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Passenger Dimensions in Sustainable Multimodal Mobility Services

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Abstract: Seamless integration of air segment in the overall multimodal mobility chain is a key challenge to provide more efficient and sustainable transport services. Technology advances offer a unique opportunity to build a new generation of transport services able to match the evolving expectations and needs of society as a whole. In this context, the passenger-centric approach represents a method to inform the design of future mobility services, supporting quality of life, security and services to citizens traveling across Europe. Relying on the concepts of inclusive design, context of use and task analysis, in this article, we present a comprehensive methodological framework for the analysis of passenger characteristics to elicit features and requirements for future multimodal mobility services, including air leg, that are relevant from the perspective of passengers. The proposed methodology was applied to a series of specific use cases envisaged for three time horizons, 2025, 2035 and 2050, in the context of a European research project. Then, passenger-focused key performance indicators and related metrics were derived to be included in a validation step, with the aim of assessing the extent of benefit for passengers that can be achieved in the forecasted scenarios. The results of the study demonstrate the relevance of human variability in the design of public services, as well as the feasibility of personalized performance assessment of mobility services.

Keywords: passenger-centric mobility; door-to-door journey; multimodal air transport; social sustainability; inclusive design

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1. Introduction

In the report "Our Common Future" published in 1987 by the World Commission on Environment and Development of the United Nations Environment Programme, sustainable development is defined as "development that ensures that the needs of this generation are met without compromising the ability of future generations to meet their own needs" [1]. According to this definition, the concept of sustainability is linked economic, social and environmental pillars. The social dimension is crucial for the sustainability of future transport [2] and has been one of the key aspects of the X-TEAM D2D (Extended ATM for Door-to-Door travel) project. X-TEAM D2D is a European research project in the context of seamless door-to-door mobility in urban and suburban, as well as regional, environments, including air travel. The concept of door-to-door multimodal journeys refers to the use of various modes of transport (air, rail, bus, road or maritime) by travellers to complete a single journey perceived as an all-in-one experience [3].

The X-TEAM D2D project has explored the scenario of the connection of a large metropolis with the surrounding area, up to the national level. Specific journey paths (use cases) are defined according to the transport and passenger service scenarios expected to be available in the coming decades, according to baseline (2025), intermediate (2035) and final

(2050) time horizons. The focus of this study is the concept of passenger-centric multimodal door-to-door journeys and its application in possible future travel paths as an approach to the social sustainability of future transport systems and services.

Multimodal infrastructure refers to the network of airports, seaports, roads, railways, public transport systems, and human-powered mobility options that are integrated and coordinated to form a transport system to move people or freight from one point to another [4,5].

A seamless multimodal experience might include, for instance, travelling on two or more forms of transport with a single ticket (e.g., rail and air). In general, the more effectively these modes support and interconnect with one another and the more seamless the intermodal connections (the movement of passengers or freight between modes of transport), the less congestion and the less stress on any individual component [6–8]. As air traffic is concentrated at hub airports, constraints arise, such as long walking distances and delays. Passengers must wait at hub airports for connecting flights, often for longer than necessary, as flight co-ordination is less efficient, and minimum connection time is long, especially at largest hubs. Furthermore, modern passengers request fast, efficient and, in many cases, environmentally friendly transport connections; the era of transport rivalry must become a thing of the past, and if mobility is to be safeguarded in the long term, the various modes of transport will have to work together [9].

What passengers demand depends on their specific needs. Meeting these needs will become an increasingly competitive endeavour [10]. Online information and electronic booking and payment systems integrating all means of transport should facilitate multimodal travel. Regardless of the sophistication of a system, it cannot achieve success if does not serve passengers. Acquiring knowledge of passenger feedback is the first step towards well-organized and satisfactory intermodal connection and interchange nodes with efficient baggage-handling logistics and integrated ticketing, which could serve as a foundation for socially sustainable transport multimodality [11]. Passengers demand that companies along the door-to-door (D2D) air travel value chain, in terms of overall experience quality [12], to adopt measures aimed at the overall personalization and digitalization of journeys, as well as establish partnerships with other providers and tech companies. Table 1 shows the key user expectations [13] and some associated key aspects of the travel experience.

Barriers related to the needs and expectations of future multimodal passengers are mainly associated possible inequalities and gaps that might arise or increase in future scenarios as a consequence of socioeconomic trends, such as gentrification or polarization of social classes [14–16]. In principle, any new product or service resulting from technological or business innovation aims to match user needs and satisfy (and possibly exceed) user expectations. In this context, eliciting passenger characteristics and needs and identifying associated meaningful key performance indicators (KPIs) are key steps with respect to the understanding of current barriers, the ideation of future mobility services, the conceptualization of new services that overcome identified barriers, the assessment of future services, the understanding of changes in environmental sustainability and user experience of newly designed services [3].

Table 1. Aspects of passenger expectations with respect to mobility services.

Passenger Expectation	Key Aspects
Convenience	• Clear indication of costs • Services offered for the selected transport path, taking into account extra comfort demands
Ease	• Accessibility of information and data, facilitating electronic data exchange across borders and timely updating of information • Simplicity in both booking and costs • Clearly identification of connections • Possibility of integrated tickets • Simplicity in understanding how to purchase tickets
Frequent and fast	• Integrated information about the whole journey, awareness about real-time data, e.g., information about strikes, disruptions and delays
Exhaustiveness	• Privacy and liability issues • High level of protection (rights, information, services, etc.) with respect to multimodal products compared to mode-specific services (single contracts versus separate contracts for each mode) • Accessibility of information regarding temporary or permanent passenger impairments (specific needs) • Luggage security (both in terms of lost and stolen luggage and) • Accessibility of vehicles, streets and stations
Reliability	• Care and assistance in the event of travel disruption • Rerouting so that passengers can arrive at their destination as soon as possible • Reimbursement and/or compensation when relevant

2. Materials and Methods

2.1. Theoretical Framework

To elicit, harmonise and appropriately consider the variety of passenger needs resulting from demographic change and new technologies and transport services available in the 2025, 2035 and 2050 time horizons as well as to accommodate the increasing awareness of multimodal passenger rights and expected service quality, a series of applicable concepts and approaches were surveyed. These concepts were selected to ensure:

- Consideration of EU principles of equality and human rights with respect to access to public services [17];
- Creation of a set of passenger-related data to be combined with air traffic management (ATM) and other transport data for an affordable, accessible and seamless multimodal travel experience; and
- Meaningful profiling of multimodal and air transport passengers.

In this view, the key reference concept is inclusive design. inclusive design related to optimization of the use of a system or a service for a user with specific needs (usually, this user is an extreme user, meaning that they have particular needs). By focusing on extreme users, many other users with similar or lesser needs will benefit from the intended system or service so that a wider diversity of people can make easy use of it [18]. Therefore, inclusive design results in a system and/or a service that is accessible to and usable by as many people as reasonably possible without the need for adaptation or specialised design for specific user categories [19]. The inclusive design framework includes the concept of transgenerational design, which is specifically aimed at making systems and services compatible with physical and sensory impairments associated with human aging and that limit major activities of daily living [20]. The inclusive design approach considers the full range of human diversity with respect to ability, language, culture, gender, age and other forms of human difference [21], supporting the elicitation of a wide range of human characteristics to cover the permanent and temporary needs of all passengers [22,23].

Table 2 below provides some examples of how travel services can accommodate the needs of many passengers by addressing the specific necessities of a traveller with special needs, according to the inclusive design approach.

Table 2. Examples of passenger typology benefiting from inclusive solutions.

Specific Disability	Technical/Organizational Solution	Other Passengers Benefiting from the Specific Solution
Deafness	Subtitled video instructions on aircraft safety procedures	Non-English-speaking passengers Elderly passengers with reduced auditory ability Passenger listening audio on personal devices
Arm/hand impairment	Luggage pickup at departure door and delivery at arrival door	Parent holding a baby

It is also clear that the ability to access and a door-to-door multimodal journey depends not only on personal characteristics but, sometimes to a greater extent, on the overall context in which passengers act and behave during their journey. According to this approach, eliciting passenger needs also requires that context and situations are properly considered; to support these aspects, we refer to the context of use concept and the task analysis technique. The concept of context of use was first introduced in the context of digital interface usability [22] and is extensively used to represent the combination of the goals, characteristics, tasks, objects and environment characterizing the situation in which users interact with a system or service [24,25]. The context of use perspective also considers the variety of real-world contexts and the three time horizon scenarios with respect to which mode of travel passengers must be enabled to access in order to appropriately address their needs. The third component of this approach to user needs analysis (and according to the use case definition) is the adoption of the task analysis technique to identify the main actions during the multimodal journey that the passengers must be able to carry out in the most efficient way. Task analysis is a well-established human factors technique [26] that has been used in the X-TEAM D2D project to break down the high-level "multimodal journey" task into a sequence of smaller and more contextualized tasks, allowing for identification of all the details of the context of use, from the environment (i.e., train station, moving bus, airport moving sidewalk, etc.) to the goal (changing a reservation, dropping off luggage, etc.), the passenger (age, impairments, scope of travel, language, etc.) and objects/equipment (smartphone, credit card, suitcase, stroller, etc.).

2.2. Passenger Characterization

Passengers deal with a number of variables when planning a door-to-door multimodal travel, as well as when rearranging travel plans in the case of disruption. The relevance and priority of each variable can differ according to the specific passenger profile. On the other hand, the passenger profile results from the combination of permanent personal characteristics (such as age, gender and permanent physical abilities) and contextual or temporary characteristics (such as the purpose of travel, the number of people travelling with the target passenger, knowledge of the sites and language of the destination, the availability of enabled credit cards, etc.). Each characteristic of a passenger profile contributes specific needs or expectations to be matched, requiring that mobility services as a whole provide specific tangible or intangible features in terms of functions supporting passenger tasks and goals. From the perspective of passenger experience, a set of high-level travel variables can be identified as relevant in terms of shaping the optimal travel pattern; each variable can be managed by the passengers through the functions or services available during the planning or execution of their D2D journey [27]. Each feature can satisfy a basic need of travellers (as is the case of slider for people with walking impairments), representing a mandatory function or service for passengers to succeed in their door-to-door journey or. From the perspective of inclusive design, this can be an additional element providing a more satisfying travel experience to passengers with varied profiles, as in the case of slider for passengers with large and heavy luggage [28]. Relying on the above conceptual references, we conducted a review of the needs of passengers according to their characteristics and journeys, taking into consideration the following multimodal travel variables:

- Travel time;
- Connections and number of modes;
- Accessibility and comfort of each travel segment;
- Cost and level and services provided;
- Personal security;
- Luggage security;
- Environmental impact;
- Ticketing;
- Early and real-time information provision;

Furthermore, we considered the following possible personal characteristics (i.e., human variables) of passenger:

- Visual impairments;
- Auditory impairments;
- Walking impairments;
- Women travelling alone;
- Families/groups with children;
- Business travellers;
- Leisure travellers;
- People travelling for personal reasons other than leisure;
- Non-native language speakers;
- Low digital trust/personal device accessibility; and
- Enabled credit card holders (or no cash availability).

The figures below provide an overview of the variables relevant to passengers; for each of these travel variables, we identified a series of transport service features enabling the management, or at least the partial control, by passengers (Figures 1 and 2). In a further step, we defined the relevance (crucial or optional) of each feature for the achievement of travel tasks according to specific passenger characteristics. Table 3 provides examples of key travel variables and the corresponding features of mobility services matching the identified needs.

Table 3. Examples of travel variables and needs according to passenger profiles with respect to the multimodal travel variable "connections and number of modes".

Feature Enabling the Management of the Variable	Mandatory for Passengers Who Are/Who Have	Appreciated by Passengers Who Are/Who Have
Making travel arrangements for a number of connections	Visual impairments Walking impairments Families/groups with children Business travellers Travelling for personal reasons other than leisure	Auditory impairments Leisure travellers Non-native language speakers
Selecting travel options according to the type of mode (i.e., no road journey, car, bike, kick scooter sharing services, etc.)	Visual impairments Auditory impairments Walking impairments	Women travelling alone Families/groups with children Leisure travellers Non-native language speakers

Table 3. *Cont.*

Feature Enabling the Management of the Variable	Mandatory for Passengers Who Are/Who Have	Appreciated by Passengers Who Are/Who Have
Arranging travel options according to length and walking time on pedestrian paths	Visual impairments Walking impairments Women travelling alone Business travellers Travelling for personal reasons other than leisure	Families/groups with children Leisure travellers
Arranging travel options according to the length of outside walks	Visual impairments Walking impairments Women travelling alone Business travellers Travelling for personal reasons other than leisure	Families/groups with children Leisure travellers
Arranging travel options according to the number of floor changes	Visual impairments Walking impairments	Families/groups with children
Arranging travel options according to the availability and position of elevators	Visual impairments Walking impairments	Families/groups with children
Arranging travel options according inclusive wayfinding infrastructure (audio and tactile for visually impaired passengers, written/graphics for auditory impaired passengers, etc.)	Visual impairments Auditory impairments Walking impairments	Women travelling alone Families/groups with children
Provision of detailed directions in the case of multiple entrance/exit points	Visual impairments Walking impairments Women travelling alone Business travellers Travelling for personal reasons other than leisure Non-native language speakers	Auditory impairments Families/groups with children Leisure travellers
Preview of waiting/entrance/exit points and routes (i.e., google street view), audio description	Walking impairments	Auditory impairments Women travelling alone Families/groups with children Business travellers Leisure travellers Travelling for personal reasons other than leisure Non-native language speakers

Passenger profiling is intended to provide the key information about passengers' expected behaviour (i.e., is voluntary or obliged choices among alternatives) that could determine the sequence of actions constituting the door-to-door travel to be executed by a given passenger in a specific time horizon. Passenger profiles contribute to the design of the workflow describing the steps of multimodal journeys, in addition to providing indicating the most plausible alternative workflow in the case of travel disturbances, for example, requesting passengers to switch to an alternative transport mode or timetable.

The X-TEAM D2D project defined 18 use cases with corresponding workflows based on two types of travellers with distinctive characteristics and occurrences in travel: business travellers (BT) and travellers visiting friends and relatives traveller (VFT); the latter comprises a group of two adults (one of whom is a senior) and a minor child with baggage visiting friends and relatives for a long weekend on the occasion of a family event (e.g., wedding). For each traveller, a use case scenario including all steps, from planning to post-travel management, were considered with respect to each of the time horizons (2025, 2035 and 2050). Each of these time horizons is assumed to be associated with different technological states and different levels of integration of transportation systems. In addition, disruptions and delays in the travel process were considered so that for each time horizon and passenger type, the journey workflow was developed according to nominal conditions, i.e., a disruption communicated before the start of the journey and with a disruption occurring during the journey. Disruptions information was assumed to be available to the traveller at two time points: information available at least five hours before departure and information becoming available during the journey. Disruptions could be the result of technical failures or error made by bus/train drivers or infrastructure operators (internal reasons), accidents concerning interactions between modes of transport (e.g., a train hitting a pedestrian at a rail crossing), adverse weather conditions, blackouts or terrorist attacks. The probability of an internal reason for a delay and accidents is comparable and much more likely than adverse weather conditions, blackouts and terrorist attacks. The time necessary for a full recovery after a disruption depends on the circumstances.

Figure 1. Features of transport services relevant to passengers with respect to travel time, connections, cost, level of services provided in advance and real-time information provision.

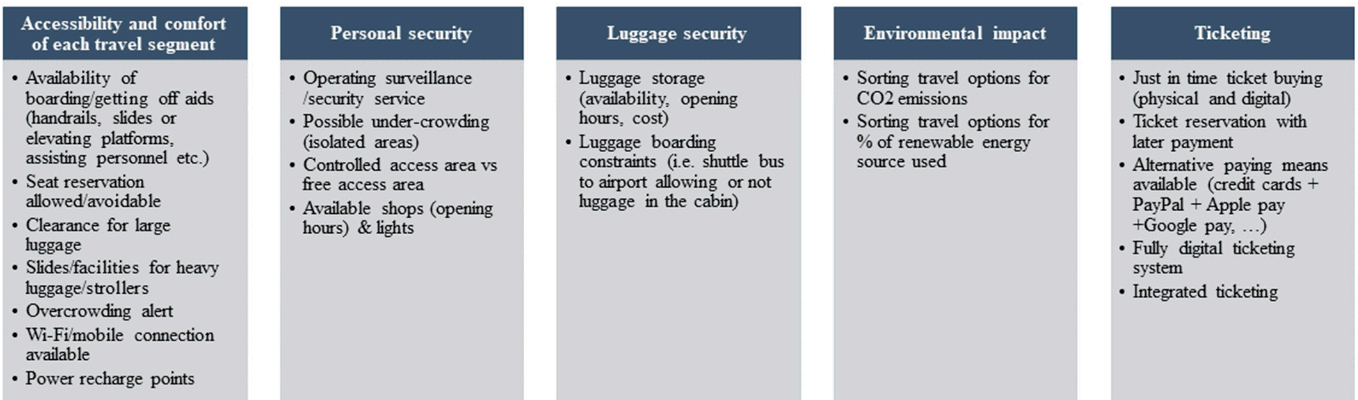

Figure 2. Features of transport services relevant to passengers with respect to accessibility and comfort of each travel segment, personal security, luggage security, environmental impact and ticketing systems.

In order to define the most plausible workflows in the 18 investigated use cases, the key characteristics and subsequently expected behaviour for each passenger type was defined, as depicted in Tables 4–6.

Table 4. Key passenger profile points for the 2025 scenario.

Passenger Type	Characteristics	Expected Behaviour
Business Traveller (BT)	Travels alone (mainly) Has time constraints/target times Has budget limits, although these generally depend on the business goal of the trip and the role of the traveller in the company Short stay and cabin luggage Might need to work during the travel time Frequent flyer/traveller Adult (18–70 years), generally in good health condition (no physical or sensorial impairments) May or may not be allowed to arrange/rearrange travel plans, depending on internal procedures	Can easily and quickly adapt to travel plan changes Habitually uses on-demand/personal transport means (e.g., taxi or car rental) Spends little time planning the trip; the trip is not arranged well in advance Chooses the fastest multimodal journey combination Chooses the most comfortable mode of travel (i.e., with reservation) May rely on travel assistance services (e.g., secretary services or traveller club services)
Other traveller (OT)	Travels in small or large groups (mainly) With the exception of specific travel reasons (a ceremony, family issues, etc.), has relatively low time constraints Has budget limits May travel with large/heavy luggage or other items, such as sport equipment, walking aids, stroller, etc. May require assistance (e.g., children, elderly and disabled people) May or may not be a frequent flyer/traveller Can of any age, from baby/children to very elderly Can have any kind of physical or sensorial impairment Is free to arrange/rearrange travel according to their preferences May be constrained in terms of payment method (i.e., unavailable credit card, unavailable cash, etc.) May encounter language/communication barriers	Carefully plans travel in advance (mostly) Could be unable or unwilling to use some modes of transport (i.e., due to accessibility barriers, costs, etc.) Could use shared modes of transport with personal accounts (car/bike sharing, Uber, etc.) May prefer cheapest travel options (disregarding comfort or travel time)

Table 5. Key passenger profile points for the 2035 scenario.

Passenger Type	Characteristics	Expected Behaviour
Business Traveller (BT)	Travels alone (mainly) Expects a very high standard of comfort Expects very short travel time Has few budget limits Travels for short stay, with small luggage Is a frequent flyer/traveller Is an adult (18–70 years), generally in good health condition (minor physical or sensorial impairments) Relies on dedicated business services for travel arrangement (no reservation or payment method constraints) Has full flexibility for change of travel plans	Spends little time in planning the trip; the trip is not arranged well in advance Uses personalized/on-demand travel services, even if at higher cost Chooses the fastest multimodal journey combination Chooses the most comfortable mode of travel (i.e., with reservation), with priority for the easiest connection Might choose mode of travel to show status, according to their position in the organization (will consider some modes of travel more representative than others, i.e., for urban air mobility) Might choose mode of travel to reinforce sustainability policies of his/her company
Other traveller (OT)	Travels in small or large groups (mainly) With the exception of specific travel reasons (a ceremony, family issues, etc.), has relatively low time constraints May travel with large/heavy luggage or other items, such as sport equipment, walking aids, stroller, etc. Has budget limits Does not have constraints with respect to reservation or payment methods May require assistance (e.g., children, elderly or disabled people) Can be of any age, from baby/children to very elderly Can have any kind of physical or sensorial impairment Is free to arrange/rearrange travel according to their preferences Is sensitive to the environmental footprint of his/her journey Has no communication limitations, thanks to technology support	Plans travel carefully and in advance (mostly) Could be unable or unwilling to use some modes of transport (i.e., due to accessibility barriers, costs, etc.) Could be willing to pay environmental footprint compensation costs Could use shared modes of transport with personal accounts (car/bike sharing, Uber, etc.)

Table 6. Key passenger profile points for the 2050 scenario.

Passenger Type	Characteristics	Expected Behaviour
Business Traveller (BT)	Travels alone (mainly) Expects very high standard of comfort Expect very short travel time Has few budget limits Might travel for long stays (as short travel for face-to-face meetings will dramatically reduce) with large/heavy luggage Is a frequent flyer/traveller Is an adult (18–75 years) with possible physical or sensorial impairments Relies on dedicated business services for travel arrangement (no reservation or payment method constraints) Has full flexibility for travel plans changes Must comply with environmental performance targets set by his/her company	Uses personalized/on-demand travel services Can easily and quickly adapt to changes in travel plans Chooses the fastest multimodal journey combination Chooses the most comfortable mode of travel /i.e., with reservation), with priority for the easiest connection If needed, will bear extra costs to pay carbon compensation or any environmental compensation amount to comply with sustainability targets of their company Might rely on travel assistance services (e.g., secretary services or traveller club services)
Other traveller (OT)	Travels in small or large groups (mainly) With the exception of specific travel reasons (a ceremony, family issues, etc.), has relatively low time constraints Has only personal items/small luggage, as luggage will be picked up and delivered door to door (except for walking aids/strollers) Has budget limits Has no constraints for reservation or payment methods Frequently travels with short stays/medium distance Might need assistance (children, elderly and disabled people) Can be of any age, from baby/children to very elderly Can have any kind of physical or sensorial impairment Is free to arrange/rearrange travel according to their preferences Is sensitive to the environmental footprint of his/her journey Has no communication limitations (due to good education and/or technology support)	The trip could be arranged with little notice Chooses the lowest environmental footprint travel option within the budget limits Uses luggage transfer services for "hands-free" travel Could use shared modes of transport with personal accounts (car/bike sharing, Uber, etc.) Will use any mode of transport (as any mode will be fully accessible)

2.3. Passenger-Centred Requirements for Multimodal D2D Journey

When planning and undertaking a trip, passengers have different needs and priorities to fulfil. These needs and proprieties are presumed to affect the tasks and decisions, as well as expectations about the quality of the transport services, and can be assigned to three stages of a journey, roughly in conformity with following three steps: pre-trip, wayside and on-board [29]; in some cases, a post-trip step is included. To execute the door-to-door journey, passengers interact with a series of information, as well as tangible and intangible infrastructure, which comprise the mobility service as a whole. This occurs in one or more travel steps, from planning to completion; as consequence, passenger-centred requirements for multimodal D2D journeys can be elicited with reference to both the journey steps and the components of the mobility service. Within this framework, the service design perspective supports [30] the passenger-centric approach sought by the X-TEAM D2D project, with the definition of requirements aimed at fitting the variety of characteristics and needs of any type of passenger. In order to fully match this scope, the definition of passenger-centred requirements of multimodal transport services was driven by the following principles:

- Inclusion of physical, social and cognitive differences to ensure equal access to D2D mobility services;
- Autonomous and independent living to safeguard human dignity and personal freedom with respect to the use of D2D mobility services; and
- Transparency of the mobility services provided to protect passenger rights and awareness.
- The Tables 7–9 below provide a list of high-level requirements of multimodal door-to-door journeys elicited according the abovementioned methodology. The requirements are defined with reference to the mobility service components, namely:

- Requirements of applications and devices enabling the use of the mobility service (organizational part of the service);
- Requirements of wayside spaces (hubs, nodes and built infrastructure); and
- Vehicle requirements.

Table 7. Requirements of applications and devices enabling the use of the mobility services.

Requirement	Relevant Journey Step			
	Pre-Trip	Wayside	On-Board	Post-Trip
Access to mobility services should rely on the lowest technological standards (to avoid any digital divide)	○	○	○	○
Personal data required to access and manage travel services should be minimized	○	○	○	○
Multiple alternative payment/refund methods should be allowed, including more than one currency; cash payments should always be possible [31]	○	○	○	○
Search tasks should allow results to be sorted by multiple criteria	○	○	○	
Information should be provided with symbols and graphics supporting the text	○	○	○	○
Information should be accessible on personalized auxiliary tools (i.e., text-to-speech systems), and information should be accessible by more than one medium (i.e., reading as an alternative to listening)		○	○	○
Information should be provided with relevance to the context (i.e., appropriate time and place for the requested action)		○	○	○
When applicable, information should be offered with multiple level of detail	○	○	○	
Information constituting the contractual basis of travel services should be accessible and retrievable at any time	○	○	○	○
Integrated ticketing of all travel legs should be available				○
Seat reservation should be available for travel legs longer than 30 min	○	○		
Automatic changes of journey plans to manage travel disruptions should be subject to confirmation; further personalization of proposed change should be allowed without extra cost (for equivalent services); information on extra costs should be clearly provided and subject to confirmation		○	○	
Information on available primary and secondary services should be available from the ticketing/booking stage	○			
If autonomous boarding and disembarking is not possible, assistance should be available without prior request or booking		○	○	

Table 8. Requirements of hubs, nodes and built infrastructure.

Requirement	Relevant Journey Step		
	Pre-Trip	**Wayside**	**On-Board**
Access, egress and turning points should be easily to independently locate according to the physical, cognitive or sensorial abilities of passengers; if not fully accessible, assistance service should be available without pre-booking.	⚬	⚬	
Long walking distances should be supported by moving aids (i.e., moving walkways, shuttles, etc.)		⚬	
Escalators, elevators and means to overcome differences in floor height should be available and included in the main walking path	⚬	⚬	
Walking times should be indicated, with multiple figures referring to a variety of passenger characteristics	⚬	⚬	
Outside walking paths should protect passengers from weather conditions (e.g., rain, cold, heat and wind)		⚬	
Racks and stands for personal mobility devices should be directly connected to access/egress points	⚬	⚬	
Racks, stands and layaway of shared mobility devices should be directly connected to access/egress points	⚬	⚬	
Healthy and comfortable indoor environmental conditions should be assured (i.e., internal air quality (IAQ), lighting and noise)		⚬	
Resting/meeting points should be available along long walking paths		⚬	
Primary services (i.e., electrical outlets, telecommunication network coverage, toilets, etc.) should be available in all areas of hub buildings		⚬	
If secondary services (i.e., passenger assistance, security points, ATMs, pharmacies, etc.) are not available in hub buildings, information on the nearest service location or access should be provided		⚬	

Multimodal travel variables, passenger characteristics and requirements for passenger-centred multimodal door-to-door journeys were reviewed in consultation with the Passengers Advisory Group of the X-TEAM D2D project, consisting of representatives of POLIS Cities and Regions for Transport Innovation (to verify the mobility the integration perspective), the EPF European Passengers Federation (to verify the evolution over time and access to services perspective), C.E.R.P.A. Italia Onlus—European Center for Research and Promotion of Accessibility (to verify the inclusion perspective) and Legambiente Italia (to verify behavioural changes and attitudes towards environmental sustainability).

Table 9. Vehicles requirements.

Requirement	Relevant Journey Step		
	Pre-Trip	Wayside	On-Board
Autonomous/independent boarding and disembarking should be ensured; if not fully accessible, assistance service should be available without pre-booking.		⚬	⚬
Primary services (i.e., Wi-Fi and toilets) should be available in the case of travel legs longer than 30 min			⚬
Seat layout should allow for passenger privacy			⚬
Seats layout and clearance should allow for accommodation of all personal belongings			⚬
Healthy and comfortable indoor environmental conditions should be assured (i.e., internal air quality (IAQ), lighting and noise)			⚬
Personalised levels of environmental conditions should be possible in the case of travel legs longer than 1 h (i.e., internal air quality (IAQ), lighting and noise)			⚬

3. Results

3.1. Application of Passenger-Centric Approach in the X-TEAM D2D Project

The X-TEAM D2D project included validation activities with the aim of evaluating the impact of envisaged future multimodal mobility services on the passenger journey; such validation was implemented in a general-purpose discrete event simulation software. Three groups of elements were implemented in the model. The first group, dynamic entities, represents passengers and vehicles transporting passengers from their point of origin to the airport. The second group, static elements, represents transport stations used by passengers to board/disembark transport vehicles. These stations serve as the entry, transfer and exit points, with a fixed location for the interconnected multimodal transport networks, and are modelled as capacitated servers. The third group is the set of nodes and edges connected into a network that vehicles and passengers use to move through the space between transport stations. Within the framework, the arrival of passengers and most modes of transportation are generated stochastically based on the project assumptions. Some modes of transport (such as buses and trains) are generated on a schedule, as observed in real-life operations.

In order to assess the efficiency and quality of the system elements, several key performance indicators (KPIs) were defined for analysis and comparison of different time horizons and different multimodal network setups. By nature, the aim of a system of performance indicators is to evaluate the success of an organization or an activity with respect to a desired output in a given context [32]. With respect to D2D multimodal journey passengers, key performances indicators should represent the relevance (key) of one or more specific aspects of the D2D mobility service to a specific type of passenger with respect to his/her expectations and needs (Performance) that can be quantitatively measured (indicator). In addition, within the X-TEAM D2D framework, KPIs should be carefully selected to either be applicable at the abstraction level set for the simulation or to provide useful information [33]. This is particularly relevant for the passenger-centric and stepwise approach of the X-TEAM D2D project because it is acknowledged that performance measurement and monitoring significantly impact the development, implementation and management of existing transport plans and programmes, largely contributing to the identification and assessment of successful alternative scenarios. Furthermore, consideration of specific passenger-related KPIs paves the way for the comparison, from the passengers' point of view, of different projects and programmes in future scenarios and to evaluate the performance of the same project and system at different time points [34]. When defining passenger-related KPIs, the following aspects should be taken into account [34]:

- Satisfaction of the transport service user, in addition to the concerns of the system operator or owner;
- Societal concerns, such as traffic efficiency, traffic safety, environmental conservation and social inclusion;
- Available resources and tools for measurements; this means that performance should be measurable with available tools and resources, costs should be reasonable with respect to budget, accuracy levels should be comparable with respect to requirements and data should be retrievable through field measurement;
- Possibility to compare future alternative scenarios and to use existing forecasting tools to define such scenarios;
- Understandability by policy makers, professionals and the general public;
- Direct measures of the issue of concern or at least maximum relevance or meaningfulness;
- The combination of modes, legs and steps of the multimodal journey; and
- Performance measures should allow for control and improvement of the measured characteristics, i.e., they should provide decision makers with relevant information for their decision-making processes.

3.2. Passenger-Focused KPIs and Metrics

Combining the passenger-centred perspective and the passenger-centred requirements defined so far, it is possible to derive passenger-focused KPIs, which should address the performance areas summarized in Table 10 [33,35].

Table 10. Relevance of KPIs according to passenger profiles.

KPI	Relevance Per Passenger Profile	Direction	Data Availability
Total travel time	BT ○○○ VFRT ○	Less time is preferred	Usually available in standardized form
Waiting time at interconnections	BT ○○○ VFRT ○○	Less time is preferred	Usually available in standardized form
Frequency (probability) of delays resulting from breakdowns/maintenance, etc.	BT ○○○ VFRT ○○	Lower probability is preferred	Possibly available but not standardized
Accessibility of wayside infrastructure	BT ○○ VFRT ○○○	Fewer barriers are preferred	Requires specific data collection
Luggage security	BT ○ VFRT ○○○	Lower probability of loss and theft is preferred	Requires specific data collection
Ticketing user-friendliness	BT ○ VFRT ○○○	Less time spent for ticketing is preferred	Requires specific data collection
Response time to service interruptions	BT ○○○ VFRT ○○	Shorter recovery time is preferred	Usually available in standardized form
Travel time reduction	BT ○○ VFRT ○○	Reduction is preferred	Usually available in standardized form
Number of modes included in a single ticket	BT ○ VFRT ○○○	More is preferred	Usually available in standardized form
Number and modes used	BT ○○○ VFRT ○○○	Less is preferred (or more available alternatives)	Possibly available but not standardized
Total cost of travel	BT ○○ VFRT ○○○	Lower cost is preferred	Usually available in standardized form

Different passengers have different needs and expectations, resulting in multimodal transport systems performing differently depending on the specific passenger type using the service (passenger perspective rather than operator perspective). Given the need to represent passenger variability through characteristics that can be measured compatibly with the available metrics adopted for defined KPIs and considering that time is a recurring metric, an example of a human variable that can be introduced to represent human variability in such validation exercises is walking speed. Walking speed varies according to age, physical and sensorial ability, gender, number of group members and many other variables. Table 11 lists walking speed according to passenger characteristics [36].

Table 11. Walking speed according to passenger category.

Passenger Characteristic	Walking Speed (m/s)
Children (<9 years) with adults (family including children)	Slowest (15th percentile): 1.02 m/s Fastest (85th percentile): 1.41 m/s
Adults < 65	Slowest (15th percentile): 1.22 m/s Fastest (85th percentile): 1.67 m/s
Adults $\geq$ 65	Slowest (15th percentile): 0.92 m/s Fastest (85th percentile): 1.44 m/s
People with impairments (including wheelchair users, visually impaired persons and persons on crutches)	Slowest (15th percentile): 0.86 m/s Fastest (85th percentile): 1.49 m/s

In a further step, a passenger population sample was built according to demographic and other changes foreseen in each of the three scenarios (i.e., more impaired people travelling in 2035, more older business travellers in 2050 [37]), which are listed in Table 12.

Table 12. Passenger composition.

Category	2025	2035	2050
% of BT passengers > 65	5.8% [38]	7% (assuming that until 2035, retirement ages will increase to varying extents among EU countries)	9% [39]
% of VFR passengers with impairments [40]	6%	8%	10%
% of VFR passengers > 65 (assuming that older and retired people travel more than younger people)	19%	25%	32%
% of VFR passengers, including children	10% (NB: this is the percentage of 0–9 year-old EU population) [41]	9% (assuming that negative demographic trends will stop after EU governments change their policies in the future)	12% (assuming that new positive demographic policies and reinforced migration/integration flows will occur in the timeframe of 2030–2040 and due to increasing migration pressures)

3.3. Simulation Results Related to Passenger KPIs

The X-TEAM D2D simulation results provide insight into differences in gains over the three time horizons for the considered passenger profiles, supporting the understanding of social sustainability aspects in future multimodal air travel services [42]. In terms of the efficiency of multimodal connections, represented in this case by waiting time, business travellers will achieve the greatest improvement if they use on-demand operating transport, such as urban air mobility or new micromobility services to cope with disruptions in the 2035 scenario and especially in the 2050, when waiting time is significantly reduced or close to zero. As passengers travelling to visit relatives and friends are more dependent on mass forms of public transport, the greatest benefit is expected to be experienced starting from 2035, when they can access affordable on-demand transport services, significantly reducing wait times. Given the purpose of the simulation, data on transport means in the 2025 time horizon were been derived from current operating services in cities considered for the USE CASES, whereas data on transport means in the 2035 and 2050 scenarios were assumed based on transport forecasts studies.

The most advantaged traveller profile in terms of travelled distance is the VFR, as this group can benefit from 5% shorter travel distance in the 2050 scenario, regardless the occurrence of disruptions. The VFR group will also benefit from a 20% reduction in travel time in the 2050 scenario compared to 2025; moreover, disruptions will not affect travel distance in the 2050 scenario for such passengers.

Both passenger profiles will experience a progressive improvement in travel speed, up to 21% in the 2050 scenario; in 2035, business passengers will experience a larger reduction in travel speed in case of disruptions, whereas in 2050, travel speed for both passenger profile should not be affected by disruptions relative to regular journeys.

4. Discussion

Sociocultural trends show an increasing consideration of the relevance of passenger diversity and social inclusion; therefore, we foresee that in the near future, passengers belonging to vulnerable categories will expect full and equal access to all transport services. As a consequence, digital (i.e., travel management mobile applications) and physical travel infrastructure (i.e., buildings, urban areas, vehicles, etc.) will have to adapt to a broad variety of needs and expectations, as well as in response to trends in recommendations and directives at the EU level. Although real-time data are expected to progressively integrate and autonomously manage travel disruptions at a wide systemic level, it is very likely that extreme weather events will increase in the 21st century in many areas of the globe, impacting normal activity affected areas; in such cases, passengers will probably be informed of the expected disruption, but it may be difficult to complete the travel experience for vulnerable categories if the mobility services are not able to meet the variety of user needs. In this study, we proposed a methodological framework to understand passenger-related variables to be taken into account in the design of future multimodal mobility services so that all European citizen will have the right and opportunity to access a fundamental services. When planning and making a journey, passengers have different needs and priorities to meet; in this study, we discussed how the relevance and priority of each variable may differ depending on the specific passenger profile, also assuming that these needs and characteristics affect travel tasks and decisions, as well as expectations with respect to the quality of transport services. To this end, 18 use cases for future mobility services were assessed in a discrete event simulation context, in which some passenger variables were modelled and assessed with specific passenger-centric metrics in order to estimate the quality of future mobility services under an inclusive approach.

The estimation of social impact, especially in terms of inclusion and equality, is a key aspect of urban development programmes, although such programmes often only focus on consultation activities and qualitative measurement. The proposed assessment framework was developed for the estimation of the passenger centeredness of a specific type of future mobility services, although it can be replicated in a variety of cities and for several settings and combinations of multimodal transport. It may be useful to exploit more quantitative methodologies to develop projects in the field of multimodal urban mobility for passengers; therefore, the research application of the presented framework in the X-TEAM D2D project could be a starting point for new mobility projects, with the aim of developing impact foresight in a more concrete and meaningful way from the citizen’s point of view. This will foster awareness of policy makers involved unban and mobility planning to implement more socially sustainable "Sustainable Urban Mobility Plans". The results of this study demonstrate the relevance of human variability in the design of public services, as well as the possibility of developing a system for personalized assessment of performance to support quality of life, security and services to citizens traveling across Europe considering multiple modes of transport, including air transport.

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