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Sustainable Mobility Design Decomposition – A Holistic Perspective

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Abstract

In the last decade, sustainable mobility has become a pivotal subject in reaching sustainability goals for 2030, not only by improving the transportation sector but also through its direct and indirect effects on human well-being and economic development. Nowadays competitive markets have presented various solutions to decision-makers who often choose a method or a combination of them without considering their consequences. This paper decomposes sustainability objectives within the mobility sector ecosystem using an axiomatic design approach, translating needs into functional requirements and identifying eco-friendly alternatives and/or practices. The outcomes enable stakeholders to scale the sustainability transition holistically within mobility ecosystems.

Keywords: Sustainability Transition; Sustainable mobility; Systems engineering; System decomposition; Axiomatic Design; Mobility ecosystems.

1. Introduction

The wide network of the mobility sector has a high potential to control environmental concerns and resource scarcity. It provides different advantages and prospects for communities, including enhanced accessibility, social integration, and improved living standards. Nevertheless, this sector was responsible for over 21% of global CO2 emissions in 2023 [1] and ranked as the second-largest emitter of pollutants worldwide as presented in Fig.1. Although the need for environmentally friendly and sustainable alternative practices has become increasingly urgent [2], balancing sustainability triple bottom line within the mobility ecosystems requires a holistic sustainability assessment focusing not only on transportation but also on thinking beyond systems interactions [3].

Over the past years, various regulations and standards, including the European Sustainability Report Standard (ESRS), sustainable development goals (SDGs), and sustainable urban mobility indicators (SUMI), have been established to accelerate sustainability transition, with the primary objective of controlling climate change [4].

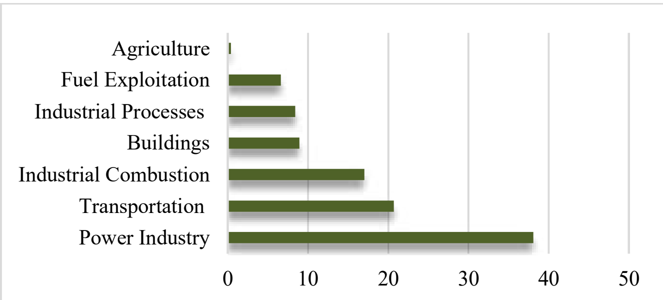

Fig.1. Distribution of CO_2 emissions worldwide in 2023 by sector (Source: Statista 2024).

Regarding sustainable mobility, SDG 11 - Sustainable Cities and Communities, addresses establishing efficient transportation and vital social services for constructing resilient and sustainable urban areas that cater to the needs of all residents. SDG 12 - Responsible Consumption and Production,

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focused on implementing sustainable manufacturing processes and fostering responsible consumption significantly reduces energy consumption and emissions. SDG 13 - Climate Action is dedicated to the adoption of low-carbon transformation strategies [5].

Today, we often hear the term "Sustainable mobility," which refers to transportation systems that meet society's needs while minimizing environmental impact [6]. Sustainable mobility is built on three essential pillars: clean mobility, safe mobility, and economically viable mobility that is inclusive and accessible to all. Understanding these principles and objectives is essential for developing effective strategies and recommendations. Axiomatic Design (AD) theory streamlines this by translating the needs into independent functional requirements, enabling a systematic approach to identify possible practical solutions [7].

Current pressure from regulations forces mobility systems to make unilateral decisions depending on the organization's goals, products, and processes, as well as the nature of the challenges it faces. The hasty implementation of any solutions without a comprehensive understanding of the system's requirements from a System of Systems (SoS) perspective will provide a temporary solution [7]. Furthermore, the main goal of sustainable mobility will be realized when independently owned, operated, and developed systems of different sectors can achieve mutual benefits by working together. Therefore, to address sustainability systematically a collaborative SoS in the wide network of mobility is needed [3]. Despite the many sustainability directives, dedicated regulations, and standards, no directing entity instructs others how and when to collaborate. Instead, the collaboration relies on independent decisions without considering external interconnections and the impacts on other partners [4]. Additionally, although nowadays regulations put a lot of pressure on the market and companies to disclose sustainability reports, companies are not able to adapt at the same speed [8]. Various technologies, methods, and strategies for developing and promoting sustainable transportation and mobility have been devised to evaluate the sustainability aspects; however, these approaches often fail to consider the interdependencies and interconnections among the various measures [9]. To alleviate such difficulties in the sustainability journey and have a targeted sustainability roadmap with clear short-term and long-term plans it is crucial to look at sustainability as a many-objective multi-agent multidisciplinary problem [10]. Furthermore, to survive in the fiercely competitive landscape of modern mobility ecosystems while covering all sustainability pillars simultaneously, a new era of collaboration taking into account the integration of business and engineering as well as the extension to social life is vital. The AD-based system design decomposition approach that was introduced in [11] is a helpful way to alleviate sustainable mobility and transportation systems challenges relying on the breaking down of needs to functional requirements and related physical solutions from the SoS level to the system and sub-systems levels.

This present paper is focused on looking at the big picture of the sustainability needs in the mobility sector and proposes a holistic system decomposition considering all mobility-related sustainability aspects simultaneously. AD-based decomposition reduces complexity and overlap among the three sustainability pillars (environmental, economic, and social), benefiting stakeholders by offering alternative methods, technologies, and ideas to support the low-carbon transition, improving outcomes for end-users, business revenues, and national image. The remaining rest of the paper is structured as follows. Section 2 introduces the AD theory and regulations. Section 3 provides a comprehensive overview of sustainable mobility. Section 4 presents the results of the study. Lastly, conclusions are drawn in Section 5.

2. Axiomatic Design theory

Axiomatic design aims to define independent requirements that fully capture design functionalities. The process starts by identifying customer needs (CNs) and deriving high-level functional requirements (FRs). Designers then find physical solutions (PSs) and alternatives for each FR, ensuring they meet specified metrics. Selecting the best PSs, a creative process, requires a comprehensive system or organizational knowledge, especially at lower decomposition levels Decomposition continues until all FRs and PSs are operational [12]. Zig-zagging is essential to check dependencies between PSs and FRs [13]. Synthesizing the best set of PSs relies on Suh's two AD axioms: the Independence Axiom and the Information Axiom. The Independence Axiom (Axiom 1) ensures FRs remain independent, while the Information Axiom (Axiom 2) minimizes the design's information content [14]. Suh’s design theory concept is illustrated in Fig. 2 and the main goals are as follows [15]:

- Make correct decisions (*effective solutions*)
- Structure the design process (*structured method*)
- Shorten lead time (*reduce iterations*)
- Deal with complex systems (*reduce complexity*)
- Improves the quality of products (*reduce failures due to dependencies*)
- Enhances creativity (*solution-neutral*)
- Change in design thinking (*think functionally first*)

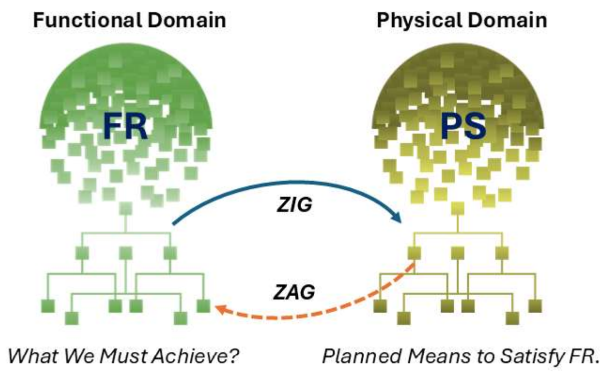

Fig. 2. Axiomatic design and Zig-zagging concept.

As illustrated in Fig. 2, after translating the needs to the main set of FRs, the ZIG step looks for conceptualization, mapping the FR-PS relationship, and proving the independent axiom. Selected solutions relevant to FRs will define the FRs of the next level through the ZAG step. This zig-zagging process continues until the designer is satisfied that no more detail is needed in the decomposition. To give more freedom of action to the designer, at higher levels of decomposition, the solutions are defined as general as possible, and gradually during the zig-zagging, FRs and PSs will become more detailed, practical, and application-dependent. AD is now recognized as a systematic design approach applicable to diverse engineering and design issues, aiming to develop more efficient, reliable, and cost-effective products or systems [16]. Additionally, AD's role in fostering creativity and agile development is elaborated in [17].

3. Sustainable Mobility: A General Insight

The concept of sustainability in the transport and mobility ecosystems has concentrated more on developing sustainable technologies and practices that aimed at making the movement and transportation of people and goods efficient and rational not only from an economic and ecological perspective but also from a social standpoint that prioritizes the safety and well-being of individuals globally. The general concept of sustainable mobility is illustrated in Fig. 3.

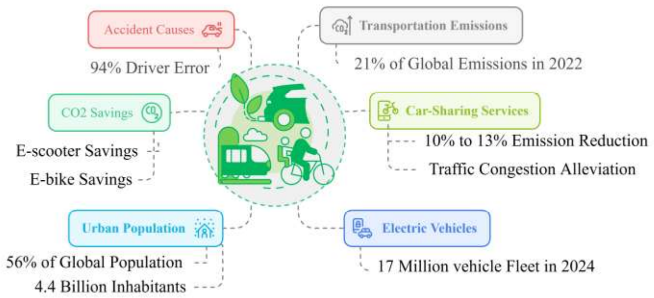

Fig. 3. General Illustration of Sustainable Mobility

Sustainable mobility is drawing researchers to investigate the influence of new technologies, ideas, and practices on the economic and environmental conditions of individuals and businesses. For example, researchers in [18] delved into the potential of digitalization to enhance transport operations while minimizing environmental issues, particularly within the context of European Union (EU) countries. The authors intended to investigate the influence of digital technologies on environmental sustainability and their ability to support the attainment of SDGs, including the reduction of carbon dioxide emissions from the transportation industry. In addition, Turan et al. [19] explored how transport optimization can aid the transition to sustainable mobility by identifying concepts within the avoid-shift-improve paradigm and reviewing relevant literature. The results in [19] show that transport optimization can reduce emissions by minimizing travel distances, improving vehicle utilization, and promoting sustainable transport modes like cargo bikes and public transport. It also emphasizes the need for changes in operational mindsets and regulatory frameworks to effectively implement these solutions for sustainable mobility. Furthermore, Li et al. [20] presented a smart stochastic architecture that optimizes renewable energy-dependent systems for sustainable urban transportation, addressing challenges in networked microgrids. The results indicated that the proposed architecture achieves a 20% reduction in carbon emissions and a 15% increase in energy efficiency, demonstrating robustness and efficiency across various scenarios, thus contributing to stable and sustainable urban transportation systems.

The results of the research done so far in the field of sustainable mobility reveal the need for a comprehensive look at this issue, by clarifying the needs and determining clear milestones and goals, targeted promising solutions can be provided considering the collaborative cooperation between the responsible bodies in different fields.

4. Sustainable Mobility Decomposition

The AD-based decomposition process begins with identifying needs. The primary high-level functional requirement is then established to determine the main physical solution and its alternatives to address the CNs. Once a solid foundation for the decomposition tree is set, it will be further divided into branches and leaves. Key items identified as primary needs stem from global climate change concerns and the drivers of the current emphasis on sustainability are presented in Table 1.

To implement the AD theory there are clear steps to follow. The problem statement and decomposition are the main two steps. Starting from these four drivers, in the continuation of this section steps adopted to decompose the sustainable mobility problem are proposed.

Table 1. Sustainable Mobility Primary Needs

Key Items/Needs	Description
Environmental	Environmental crisis and global warming concerns.
Regulatory	New and upcoming sustainable mobility regulations, standards, and policies.
Economic opportunities	Green marketing and lower total cost of ownership (TCO) considering environmental impact.
Human Needs	Demands for sustainable Mobility as a Service (MaaS).

4.1. Problem statement (needs & objectives)

According to the quote of Charles Kettering, "A problem well-defined is a problem half-solved", a clear problem statement is a critical step before diving into solving the problem. In the following, the problem of sustainable mobility discussed in this study is clarified by asking and answering short questions:

1. What is the high-level need that a system will meet? (FR0)

FR0 – Align the transportation sector with sustainability needs
PS0 – Sustainable mobility ecosystem development plan
FR0 measure (FRm) – sustainability metrics in mobility sectors based on SUMI, which serve as a valuable resource for cities and urban areas to assess the strengths and weaknesses of their mobility system and pinpoint areas for improvement.

2. List the use cases that are part of the problem statement, that the solution should support.

UC1: Mobility Ecosystems Sustainability Assessment
UC2: Public and Private Transportation Management
UC3: Mobility Planning Improvement

UC4: Generate Sustainability Reports
UC5: Transportation Hub Mapping
UC6: Public-Private Partnerships Improvement
UC7: Carbon Tracking and Emission Offsetting
UC8: Low-impact Housing Development

3. What is the value proposition that will differentiate our solution from others?

- Depicting a big picture of the sustainable mobility
- Comprehensive sustainable mobility decomposition considering all sustainability aspects simultaneously

4. Identify other alternative solutions:

PS0-Alternative1 – Vehicles Electrification
PS0-Alternative2 – Public Transportation Promotion
PS0-Alternative3 – Fuel Efficiency Improvement Plan
PS0-Alternative4 – Smart Connected Urban Planning

5. Define system boundary in terms of internal and external actors interacting with the System of Interest (SoI).

A system of interest is composed of a system (including sub-systems), boundary, and environment, which can be defined in addressing any problem. Considering mobility ecosystems as a system including its internal actors, the environment comprises external actors that are not part of the system but have direct and indirect impacts (see Fig. 4). The system's boundary is where the system concludes and the environment starts.

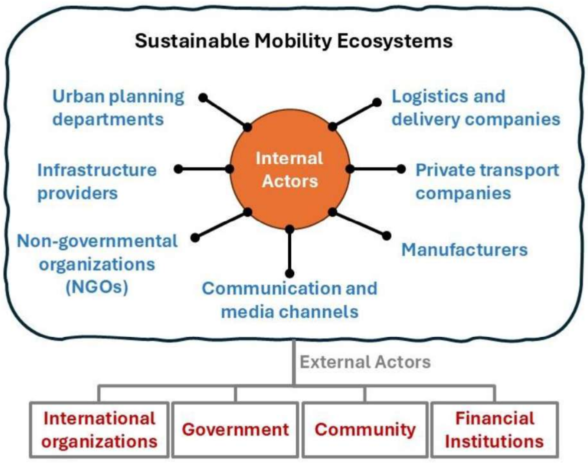

Fig. 4. Sustainable Mobility: External and Internal Stakeholders

4.2. Decomposition

In this section, sustainable mobility decomposition covering all sustainability pillars is proposed. The main level of the FRs-PSs is shown in Fig. 5 in which FR1 is related to emissions, FR2 is about energy consumption, FR3 and FR4 cover the economic side from a circular economy and affordability points of view, and the last two FRs are relevant to the social aspect. The independence between the FRs at this level supports Axiom 1 of the AD theory and helps decrease the level of the system's complexity in the further level of the decomposition, alleviating the FRs interaction. The next levels of decomposition with parents, which resulted from previous level solutions and related children, are presented in Table 2. Since the circular economy concept in the field of sustainable mobility (i.e. PS3 in Table 2) is a wide topic and decomposing it requires more space, it is decomposed to just one level more and its next-level FRs and PSs are not presented in this article due to limitations on the number of pages.

Looking at the big picture of sustainable mobility in Table 2 indicates the wide range of topics that should be considered when any decision wants to be made. This clarifies the need for thinking beyond systems to achieve a targeted sustainability roadmap in the mobility sector. Although today's dedicated sustainability regulations are forcing companies to move toward sustainability, their interconnectedness is crucial in achieving the main sustainability objectives that should not be underestimated. As much as humans are decision-makers in this matter, they will be directly or indirectly affected by the results of their decisions. Different points of view will lead to different paths and solutions, and at the same time, today's intensely competitive environment also forces large and small influential companies to lean more in a direction that improves their situation in this competitive playground to some extent. In the complex network of the mobility sector and its direct interaction with society, the sensitivity of deciding on the right solution for each FR increases and it is necessary to have expert analysis and foresight before any management decision and investing in innovative ideas. Comprehensive sustainability assessment with the online ability to follow the impact of decisions using model-based systems engineering tools makes it possible to better manage the level of impacts and make general decisions as much as possible with the same weighting to all pillars of sustainability.

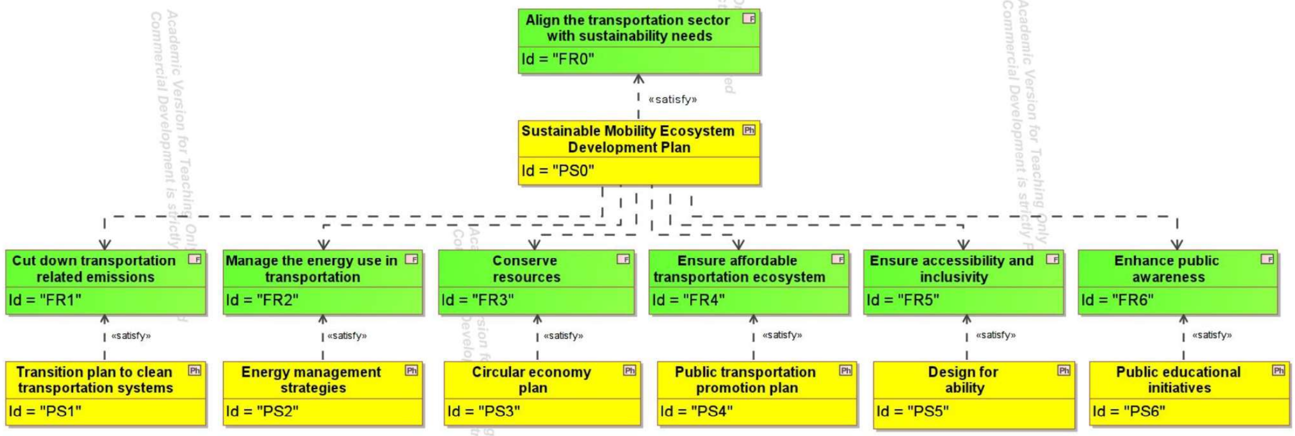

Fig. 5. Sustainable Mobility Decomposition: the first-level FRs-PS

5. Conclusion

This paper presents a holistic approach to decomposing sustainable mobility using axiomatic design theory. By adopting the AD theory and systems engineering approach, the complexity and overlap among the sustainability pillars can be reduced. The decomposition proposed in this study covers the triple bottom line of sustainability - environmental, economic, and social aspects. The decomposition starts with identifying customer needs and deriving high-level functional requirements, followed by finding physical solutions for each requirement. The process is iterative and continues until all requirements and solutions are operational. Results illustrate that a comprehensive sustainable mobility decomposition can scale up the mobility sector transition towards targeted green and sustainable alternatives.

The future directions of the proposed research will center around a quantitative decomposition based on clear and standardized measures, extending it to more detailed leaves for each branch. The reliability and robustness of the achieved set of solutions in the presence of various uncertainty sources should be assessed to ensure the resiliency of the decisions [21]. Different perspectives from relevant stakeholders, including businesses, policymakers, and citizens could be added to enhance the practicality of the decomposition. Moreover, investigations into practical applications that address specific regional needs would confirm and validate the effectiveness of research. Additionally, the ability to trace changes and adapt to new regulations, standards, and policies using model-based systems engineering tools would increase the approach's applicability, enabling it to identify hotspots earlier and make resilient decisions.

Table 2. Sustainable Mobility Detailed Decomposition

FR-ID	FR Title	PS-ID	PS Title
FR0	**Align the Transportation Sector with Sustainability Needs**	**PS0**	**Sustainable Mobility Ecosystem Development Plan**
FR1	**Cut Down Transportation-Related Emissions**	**PS1**	**Transition Plan to Clean Transportation Systems**
FR1.1	**Encourage People**	**PS1.1**	**Policies and Regulations**
FR1.1.1	*Mitigate Transportation Demand*	*PS1.1.1*	*Remote Working Plan*
FR1.1.2	*Create Types of Bonuses*	*PS1.1.2*	*Bank Loan Plan*
FR1.1.3	*Propose Specialized Coverage of Value-Added Benefits*	*PS1.1.3*	*Flexible and Specific Insurance Plan*
FR1.1.4	*Foster Toward Alternative Fuels*	*PS1.1.4*	*Less Tax Plan*
FR1.2	**Enhance Transportation System**	**PS1.2**	**Retrofit Strategy**
FR1.2.1	*Improve the old transportation systems*	*PS1.2.1*	*Advanced Technologies*
FR1.2.2	*Change the Conventional Cars with a Hybrid*	*PS1.2.2*	*Innovative Design Strategy*
FR1.3	**Ensure Availability of Infrastructure**	**PS1.3**	**Green Infrastructure Plan**
FR1.3.1	*Provide Road Accessibility*	*PS1.3.1*	*User-friendly Road Design*
FR1.3.2	*Create Safe Stations*	*PS1.3.2*	*Safety Standards*
FR1.3.3	*Provide Charging Stations*	*PS1.3.3*	*Renewable Charging Plan*
FR2	**Manage the Energy Use in Transportation**	**PS2**	**Energy Management Strategies**
FR2.1	**Mitigate Energy Consumption**	**PS2.1**	**Energy Auditing Systems**
FR2.1.1	*Identify Energy Hotspots*	*PS2.1.1*	*Data Collection and Sensors*
FR2.1.2	*Enhance Energy Efficiency*	*PS2.1.2*	*Design for Efficiency*
FR2.1.3	*Mitigate Cost*	*PS2.1.3*	*Energy Management Platforms*
FR2.2	**Manage Trips Journey**	**PS2.2**	**Route Optimization Strategies**
FR2.2.1	*Mitigate Traffic Congestion*	*PS2.2.1*	*AI Driving Logistics*
FR2.2.2	*Create Alternative Route Infrastructure Options*	*PS2.2.2*	*Route Construction Optimization*
FR2.2.3	*Ensure Alternative Energy Supply*	*PS2.2.3*	*Online Charging Availability Tracking*
FR3	**Conserve Resources**	**PS3**	**Circular Economy Plan**
FR3.1	Prioritize Circular Products	PS3.1	Circular Procurement Policies
FR3.2	Mitigate Waste	PS3.2	Zero-Waste Plan
FR3.3	Prolong Product Life Cycles	PS3.3	Predictive Maintenance
FR3.4	Promote Sustainable Production	PS3.4	Design for Eco-Friendly
FR3.5	Create a Resilience Business Strategy	PS3.5	Robust Business Plan
FR4	**Ensure Affordable Transportation Ecosystem**	**PS4**	**Public Transportation Promotion Plan**
FR4.1	**Alleviate Transportation Costs**	**PS4.1**	**Financial Support Plan**
FR4.1.1	*Identify Alternative Suppliers*	*PS4.1.1*	*Supplier Databases and Online Marketplaces*
FR4.1.2	*Create Collaborative Business*	*PS4.1.2*	*Public-Private Partnerships (PPPs)*
FR4.1.3	*Improve Economic Mobility*	*PS4.1.3*	*Efficient Business Models*
FR4.2	**Alleviate Operational Costs**	**PS4.2**	**Digital Transformation and Data-Driven Planning**
FR4.2.1	*Identify Cost Reduction Hotspots*	*PS4.2.1*	*Data-Driven Decision-Making*
FR4.2.2	*Create Targeted Marketing and Personalization*	*PS4.2.2*	*Customer-Centric Digital Transformation*
FR4.2.3	*Forecast Demand*	*PS4.2.3*	*Supply Chain Management Plan*
FR4.2.4	*Lighten Manual Labor*	*PS4.2.4*	*Processes Automation*
FR4.3	**Encourage Sustainable Urban Development**	**PS4.3**	**Smart Mobility Hubs**
FR4.3.1	*Create Low-Impact Zones*	*PS4.3.1*	*Zoning Policies Supporting Sustainability*
FR4.3.2	*Enhance Data-Driven Urban Planning*	*PS4.3.2*	*IoT Sensors and Data-Sharing Agreements with Transportation Providers*
FR4.3.3	*Improve Urban Aesthetics and Quality of Life*	*PS4.3.3*	*Design Eco-Friendly Hubs*
FR4.4	**Foster Social and Behavioural Change**	**PS4.4**	**Integrated Multi-Modal Mobility Platforms**
FR4.4.1	*Clarify the Difference between Mobility Options*	*PS4.4.1*	*Holistic Comparison Platform APPs*
FR4.4.2	*Enhance Connectivity and Convenience*	*PS4.4.2*	*Integrated Real-time Digital Apps*
FR4.5	Create Flexible Working Time	PS4.5	Remote Work Options
FR4.5.1	*Create Flexible Policies*	*PS4.5.1*	*Remote Work Standards*

FR4.5.2	*Manage Long-Distance Commuting*	*PS4.5.2*	*Adaptive Transit Planning*
FR4.5.3	*Promote Shared Workspaces IN Residential Areas*	*PS4.5.3*	*Remote Work Hubs or Coworking Spaces*
FR5	**Ensure Accessibility and Inclusivity**	**PS5**	**Design for Ability**
FR5.1	**Define Policies and Regulations for Accessibility**	**PS5.1**	**Accessibility Guidelines and Standards**
FR5.1.1	*Promote Accessible and Sustainable Urbanization*	*PS5.1.1*	*Sustainable Cities and Communities (SDG 11)*
FR5.1.2	*Adopt Inclusive Policies Across Public Spaces and Transportation Networks*	*PS5.1.2*	*Reduced Inequalities (SDG 10)*
FR5.1.3	*Promote the Full Participation of People with Disabilities*	*PS5.1.3*	*European Accessibility Act (EAA)*
FR5.1.4	*Define Guidelines for Making Web/Application Content Accessible to People with Disabilities*	*PS5.1.4*	*Web Content Accessibility Guidelines (WCAG)*
FR5.2	**Ensure Transit Infrastructure is Fully Accessible to All People**	**PS5.2**	**Universal Design Principles for Design Infrastructure**
FR5.2.1	*Improve Physical Accessibility*	*PS5.2.1*	*Accessible Entrances and Ramps*
FR5.2.2	*Ensure Wayfinding and Navigation*	*PS5.2.2*	*Tactile Pathways and Braille Signage*
FR5.2.3	*Facilitate Transit*	*PS5.2.3*	*Flexible and adaptable transit services*
FR5.2.4	*Accommodate Individuals with Sensory Sensitivities, Autism, and Cognitive Disabilities*	*PS5.2.4*	*Sensory and Cognitive Accessibility*
FR5.3	**Make Information Accessible to a Diverse Range of Abilities**	**PS5.3**	**Inclusive Digital Tools and Assistance**
FR5.3.1	*Ensure Transit Staff are Trained to Assist Passengers*	*PS5.3.1*	*Human-Centered Training programs*
FR5.3.2	*Enhance Inclusivity in Applications*	*PS5.3.2*	*Multi-Language and Multi-Sensory Programs*
FR5.3.3	*Simplify Payment Processes*	*PS5.3.3*	*User-Friendly Ticketing and Payment Systems*
FR6	**Enhance Public Awareness**	**PS6**	**Public Educational Initiatives**
FR6.1	**Educate People about Sustainable Transportation**	**PS6.1**	**Public Campaigns**
FR6.1.1	*Promote Eco-Friendly Behavior Practices*	*PS6.1.1*	*Public Events and Workshops*
FR6.1.2	*Shape Future Habits*	*PS6.1.2*	*Educational Programs for Schools and Universities*
FR6.2	**Disseminate Sustainable Transportation Solutions**	**PS6.2**	**Digital Outreach: Internet and TV advertising, etc.**
FR6.2.1	*Inform Sustainability Improvement due to New Technologies*	*PS6.2.1*	*Advertising Billboards*
FR6.2.2	*Foster Low-Impact Living*	*PS6.2.2*	*Influencer Partnerships Through Social Media*

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