262, 2012.

[130] W. Liu and Z. Zhang, ‘Prioritization of highway maintenance functions using multi-attribute decision making with fuzzy pairwise comparison.’, Southwest Region University Transportation Center (US), 2011.

[131] Y.-M. Wang and Y. Luo, ‘On rank reversal in decision analysis’, *Math. Comput. Model.*, vol. 49, no. 5–6, pp. 1221–1229, 2009.

[132] A. Gnanavelbabu and P. Arunagiri, ‘Ranking of MUDA using AHP and Fuzzy AHP algorithm’, *Mater. Today Proc.*, vol. 5, no. 5, Part 2, pp. 13406–13412, 2018, doi: https://doi.org/10.1016/j.matpr.2018.02.334.

[133] S. Kubler, J. Robert, W. Derigent, A. Voisin, and Y. Le Traon, ‘A state-of the-art survey & testbed of fuzzy AHP (FAHP) applications’, *Expert Syst. Appl.*, vol. 65, pp. 398–422, 2016.

[134] S. Ozdemir and Y. Ozdemir, ‘Prioritizing store plan alternatives produced with shape grammar using multi-criteria decision-making techniques’, *Environ. Plan. B Urban Anal. City Sci.*, vol. 0, p. 026581351668656, 2017, doi: 10.1177/0265813516686566.

[135] D. Krajnc and P. Glavič, ‘A model for integrated assessment of sustainable development’, *Resour. Conserv. Recycl.*, vol. 43, pp. 189–208, 2005, doi: 10.1016/j.resconrec.2004.06.002.

[136] Y. O. Ouma, J. Opudo, and S. Nyambenya, ‘Comparison of fuzzy AHP and fuzzy TOPSIS for road pavement maintenance prioritization: methodological exposition and case study’, *Adv. Civ. Eng.*, vol. 2015, 2015.

[137] L. A. Zadeh, ‘Fuzzy sets’, *Inf. Control*, vol. 8, no. 3, pp. 338–353, 1965.

[138] V. Belton and T. Stewart, *Multiple criteria decision analysis: an integrated approach*. Springer Science & Business Media, 2002.

[139] F. Kong and H. Liu, ‘Applying fuzzy analytic hierarchy process to evaluate success factors of e-commerce’, *Int. J. Inf. Syst. Sci.*, vol. 1, no. 3–4, pp. 406–412, 2005.

[140] J. J. Buckley, ‘Fuzzy hierarchical analysis’, *Fuzzy Sets Syst.*, vol. 17, no. 3, pp. 233–247, 1985, doi: https://doi.org/10.1016/0165-0114(85)90090-9.

[141] T.-Y. Hsieh, S.-T. Lu, and G.-H. Tzeng, ‘Fuzzy MCDM approach for planning and design tenders selection in public office buildings’, *Int. J. Proj. Manag.*, vol. 22, pp. 573–584, Oct. 2004, doi: 10.1016/j.ijproman.2004.01.002.

[142] J. J. Buckley, ‘Ranking alternatives using fuzzy numbers’, *Fuzzy Sets Syst.*, vol. 15, no. 1, pp. 21–31, 1985.

[143] J. M. Andrić and D.-G. Lu, ‘Risk assessment of bridges under multiple hazards in operation period’, *Saf. Sci.*, vol. 83, pp. 80–92, 2016.

[144] C.-N. Liao, ‘Fuzzy analytical hierarchy process and multi-segment goal programming applied to new product segmented under price strategy’, *Comput. Ind. Eng.*, vol. 61, no. 3, pp. 831–841, 2011.

[145] D.-Y. Chang, ‘Applications of the extent analysis method on fuzzy AHP’, *Eur. J. Oper. Res.*, vol. 95, no. 3, pp. 649–655, 1996.

[146] Y. O. Ouma, C. Yabann, M. Kirichu, and R. Tateishi, ‘Optimization of urban highway bypass horizontal alignment: a methodological overview of intelligent spatial MCDA approach using fuzzy AHP and GIS’, *Adv. Civ. Eng.*, vol. 2014, 2014.

[147] A. Kaufman and M. M. Gupta, *Introduction to fuzzy arithmetic*. Van Nostrand Reinhold Company New York, 1991.

[148] A. Özdağoğlu and G. Özdağoğlu, ‘Comparison of AHP and fuzzy AHP for the multi-criteria decision making processes with linguistic evaluations’, 2007.

[149] J. Agarwal, R. Nagpal, and R. Sehgal, ‘Reliability of Component based Software System using Fuzzy AHP and Fuzzy TOPSIS’, *Int. J. Comput. Appl.*, vol. 975, p. 8887, 2014.

[150] J. J. Buckley and V. Uppuluri, ‘Fuzzy hierarchical analysis’, in *Uncertainty in Risk Assessment, Risk Management, and Decision Making,* Springer, 1987, pp. 389–401.

[151] X. Li, K. Wang, L. Liu, J. Xin, H. Yang, and C. Gao, ‘Application of the entropy weight and TOPSIS method in safety evaluation of coal mines’, *Procedia Eng.*, vol. 26, pp. 2085–2091, 2011.

[152] Lunds Kommun, ‘LUNDAMATS III Strategy for a sustainble transport system in Lund Municipality’, May 2014. [Online]. Available: https://www.lund.se/globalassets/lund.se/traf_infra/lundamats/lundamats_iii_eng.pdf.

[153] Lunds Kommun, ‘Tramway lund C - ESS city planning and tomorrow´s Lund’, Dec. 2017.

[154] City of Copenhagen, ‘CPH 2025 Climate Plan Roadmap 2017-2020’, 2016.

[155] City of Copenhagen, ‘EU - Tender trafikmodel appendix 3: requeriments specification’, Nov. 2017.

[156] Ministry of Transport, ‘The danish transport system’, 2012.

[157] Instituto Nacional de Estatística and Área metropolitana do Porto, ‘Mobilidade e funcionalidade do território nas áreas metropolitanas do Porto e de Lisboa’, 2017.

[158] Instituto Nacional de Estatística, ‘Inquérito à Mobilidade (IMob)’, 2017.

[159] Findeter, ‘Plan maestro de movilidad y espacio publico’, 2018.

[160] Transport Analysis, ‘Road traffic injuries’, 2019. [Online]. Available: https://www.trafa.se/en/road-traffic/road-traffic-injuries/.

[161] European Environment Agency, ‘Air pollution’, 2019. [Online]. Available: https://www.eea.europa.eu/themes/air/.

[162] skanetrafiken, ‘Biljetter’, 2020. [Online]. Available: https://www.skanetrafiken.se/.

[163] European Environment Agency, ‘Occupancy rates of passenger vehicles’, 2004. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/occupancy-rates-of-passenger-vehicles-3.

[164] lundahoj, ‘THE BIKE’, 2019. [Online]. Available: http://lundahoj.se/en/om-lundacykeln/cykeln/.

[165] Statistics Denmark, ‘Traffic accidents’, 2019. [Online]. Available: https://www.dst.dk/en/Statistik/emner/levevilkaar/trafikulykker.

[166] Aarhus University DCE – Danish Centre for Environment and Energy, ‘The danish air quality monitoring programme’, 2018.

[167] S. Dixon, H. Irshad, D. M. Pankratz, and J. Bornstein, 'The 2019 Deloitte City Mobility Index Gauging global readiness for the future of mobility', 2019.

[168] Din Offentlige Transport, 'Zoner og priser', 2020. [Online]. Available: https://dinoffentligetransport.dk/.

[169] Copenhagenize, 'Copenhagenize index', 2019. [Online]. Available: https://copenhagenizeindex.eu/.

[170] Autoridade Nacional Segurança Rodoviária, 'Relatórios de sinistralidade', 2019. [Online]. Available: http://www.ansr.pt/Estatisticas/RelatoriosDeSinistralidade/Pages/default.aspx.

[171] QualAR - Qualidade do AR, 'Índice QualAr', 2019. [Online]. Available: https://qualar.apambiente.pt/node/indice-qualar.

[172] Agencia Nacional de Seguridad Vial, 'Boletín estadístico Colombia', 2019. [Online]. Available: https://ansv.gov.co/observatorio/public/documentos/boletin_mensual_nacional_agosto.pdf.

[173] Cortolima, 'Calidad del Aire', 2019. [Online]. Available: https://www.cortolima.gov.co/.

[174] Ibagué cómo vamos, 'Encuesta de percepción ciudadana', 2019. [Online]. Available: https://ibaguecomovamos.org/categoria/percepcion-ciudadana/2019-percepcion-ciudadana/.

[175] J. WANG, H. LU, and H. PENG, 'System Dynamics Model of Urban Transportation System and Its Application', *J. Transp. Syst. Eng. Inf. Technol.*, vol. 8, no. 3, pp. 83–89, Jun. 2008, doi: 10.1016/S1570-6672(08)60027-6.

[176] J. Springael, P. L. Kunsch, and J.-P. Brans, 'A multicriteria-based system dynamics modelling of traffic congestion caused by urban commuters', *Cent. Eur. J. Oper. Res.*, vol. 10, no. 1, pp. 81–97, 2002.

[177] M. Wegener, 'Overview of land-use transport models', *Handb. Transp. Geogr. Spat. Syst.*, vol. 5, pp. 127–146, 2004.

[178] Y. Barlas, 'System dynamics: systemic feedback modeling for policy analysis. Encylopedia for life support systems', 2002.

[179] D. Collste, M. Pedercini, and S. E. Cornell, 'Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies', *Sustain. Sci.*, vol. 12, no. 6, pp. 921–931, 2017.

[180] J. Sterman, 'Business Dynamics: Modeling and Simulation for a Complex World', 2000.

[181] J. W. Forrester, ‘Industrial Dynamics. A major breakthrough for decision makers’, *Harv. Bus. Rev.*, vol. 36, no. 4, pp. 37–66, 1958.

[182] C. Li, J. Ren, and H. Wang, ‘A system dynamics simulation model of chemical supply chain transportation risk management systems’, *Comput. Chem. Eng.*, vol. 89, pp. 71–83, 2016.

[183] F. Armah, D. Yawson, and A. Pappoe, ‘A Systems Dynamics Approach to Explore Traffic Congestion and Air Pollution Link in the City of Accra, Ghana’, *Sustainability*, vol. 2, 2010, doi: 10.3390/su2010252.

[184] S. Shepherd, ‘A review of system dynamics models applied in transportation’, *Transp. B Transp. Dyn.*, vol. 2, no. 2, pp. 83–105, 2014.

[185] R. Sayyadi and A. Awasthi, ‘A system dynamics based simulation model to evaluate regulatory policies for sustainable transportation planning’, *Int. J. Model. Simul.*, vol. 37, no. 1, pp. 25–35, 2017.

[186] P.-M. Boulanger and T. Bréchet, ‘Models for policy-making in sustainable development: The state of the art and perspectives for research’, *Ecol. Econ.*, vol. 55, no. 3, pp. 337–350, 2005.

[187] L. Guo, Y. Qu, C. Wu, and X. Wang, ‘Identifying a pathway towards green growth of Chinese industrial regions based on a system dynamics approach’, *Resour. Conserv. Recycl.*, vol. 128, pp. 143–154, 2018.

[188] K. Neumann, ‘Know why’thinking as a new approach to systems thinking’, *Emergence Complex. Organ.*, vol. 15, no. 3, pp. 81–93, 2013.

[189] A. A. Wieser, M. Scherz, S. Maier, A. Passer, and H. Kreiner, ‘Implementation of Sustainable Development Goals in construction industry-a systemic consideration of synergies and trade-offs’, 2019, vol. 323, no. 1, p. 012177.

[190] K. Neumann, C. Anderson, and M. Denich, ‘Participatory, explorative, qualitative modeling: Application of the iMODELER software to assess trade-offs among the SDGs’, *Econ. Open-Access Open-Assess. E-J.*, vol. 12, no. 2018–25, pp. 1–19, 2018.

[191] K. D. Goepel, ‘Implementation of an online software tool for the analytic hierarchy process (AHP-OS)’, *Int. J. Anal. Hierarchy Process*, vol. 10, no. 3, 2018.