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Sustainable Mobility as a Service: Supply Analysis and Test Cases

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Abstract: Urban mobility is one of the main issues in the pursuit of sustainability. The United Nations 2030 Agenda assigns mobility and transport central roles in sustainable development and its components: economic, social, and environment. In this context, the emerging concept of Mobility as a Service (MaaS) offers an alternative to unsustainable mobility, often based on private car use. From the point of view of sustainable mobility, the MaaS paradigm implies greater insights into the transport system and its components (supply, demand, and reciprocal interactions). This paper proposes an approach to the transport system aimed at overcoming the current barriers to the implementation of the paradigm. The focus is on the implications for the transport supply subsystem. The investigation method is based on the analysis of the main components of such subsystem (governance, immaterial, material, equipment) and its role in the entire transport system. Starting with the first experiences of Finnish cities, the paper investigates some real case studies, which are experimenting with MaaS, to find common and uncommon elements. From the analyses, it emerges that the scientific literature and real experiences mainly focus on the immaterial components alone. To address the challenges related to sustainable mobility, this paper underlines the need to consider all components within a transport system approach. The findings of the paper are useful in several contexts. In the context of research, the paper offers an analysis of the transport supply system from the point of view of the MaaS paradigm. In the real context, the paper offers further useful insights for operators and decision-makers who intend to increase the knowledge and skills necessary to face challenges related to the introduction of MaaS.

Keywords: sustainable mobility; smart city; Mobility as a Service (Maas); transport system; supply; transport simulation models

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1. Introduction

Among current and future urban challenges, mobility is one of the main issues in the pursuit of sustainability. The United Nations 2030 Agenda assigns mobility and transport central roles in sustainable development and its components: economic, social, and environmental [1]. The European Commission identifies sustainable transport as one of the three pillars of the smart city along with information and telecommunication technologies (ICT) and energy. As far as it concerns to people's sustainable mobility, European guidelines indicate door-to-door mobility services as one of the main smart city solutions to meet the travel needs of users [2].

Digitalization processes, disruptive technologies, sharing economy, and advancements in transport engineering offer opportunities to achieve sustainable mobility [3,4]. One of these opportunities is linked to the emerging concept of Mobility as a Service (MaaS). This is a user-centred form of mobility that combines and integrates material and immaterial services with the aim of offering an alternative to unsustainable mobility, often based on the use of a private car [5].

Traditional transport infrastructures and services are enriched with data and information deriving from ICTs to produce the new material and immaterial services offered by MaaS. As is the case with the telecommunication and media services sectors, the MaaS paradigm converts transport services into travel packages with societal implications, such as those produced by disruptive technologies. Users can purchase a mobility package offered by an intermediate operator that combines multiple transport services provided by one or more operators [6]. This implies the involvement of operators who combine real transport services and related information. This is also possible thanks to intelligent transport systems (ITS), which integrate information and communication technologies (ICT), transport system models (TSM), and decision support systems (DSS) [7,8]. Despite the various advances in the development of the MaaS concept, the concrete developments of MaaS are still limited [9]. According to Vitetta [10], and in the perspective of Agenda 2030, the MaaS concept should evolve towards Sustainable MaaS (S-MaaS). The previous MaaS solutions are called MaaS 1.0, or I-MaaS (ICT MaaS), which focus on problems related to integrating services into a digital platform for users. Some scientific papers describe the MaaS framework of MaaS 2.0, or T-MaaS (TSM and ICT MaaS) [10]. MaaS evolutions up to MaaS 3.0, or S-MaaS, have different implications. Considering the transport system, it is possible to analyse the implications on the components of demand and supply. This paper focuses on the supply component.

This paper is the product of a research project aimed at adopting a transport system approach in the MaaS paradigm; the focus is on the evolution of the supply subsystem towards MaaS 3.0 [10]. Not exhaustively, transport supply includes institutional, immaterial, organizational, and material components. Current studies and experiences are used to analyse some MaaS implications on the supply system. The main focus is on the integration of information, data, and mobility services. Butler et al. [11] identified the main barriers limiting the diffusion of MaaS. Supply-side barriers relate to public–private cooperation, cyber security, business support, and the coverage of public transport infrastructure. The literature is mainly limited to MaaS implications concerning the immaterial component; analyses relating to a combination of one or more components are limited.

To make up for the shortcomings of the current literature, this paper seeks to broaden the perspective, extending the range of analysis to the four components introduced. It is necessary to identify the role of the four components in the entire transport system towards MaaS 3.0.

For these reasons, the objectives of this paper are: (1) to adopt a transport system approach to analyse S-MaaS implications on the four components of transport supply; (2) to represent each component of the transport supply as a set of quantitative variables inside a TSM framework; (3) and to verify the level of advancement of the S-MaaS paradigm in each component to investigate some real case studies, referred to as operating or pilot MaaS applications. The main scientific contribution concerns the analysis of the S-MaaS concept and its implications for transport supply, underlining the need to adopt a transport system approach to face with challenges related to sustainable mobility.

Based on these objectives, after this introduction, the paper consists of four sections:

- in line with objective (1), Section 2 analyses the S-MaaS implications on the four components of supply;
- referring to objective (2), Section 3 focuses on TSM for the simulation of the transport supply subsystem;
- as regards objective (3), Section 4 reports a review of real advanced case studies that are experimenting with MaaS, focusing on their implications for the four components of transport supply; and Section 5 discusses and compares common and uncommon factors among the selected case studies aiming to underline the current limitations and the need to adopt a transport system approach.

2. Transport Supply Components in the MaaS Context

The MaaS paradigm implies the evolution of components of the transport supply subsystem. A possible and unexhaustive classification of these components includes (Figure 1):

- *governance* components, including:
    - *institutional* components, including new regulations and public and private actors that stimulate MaaS implementation, both in short- and long-term perspectives [12,13];
    - *managerial* components, including new services (e.g., sharing mobility), new business models, new actors and their responsibilities, and interaction with citizens; with the support of digital technologies, MaaS integrates conventional and shared mobility services to provide tailored options for transport user needs [6,14,15];
- *immaterial* components relating to ITS that allow the implementation of MaaS up to the second generation; immaterial components enrich traditional physical transport infrastructures and services to provide optimized travel options that meet user needs [16];
- *material* components, including physical energy and transport infrastructures that must be adapted to sustainable urban challenges while awaiting the balance between people (social sustainability), the planet (environmental sustainability), and businesses (economic sustainability) [12];
- *equipment* components, including all means of transport and related technical characteristics, advanced technologies for advanced technologies for smart grids, and automation [17,18].

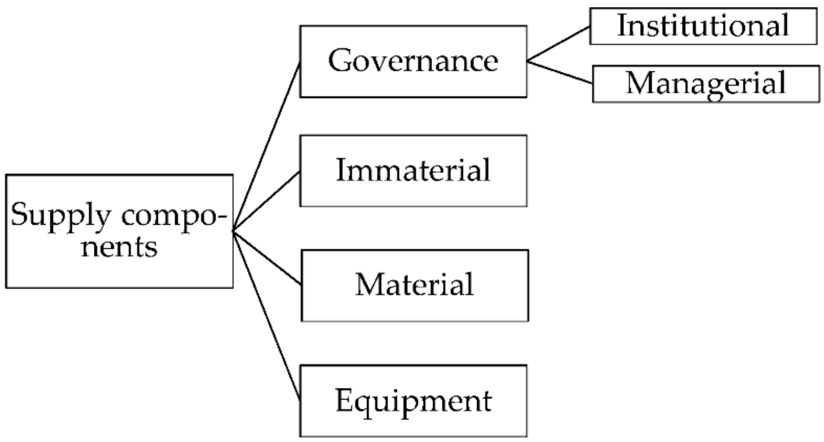

Figure 1. Transport supply components.

The following subsections report the main findings of a review of all components.

2.1. Governance Components

The MaaS paradigm implies the introduction of new forms of governance for the transport system. As far as transport supply is concerned, it is possible to distinguish two classes of actors involved [5]:

- Public Authorities (PA) that govern the entire transport system, seeking the equilibrium among all sustainability components (institutional components; Section 2.1.1);
- Companies (CO) that provide transport (MaaS companies) and information (MaaS operator) services, increasing the level of integration (managerial components; Section 2.1.2).

2.1.1. Institutional Components

Institutional transport supply components include the actions promoted by all levels of government responsible for the transport system, in the whole or partially (infrastructures and/or services). Regarding their responsibilities, institutions should act as transport system planners and play a relevant role in supporting the implementation of MaaS. A shared policy framework facilitates the development and diffusion of MaaS towards the MaaS 3.0 macro level.

In this context, it is necessary to underline the role of the government. MaaS can be driven by the market with limited government interference and never aligned to public goals (deregulated MaaS). In contrast, "government-led" MaaS (or the government-contracted model) is characterized by conditions and rules imposed for the services provided, defined to achieve societal objectives [19]. This last model adds an institutional overlay that regulates the market to find equilibrium among the different sustainability components.

In different territorial dimensions (national, regional, and local), governments can support MaaS development, but they have difficulties in defining policies aimed at achieving sustainable objectives, especially considering the limited availability of information about transport systems. Therefore, it is necessary to innovate government policies, starting with the empowerment of public decisionmakers in collaboration with other partners towards sustainable mobility objectives [20].

The institutions can provide different types of support [21], including "hard" regulations, referring to the government-contracted model; "soft" actions, including guidelines, letters of intent, or information provision; and financial support to realise immaterial or material components or mobility services.

Smith and Hensher [9] proposed the "Mobility as a Service Public Policy Framework", by considering MaaS as an opportunity to redefine public transport and its financing. The framework is based on the temporal evolution of possible activities to promote MaaS: Strategic comprehending activities (with a long-term time horizon (>15 years)) aimed at modifying cultural and personal attitudes about the mobility system; tactical comprehending activities (with a mid-term time horizon (5–15 years)) aimed at modifying service regimes; operational comprehending practices (with a short-term time horizon (0–5 years)) and concrete actions to improve mobility services. "Reflexive activities" involve monitoring and evaluating practices in order to align the expected and real effects produced by all planned and implemented activities.

Hut et al. [22] underline the necessity to provide neutral and national platforms to offer equal terms for all mobility service providers. This is very important, for example, for the development of the MaaS paradigm in rural contexts characterized by a low level of mobility demand.

In summary, S-MaaS has implications for the related institutional supply components (Figure 2):

- the level of government that defines rules or institutions to regulate the transport system (territorial dimension);
- the temporal evolution of possible activities to promote MaaS (temporal dimension);
- the type of support for MaaS implementation, including hard actions, soft actions, and financial supports (support dimension).

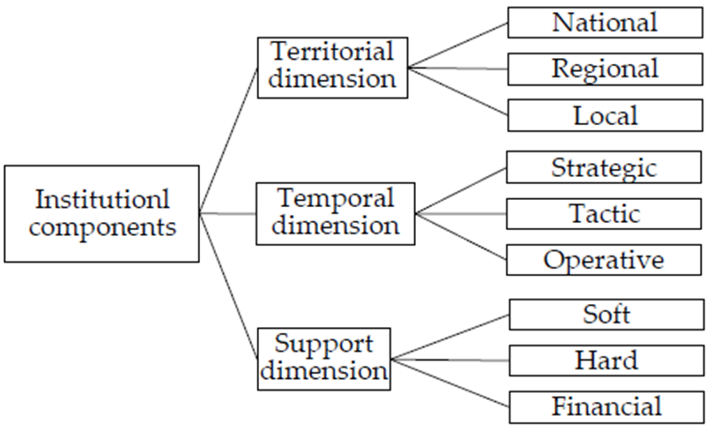

Figure 2. Governance: institutional components.

2.1.2. Managerial Components

The components of managerial transport supply include, on one hand, MaaS information and transport services that integrate conventional and shared services and, on the other hand, different business models for the provision of services. Using the MaaS platform, the MaaS operator becomes the interface between users and mobility service providers (MSPs).

MaaS requires enhanced coordination between different types of mobility services for individual and collective mobility. Traditionally, these services are planned and offered with limited forms of physical and organizational integration. Wong et al. [19] clarified that integration means increasing temporal and spatial efficiency. Temporal efficiency is related to the proportion of time that a vehicle spends in the system; it is connected to infrastructure capacity. Spatial efficiency is related to the proportion of vehicle space occupied by passengers; it is also connected to infrastructure capacity. The authors propose a "modal efficiency framework", classifying modes of transport in a space–time plane defined by axes representing spatial and temporal efficiencies. The final aim is to identify the most appropriate mode of transport for the specific urban context, according to the policy objectives. In opposition to the traditional approach, the MaaS paradigm implies an increased level of integration between consolidated and new forms of transport services and the involved actors.

Shared services include different kinds of mobility services. It is possible to distinguish between transport services that share the vehicle (with a free-floating or station-based approach), the ride (including "ride-hailing" and "ride-sharing", sharing respectively, the vehicle and driver or only the same vehicle), or parking public/private spaces and the point of recharge.

This is made possible by adopting new business models based on collaboration among MaaS companies (public and private), MaaS operators and integrators, and system planners (e.g., public authorities).

In synthesis, S-MaaS has implications for managerial supply components inside a transport system, in relation to (Figure 3):

- The mobility services offered by one or more MSPs and their combinations and by considering personal modes (e.g., private cars or bicycles); the MaaS system includes services that can share the vehicle (e.g., car sharing, bike sharing), the ride (e.g., ride-hailing, which includes the driver in the service, and ride-sharing, which does not include the driver), or the parking/charge places;
- The business models adopted for services management; a possible classification depends on the institutional assets of the subject that designs and manages the MaaS system, which can be private or in partnership [23] and can take the following forms:
    - Public, or top-down, including the government-to-customer form, or G2C;
    - Private, or bottom-up, including the business-to-consumer form, or B2C;
    - Public–private partnership, including the business-to-business-to-consumer form, or B2B2C, and the government-to-business-to-consumer form, or G2B2C.

2.2. Immaterial Components

Immaterial transport supply components include products and services provided by ICT tools, TSM, and DSS inside an ITS [7,10]. The priority for MaaS implementation is collecting, integrating, and providing data and information to (virtual and real) operators and users. MaaS requires the design and implementation of a digital platform that is a component of the ITS and represents the interface between MaaS operators, MaaS companies, and MaaS users. On the one hand, ITS supports MaaS design by providing integrated transport system configurations (mobility services and infrastructures); on the other hand, ITS supports MaaS users to choose and purchase personalized travel options, offering information, booking, ticketing, and validation services statically or dynamically [24].

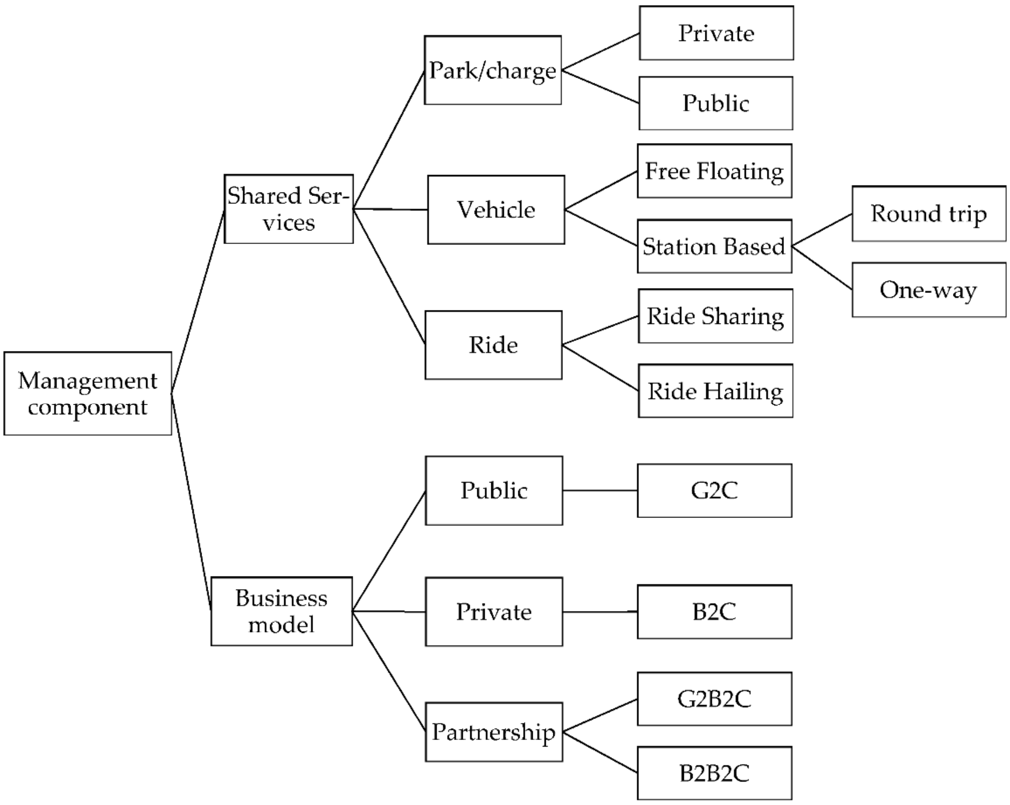

Figure 3. Governance: managerial components.

Aditjandra [25] presents a review of journey planners that provide dynamic travel information and multimodal trip-planning services, available for query at any place or time. The provision of real-time information is connected to the necessity of acquiring dynamic data information services and digital map presentations.

In synthesis, S-MaaS has implications for immaterial supply components in relation to (Figure 4):

- Data and information for public and private operators and users;
- Booking, ticketing, and validation services that allow users to purchase a package of trips by means of one or more transport modes and pricing policies that can be usage-dependent (pay-as-you-go: PAYG) or independent of usage (account-based ticketing: ABT);
- Bundles that combine traditional and shared mobility services.

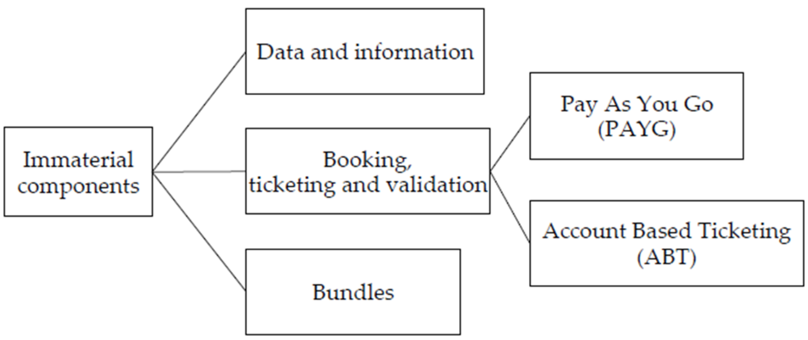

Figure 4. Immaterial components.

2.3. Material Components

Material transport supply components include a combination of physical, linear, and punctual infrastructures. These components include both physical transports and energy facilities (roads, tracks, and charging stations), requiring relevant investments [26,27].

In the literature, there are limited works that discuss the MaaS implications for the material transport system's components [13]. Despite to the great attention to immaterial components, the MaaS paradigm implies advancements in the development and management of physical infrastructure. The European smart city concept stressed the necessity of integrating transport energy with ICT infrastructures and services [28]. S-MaaS implies a rethinking of infrastructures in the design and development process aimed at configuring public spaces in a more sustainable way [12,29]. For instance, parking infrastructures represent a possible area of integration where it is necessary to reach a convergence between the MaaS actors (users, managers, and planners) [30]. In the S-MaaS context, to incentivize sustainable mobility options, it is necessary to introduce restrictions on available personal urban parking spaces or increase parking fares.

In the past, transport infrastructures have mainly been developed to facilitate travel by a single mode of transport (e.g., private cars). From planning to implementation, the technical parameters of transport infrastructures were defined to respond to the expected traffic flows of a single mode of transport (monomodal, e.g., private cars). In a MaaS context, different punctual and linear transport infrastructures have to be configured as integrated and multimodal transport networks. For this reason, the nodes must be designed to facilitate the interchanges between different transport modes (e.g., park and ride facilities). Energy and transport infrastructure providers (ETIPs) must ensure a high level of reliability in transport networks where MaaS operates [13].

ETIPs play a twofold role: On the transport side, providers have to ensure interconnections in multimodal transportation and enable traffic flow management supported by historical and real-time data; on the energy side, providers have to ensure facilities that offer power for all types of vehicles (electrical hydrogen, etc.) using recharging infrastructures [31].

One of the main S-MaaS implications regards the effective use of physical and energy infrastructures, improving traffic and capacity management. In the S-MaaS context, it is essential that infrastructure parameters be defined according to mobility services and then mobility's needs [15].

System public planners and administrators can work with private actors to maintain punctual and linear infrastructure. Digital technologies, included in this paper in the immaterial components, complete the material components, allowing constant and real-time monitoring [29,32,33].

In synthesis, S-MaaS has implications for material supply components in relation to transport and energy and punctual and linear physical infrastructures (Figure 5).

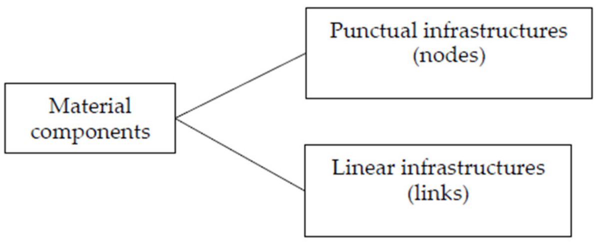

Figure 5. Material components.

2.4. Equipment Component

The equipment supply component includes physical vehicles needed to provide transport services and move people (vehicles, rolling stock, etc.).

It is necessary to individuate the physical characteristics in terms of vehicle capacity and geometrical dimensions that should be adequate for satisfying users' mobility needs and an urban context.

Mobility evolution implies advancements in connected, autonomous, and electrical vehicles (CAEV). The scientific literature about CAEV evolution offers a wide range of studies about the strengths and weaknesses of this form of mobility [17,34]. S-MaaS implies the necessity of increasing the efficiency (e.g., reducing energy consumption) and effectiveness (e.g., increasing the use of the transport capacity) of the entire transport system [18,35]. Thus, S-MaaS has implications for equipment supply components in relation to the physical characteristics of vehicles (e.g., seat capacity), including technology for power, connection, and automation (Figure 6).

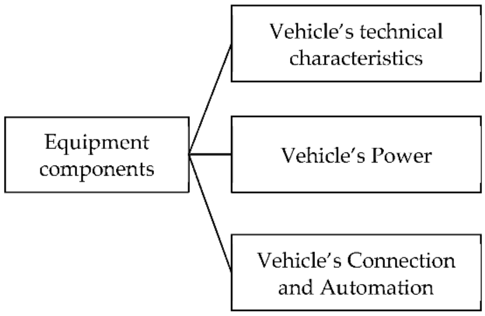

Figure 6. Equipment components.

3. Transport Supply Models to Evaluate Sustainability

The literature shows a limited adoption of the transport system approach. Within the research project introduced by Vitetta [10], this paper proposes the use of transport system models (TSMs) to evaluate the contributions of transport infrastructures and services to sustainability. The goal is to support planning and design processes to configure transport systems towards MaaS 3.0. In particular, this paper focuses on models to simulate transport supply systems. All components classified in Section 2 become quantitative variables inside the TSM framework. This class of models is influenced by the output of demand management models, which can be classified as information, strategy, and incentives (see [7]). By combining these demand variables with other external data (e.g., meteorological conditions, macroeconomic situation, etc.), supply models support the definition of the designed variables of each transport supply component illustrated in Section 2. A schematic representation of the modelling framework is reported in Figure 7. The dotted lines indicate framework parts developed by other authors [7,12,15,36].

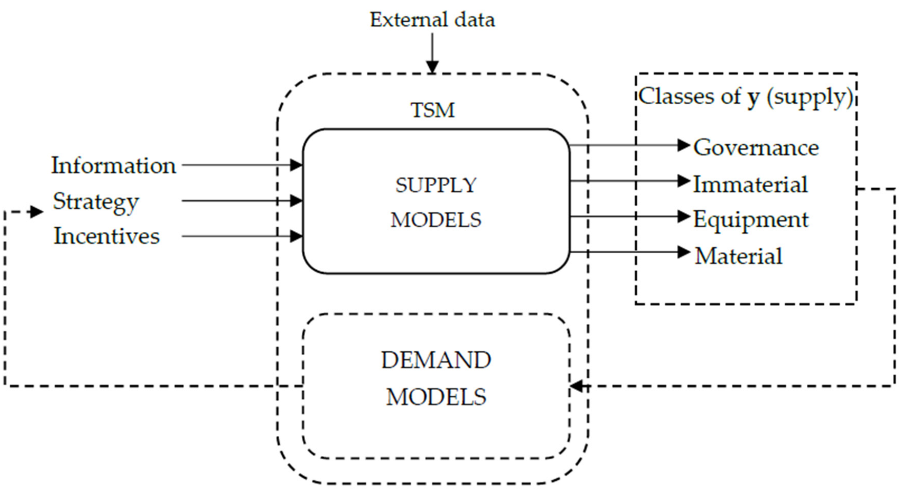

Figure 7. Supply models inside the TSM framework.

The asset of the transport supply subsystem produces performance concerning each sustainability component. S-MaaS aims to reduce the negative impacts on all sustainability components produced by the transport system, respecting the technical, behavioural, and normative constraints.

TSMs allow for the quantitative evaluation of the objectives (Section 3.1) and constraints (Section 3.2).

3.1. Objectives

In ex ante evaluations, it is possible to evaluate if the planned actions (regarding one or more transport supply components) reach the sustainability objectives. According to Vitetta [10], a general formulation of the objective function is:

$$Minimum_{y,f}\ (or\ Maximum)\ \boldsymbol{\phi}(\mathbf{y}, \mathbf{f}) \tag{1}$$

where

- $\boldsymbol{\phi}(\bullet)$ is the objective function (e.g. total travel times);
- $\mathbf{f}$ is the vector of the link user flows;
- $\mathbf{y}$ is the vector of decision or control variables for the supply subsystem (e.g. timetables, fares); it can be divided into the supply classes governance, immaterial, equipment, and material.

By focusing on transport supply components, the following subsections explicate sustainable mobility objectives for the economic (Section 3.1.1), environmental (Section 3.1.2), and social (Section 3.1.3) components of a multi-criteria approach.

3.1.1. Economic Sustainability

Economic sustainability refers to the impacts of a transport system on businesses or, more generally, on economic growth. S-MaaS aims to optimize the use of economic resources to reduce transport user costs.

Adopting the network-based approach, economic sustainability performance depends on transport user costs, which can be calculated by adopting the following formulations:

$$\mathbf{c} = \gamma(\mathbf{f}) \tag{2}$$

$$\mathbf{g} = \mathbf{g_{NA}} + \mathbf{g_A} = \Delta^{\mathrm{T}}\ \mathbf{c} \tag{3}$$

$$\mathbf{f} = \boldsymbol{\Delta}\ \mathbf{h} \tag{4}$$

where

$\mathbf{c}$ and $\mathbf{g}$	are, respectively, the vectors of generalized link and path costs, combining different components (money, time, energy, etc.);
$\mathbf{f}$ and $\mathbf{h}$	are, respectively, the vectors of the link and path flows;
$\boldsymbol{\gamma}(\bullet)$	is the vector of the link–cost flow functions;
g_{NA} and g_A	are the vectors of, respectively, nonadditive and additive generalised costs;
Δ	is the link path incidence matrix.

The modelling approach to representing a transport supply system in a static condition (i.e., without considering explicitly the temporal evolution of performances) evolves towards a dynamic approach by considering the temporal lags (t and τ) introduced by Russo [12]. The MaaS paradigm imposes the adoption of a schedule-based approach to represent the temporal connections inside the same transport mode or modes offered by different operators (e.g., urban and extra-urban buses) [37–39], as well as to forecast travel times [40,41]. For instance, Figure 8 represents the interchange node inside an intermodal transport network that links two transit lines of different modes (e.g., bus and train). The connection in the space has to also be represented in the time dimension to take into account the temporal compatibility of the user's transfer from runs belonging to the bus line "a" to the runs belonging to the train line "b".

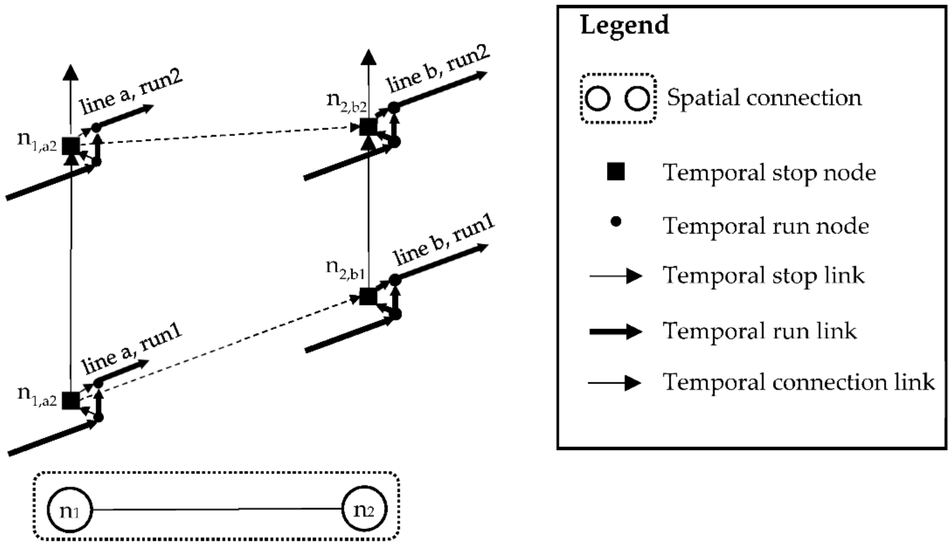

Figure 8. Spatiotemporal connections of an interchange node.

Economic sustainability can be measured for a single element (e.g., link or node) or the entire transport network.

By integrating transport demand and supply models, it is possible to evaluate user satisfaction or the maximum expected value of the utility related to all travel alternatives. The quantitative attributes, calculated with the application of transport supply cost functions, feed demand models [42]; for example, the quality of collective transport services can be represented with the attributes of a behavioural demand model to simulate user travel choices [43].

3.1.2. Environmental Sustainability

Environmental sustainability refers to the impacts of the transport system on the planet or, more generally, on the use of natural resources.

Adopting the network-based approach [42], environmental sustainability performance depends on the level of a vehicle's emissions (**e**) and concentrations (**μ**) relative to the specific negative impact (noise or pollution), which depend on the type of vehicle's power (**p**) (e.g., electrical, internal combustion engine), link flows (**f**), and speed (**v**); they can be calculated adopting the following formulation:

$$\mathbf{e} = \boldsymbol{\Gamma}(\mathbf{p}, \mathbf{f}, \mathbf{v}) \tag{5}$$

where $\boldsymbol{\Gamma}(\bullet)$ is the vector of function to estimate emission [42].

By considering zoning to discretise the continuum territory, for each zone, it is possible to estimate the concentration level of the impact, which depends on the emission (**e**) and meteorological conditions (**m**):

$$\boldsymbol{\mu} = \boldsymbol{\zeta}(\mathbf{e}, \mathbf{m}) \tag{6}$$

where $\boldsymbol{\zeta}(\bullet)$ is the vector of functions to estimate the concentration in each zone.

3.1.3. Social Sustainability

Social sustainability refers to the impacts of the transport system on people or, more generally, levels of health and liveability in communities.

A possible measure of social sustainability is territorial accessibility with respect to a set of opportunities. In the case of passenger transport, by considering all zones in which the territory is discretised, accessibility can be expressed as a relationship between the activity system in a territorial area and the transportation system serving it [42]. A possible formulation of the accessibility of all zones (A) is:

$$\mathbf{A} = \boldsymbol{\xi}(\mathbf{g}, \mathbf{o}) \tag{7}$$

where

g	is the vector of path costs for connecting each pair of origin/destination zones;
o	is the vector of the indicators of the opportunities in the zone (activities and services); to measure active accessibility, the opportunities in the destination zones are considered, and for measuring passive accessibility, the opportunities in the origin zones are considered;
ξ(●)	is the vector of functions measuring accessibility in each zone [42].

3.2. Constraints

Sustainable mobility objectives have to be reached while also respecting a set of constraints that, in most cases, represent a limitation on the available resources for implementing MaaS solutions.

It is possible to define three classes of constraints:

- behavioural constraints, related to supply–demand interactions, which ensure conservation flows at all network levels (junctions, path level, origin–destination) for all user categories, services, and modes;
- technical constraints, related to the available resources (e.g., financial, vehicle capacity, etc.), which ensure the feasibility of MaaS solutions offered to users;
- external constraints, related to the set of indications and rules on the territorial system, deriving from different levels of government (see Section 2.1.1), which ensure the respect of quantitative parameters or targets concerning different sustainability components (e.g., quantity of pollution for environmental sustainability or number of road accidents for social sustainability).

The behavioural constraints are nonlinear and can be expressed with the fixed-point formulation of the static approach or with the within-day or day-to-day approaches of the dynamic approach [42,44,45]. The nonlinear constraints can be added to the linear constraints, which ensure the conservation flows.

It is possible to express the other classes of constraints with an analytical formulation that measures:

- the distance from specific targets (e.g., Sustainable Development Goals, SDG targets); for instance, it is possible to measure the Euclidean distance between the sustainability indicators:

  $$\mathrm{d} = \sum_{\mathrm{i}} [(\mathrm{s_i} - \mathrm{s_i}')^2]^{0.5} \tag{8}$$

  where

  s is the vector of indicators that measure each sustainability component (economic, social, and environmental) with entry $\mathrm{s_i}$;

  s′ the vector of indicators that measure each target related to each sustainability component with entry $\mathrm{s_i}'$;

- the respect of the quantitative parameters defined for each variable representing transport supply (**y**); for instance, it is possible to measure the respect of an upper level of available resources:

  $$\mathbf{y} \le \mathbf{y}'$$

  where

  y is the vector of indicators that measure each variable (e.g., number of available electrical vehicles with respect to seating capacity and battery autonomy);

  y′ is the vector of indicators that measure resources (e.g., 10 vehicles with 15 seats and batteries with 30kwh capacities).

4. A Review of Real Case Studies

A set of real case studies were selected to individuate concrete examples of the MaaS implications for each transport supply component introduced in Section 2. The selected countries and cities represent some of the most advanced case studies where the MaaS paradigm is a reality. The case study described in Section 4.5 represents a potential territory where S-MaaS can be designed with the support of TSMs.

4.1. Governance Components

This section reports a review of real contexts that are experimenting with the MaaS paradigm with respect to the governance components introduced in Section 2.1; in particular, Sections 4.1.1 and 4.1.2 illustrate, respectively, experiences with institutional and managerial subcomponents.

In recent years, different public and private authorities have promoted research, pilot projects, collaboration programs, and new forms of mobility services to experiment with the MaaS paradigm [9].

4.1.1. Institutional Components

The selected case studies adopted different institutional actions that are classified in relation to the government dimensions introduced in Section 2.1.1.

As regards the territorial dimension, some countries have introduced specific national laws to promote sustainable mobility (e.g., France) or the MaaS paradigm (e.g., Finland, Austria) [46]. In other countries, national, regional, and local government levels collaborate to promote MaaS initiatives (e.g., Austria, France, the Netherlands, and Italy).

Regarding the temporal dimension, the most advanced cities (e.g., Helsinki) have defined strategic, tactical, and operational measures to implement the MaaS paradigm (see, for instance, the experiences of the City of Helsinki [47]).

Regarding the support dimension, the most frequent actions regard financial resources supporting pilot projects or MaaS platforms. For instance, MaaS Global in Finland [48], WienMobil in Austria [49], and BIP in Italy [50] were supported by national or regional funding.

4.1.2. Managerial Components

The pioneer cities that implemented MaaS are Helsinki and Vienna, where all local and regional public transports (buses, trams, metros, regional trains, etc.) are integrated into a MaaS market.

The implemented MaaS experiences can be grouped into two main classes:

- Top-down initiatives, mainly led by public authorities; the most representative is MaaS WienMobil, developed by the public transport operator Wiener Lienen, operating in Vienna [51]; it is an example of a G2C business model; other applications of the G2C business model have been developed in Stockholm, Hannover, Hamburg, Paris, Madrid, and Turin;
- Bottom-up initiatives, mainly led by private organisations the most representative is MaaS Global, born in Helsinki, which is an example of B2C business model that offers its applications (Whim) in different cities [48]; other applications of the B2C business model have been developed in Turku, Brussels, and Amsterdam [52].

One of the key challenges that cities face in implementing the MaaS paradigm is related to the necessity to uniformise the mobility market. It is necessary to align traditional public transport, new mobility services, and the corresponding new players [53,54]. Some examples of active bundles in real case studies are presented in Table 1.

Table 1. Some examples of bundles.

	City	Helsinki	Turku	Vienna	Brussels	Stockholm
	Platform	WhimApp	WhimApp	WhimApp	WhimApp	UbiGo
public transport	regional	unlimited/month	unlimited/month		minutes/years	unlimited/month
	urban	unlimited/month	unlimited/month	unlimited/day	minutes/years	unlimited/month
vehicle	car sharing	discount/month	discount/month	-	PAYG	PAYG
	bike sharing	minutes/day	minutes/day	-	minutes/day	one hour/day
	e-scooter sharing	minutes/month	minutes/month	minutes/day	minutes/day	-
rides	public taxi	discount/month	discount/month	PAYG	PAYG	-

PAYG: Pay as you go.

4.2. Immaterial Components

Many cities are working to develop integrated, immaterial platforms able to perform different functions (services management, information, journey planning, ticketing, etc.).

The common objective of the platforms is to present the transport infrastructures and services as integrated systems that offer mobility options to users as homogeneous alternatives to private modes of transport.

To enable MaaS solutions in terms of immaterial components, the aforementioned initiatives concern the sharing of data and information. For instance, in Scandinavia, the Open Mobility Data in the Nordics (Odin) project aims to create a unified mobility market across the Nordic regions. The project is funded by the Swedish infrastructure manager and the Swedish Innovation Agency and coordinated by a research institute that promotes sustainable mobility work in ICT [55]. The publication of open historical and real-time data and application programming interface (API) is a common initiative of the selected case studies (Helsinki, Turku, Wien, Stockholm, Paris, Amsterdam, Madrid, Turin) [46].

The 2017 Finnish Transport Code (Liikennekaari), forced all MSPs to provide open data and API [6]. Some MaaS operators provide "orchestration functionalities" that enrich basic "plan–book–ticket–pay" MaaS functionalities [30]. For instance, the Digitransit system developed for Helsinki is an opensource platform that offers open data and functions for journey-planning [56]. In the city of Turku, the start-up Tuup used public API to develop a MaaS application for ticketing. The platform developed for the Stockholm region offers big data that, on one side, are inputs for network design and, on the other, produce information for supporting users in their mobility package choices [57]. Open data and API enable cooperation between different virtual and real operators. The public platform developed by Upstream Mobility for the city of Vienna is capable of interfacing with different MaaS operators. Recently, MaaS Global, originally developed for Helsinki, collaborated with Upstream Mobility to adopt Whim services in Vienna. The graph integration platform (GIP) is a multimodal transport supply model for the whole of Austria. The Austrian Multimodal Journey Planner (VAO) uses the GIP model to provide multimodal routes throughout Austria [46]. The "MaaS Madrid" platform collects data deriving from transport services operators and offers immaterial services that allow users to access information in real-time. In the next phases of MaaS implementation, the platform will enable the collection of aggregated, anonymous, real-time data from the app, which may be useful in the urban transport planning process [58].

4.3. Material Components

In the past, some cities have invested in transport infrastructure for public and active transportation (e.g., transit, cycling, and pedestrian infrastructures) in order to realise sustainable mobility (e.g., Helsinki, Wien, Amsterdam). From the MaaS perspective, these cities are advantaged because this is an initial condition to allow journeys across different transport modes. MaaS initiatives imply a high level of efficiency and effectiveness in existing infrastructures. The final objective is the optimal use of transport network capacity and its elements (nodes and links). Cities are working in collaboration with private operators to realise and maintain punctual transports (e.g., bike racks) and linear infrastructures (e.g., bike lanes). The physical asset is enriched by ICT, allowing for constant and real-time monitoring functions (see the immaterial components discussed above). Collected information about mobility needs and capacity consumption became inputs for designing mobility services and, if necessary, the realization of new infrastructures.

However, the infrastructural implications of MaaS in real contexts represent an undefined field.

In relation to the vehicle material component, consider the cities that are implementing initiatives with respect to electrical, connected, and autonomous mobility. The city of Helsinki is experimenting with self-driving buses and robot taxis that feed into the railway transport system. The city is working on implementing and maintaining the physical and digital infrastructure required by autonomous mobility [47].

In relation to punctual infrastructures, the investigated case studies show initiatives to develop parking places and interchanges poles.

Stockholm's vision follows a mobility model without cars, and MaaS could be a solution. According to this long-term vision, the "green parking" initiative combines material and managerial MaaS components. Parking design for newly built housing adds conditions regarding its location and, in particular, proximity to public transport. The number of parking spots depends on the planned mobility packages (e.g., car/bike sharing, bike room facilities, etc.) for the new buildings. The idea is to offer different transport alternatives to decrease the necessity of car ownership.

Some cities are developing physical points dedicated to passenger mobility. Helsinki is planning pickup and drop-off areas for self-driving vehicles dedicated to passenger mobility [47]. The City of Hamburg has developed the Hochbahn as an element of the Switch platform, with the function intended to favour interchanges between different transport modes. In 2018, 17 points were available, connecting the metro and 28 decentralized neighbourhoods [59].

4.4. Equipment Components

Different cities are working on the electrification of transport vehicles. Furthermore, the automotive industry is adapting its products in relation to autonomous vehicles and their energy consumption [60]. The MaaS paradigm implies that the industry faces a transformation process from "car sale" to "mobility package purchase" [61]. While the electrification of fleets is underway in many of the cities analysed (Helsinki, Stockholm, Hannover, Paris, Brussels, Madrid), experiments on connected and autonomous vehicles (CAV) are still being performed in pilot projects (Helsinki, Madrid, Vienna, Hamburg). MaaS is an opportunity to implement connected and autonomous electric vehicles (CAEV) [62].

4.5. Transport Supply Models for a Case Study

In the context of the research project mentioned in the introduction, a case study is in progress. The study area is the territorial area of the Strait of Messina in the south of Italy. The area is characterized by a physical barrier related to the sea that separates the cities of Messina and Reggio Calabria (about 3 km). The number of maritime runs that cross the strait in a day is 70 runs/day in both directions. In terms of passengers, there are about 21,000 users/day in both directions [63]. Different transport operators manage the infrastructures and services of all transport modes (air, water, rail, road). There is no coordination between the terrestrial and maritime transport services, but there are some potentialities to implement the MaaS paradigm. For this reason, some hypothetical scenarios were designed and simulated to estimate the potential effects on all sustainability components.

With this aim, a pilot survey was carried out to evaluate the potential impacts produced by integrating the four supply components toward the S-MaaS perspective. The simulated scenarios regard:

- The governance component, with the introduction of:

1. A new institution (Strait Authority) that regulates and plans the transport system in the area (PA);
2. A new MaaS operator that integrates conventional and advanced mobility services, adopting a digital platform where data and information about passenger mobility converge (CO);

- The immaterial component, which integrates a set of monitoring technologies (ICT tools) and TSM inside an ITS platform that, on one side, supports the governance components (PA and CO) and, on the other, provides information, booking, and ticketing function for passenger mobility;
- The material component, which includes existing and planned physical maritime and terrestrial transport nodes and links (e.g., new berths, a new terrestrial transit system);
- The equipment component, which includes the existing and planned means of terrestrial transport means for providing conventional and sharing mobility services.

Table 2 reports a comparison between the current and planned scenarios. By referring to maritime transport supply, MaaS implications are described adopting a synthetic, quantitative indicator for each component.

Table 2. The strait of Messina: scenario comparison for maritime transport.

Scenario	**GOVERNANCE** Institutional (PA)	Managerial (CO)	**IMMATERIAL (CO)**	**MATERIAL (PA, CO)**	**EQUIPMENT (PA, CO)**
Current (without MaaS)	3 institutions	3 transport operators	single websites	4 ports	Single fleets
Planned (without MaaS)	1 MaaS planner	1 MaaS operator	1 MaaS platform	2 interchange nodes	Shared fleets

A set of transport supply models support the simulation of the intermodal transport system for the current and planned scenarios. A schedule-based approach was adopted to increase coordination between the timetables of the different transport operators and to reduce the barrier's impacts. The model's application generates quantitative attributes that are useful for motivational surveys used to promote MaaS scenarios to users [64].

From the analyses of the current scenario, it emerges that, in a typical working day, passenger mobility is characterized by:

- Total distances travelled by all users, equal to about 10,000,000 km/day;
- Total times spent by all users on extra-urban trips, about 209,000 h/days;
- The expected values of travel times are 45 min by car and 78 min by public transport.

MaaS scenarios potentially reduce travel distances and times and increase the modal share of collective transport services towards a sustainable perspective.

5. Discussion and Final Remarks

5.1. Discussion

From the above analyses, it emerges that MaaS is an opportunity to address the mobility challenges related to sustainability. Advances in material and immaterial technologies are enabling the implementation of the MaaS paradigm. However, further progress is needed to evolve towards MaaS 3.0 and, thus, to implement the S-MaaS concept. The paradigm has implications for entire transport systems because changes to the asset of infrastructures and services produce effects in terms of demand–supply interactions. This paper has focused on MaaS implications for transport supply and its four components. It is necessary to underline that the transport system is complex because it involves different actors who often have conflicting interests with respect to objectives of sustainability.

The MaaS implications for the four supply components were investigated in a set of selected European cities. Each case study shows a different level of advancement in each component. Table 3 summarizes the information gathered about MaaS progress in each case study. A qualitative indicator shows the level of progress of the cities analysed with respect to each supply component (*, minimum level; ** medium level; *** maximum level), assuming the performances of Helsinki as maximum level. Note that the pioneer city, Helsinki, has implemented actions for all components. The city represents a best practice for public administrations (PA) and companies (CO). All the selected cities have worked on the development of MaaS platforms for the integration of information and ticketing (immaterial components). Experience in the material and equipment components (especially for automated vehicles) is limited. The case of the Strait of Messina, presented in Section 4.5, shows a territory with different potentials but a set of limits common to different realities that would implement the MaaS paradigm. A great deal of effort is necessary to design an entire transport system to find a balance between all the components of sustainability. As for TSMs, it should be noted that the most advanced case studies show an advanced level of TSM (see, for example, the Digitransit platform, which supports the construction of transport supply models at the national level [55]). However, based on the author's knowledge, a platform that implements a TSM framework to support transport system planning and design processes has not been fully implemented. This confirms the necessity of adopting a TSM framework integrated with ICT tools in an ITS that supports decisionmakers in implementing the S-MaaS paradigm. This implies a theoretical effort to overcome the research gaps, but it also has practical implications for executives and policymakers who might be using ITS in their real-world businesses.

Table 3. Real advanced case studies: review of the supply components.

Country	**City**	**GOVERNANCE Institutional (PA)**	**GOVERNANCE Managerial (CO)**	**IMMATERIAL (CO)**	**MATERIAL (PA, CO)**	**EQUIPMENT (PA, CO)**	**TSM (PA, CO)**
Finland	Helsinki	***	**	***	**	**	***
Finland	Turku	**	***	***	-	*	***
Austria	Wien	**	**	***	-	**	***
Scandinavia	Stockholm	*	**	*	**	*	**
Germany	Hannover	*	***	**	-	*	*
Germany	Hamburg	*	**	**	**	*	*
France	Paris	*	**	**	-	*	*
Belgium	Brussels	*	**	**	-	*	*
Netherlands	Amsterdam	**	***	**	-	*	**
Spain	Madrid	*	**	**	**	**	*
Italy	Turin	*	*	*	-	*	*
Italy	Strait of Messina	*	-	-	*	-	**

PA: Public authorities; CO: companies; *: minimum advancement; **: medium advancement; ***: maximum advancement; -: limited information.

5.2. Final Remarks

In conclusion, this paper analysed S-MaaS implications for transport supply subsystems. The literature offers limited inputs to guide public policymakers in planning and implementation processes toward MaaS 3.0. This paper offers a scientific contribution with a focus on the subcomponent of transport supply. The four components analysed, as elements of transport systems, can be modelled inside a TSM framework. The weaknesses of the study concern two main points: the implementation of the TSM framework in a real case study; the limited set of real case studies analysed.

Future developments for this research should yield more insights on:

- the governance component, with analyses on the possibilities of MaaS to find a balance between societal goals, promoted by public administrations, and technical constraints, imposed on private and public companies;
- the immaterial components, with studies and real experiments to enhance exchanges between ICT and TSMs inside ITSs to improve the modelling capability of MaaS implications for transport systems in order to increase sustainable mobility;

- the material components, focusing on the MaaS implications for transport infrastructures and on the possibility of enhancing physical integrations between the different modes;
- the components of the equipment, to better understand the mutual interactions between MaaS and CAEV evolution;
- the implementation of the TSM framework in a real case study.

More generally, it is necessary to increase knowledge on the potential positive and negative impacts of MaaS on transport systems in order to increase sustainable mobility in the short and long-term.

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