Achieving Interoperability in Mobility as a Service: A Data Ecosystem leveraging Semantic Web Technologies

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Abstract

As urbanization continues to accelerate worldwide, the need for efficient and interconnected transportation systems becomes increasingly critical. Mobility as a Service (MaaS) has emerged as a promising solution to address this challenge by integrating various modes of transportation into a seamless and user-centric experience. However, the success of MaaS hinges on achieving robust interoperability among stakeholders, a task fraught with complexities and disagreements.

This research delves into the heart of MaaS interoperability, aiming to design a solution that standardises the entry of transport operators into MaaS data ecosystems. Through a comprehensive qualitative study involving 65 diverse experts, this investigation identifies nine key areas of disagreement regarding MaaS implementation, shedding light on the underlying rationale behind these disputes. Two distinct mindsets, "Private car-first" and "Public transport-first," emerge as influential factors shaping these disagreements caused by the transportation challenges faced by the participants.

The study also unveils the current and desired levels of business and data interoperability within MaaS ecosystems, revealing the challenges and efforts taken to bridge the gap. The analysis results in a set of interoperability requirements for business and data including adhering to open standards, cross-mode interoperability, cross-domain interoperability, adaptive business models, standardised contracts, among others. The results contribute to policy and regulatory frameworks needed to foster interoperable MaaS ecosystems by offering an interoperability roadmap as a guidance tool.

At the heart of this research lies the innovative Mobility Profiles Taxonomy, a solution designed to standardize the entry of transport operators into MaaS data ecosystems. The taxonomy classifies the different types of operations into five core layers: Planning, Drivers, Booking, Ticketing, and Payment. Each layer consists of distinct cases which, when put together, encompass a complete operator's data profile required tomove a passenger from A to B. This taxonomy, marked by modularity, customization, and alignment features, promises to prevent the creation of silo-ed Mobility Data Spaces. While a machine-readable version remains a future endeavor, a demonstration of a data exchange process shows the practicality of applying the taxonomy, with the incorporation of Semantic Web Technologies, showcasing the potential of its use for automated data exchange. The development of these

Mobility Profiles provide a structured framework for standardising Data Spaces but also enable the identification of vertical and horizontal gaps in interoperability across these operator profiles.

However, this journey is not without limitations, including the specific scope of the taxonomy and the need for further validation and quantification of the proposed solutions. Nonetheless, the research paves the way for future investigations, urging a deeper dive into regional intricacies, user profiles, and extended areas of interoperability.

By combining the proposed roadmap and taxonomy, this research offers a thorough guide for the development of Mobility as a Service ecosystems with a core focus on the maturity of interoperability. Setting the defined interoperability requirements as a target for ecosystems is expected to enable a better integration at a legal, organisational, semantic, and technical layer. The roadmap serves as a high level reference for designing policies that address legal and organisational interoperability, whilst the taxonomy contributes to alleviating existing semantic and technical interoperability challenges. By addressing disagreements, defining requirements, and proposing an innovative taxonomy, the research lays the foundation for a more interconnected and efficient future of urban mobility.

List of Publications

Ghazy, S., Jing Ying, W., Hoe Tang, Y., and Colpaert, P. (September 2023). Mobility Profiles: A Taxonomy for the Standardisation of Mobility Data Spaces. https://ceur-ws.org/Vol-3510/paper_sem4tra_3.pdf

Ghazy, S., Jing Ying, W., Colpaert, P., Hoe Tang, Y., and Chan, A. (2021). Linked MaaS: a vision for leveraging Semantic Web Technologies for Mobility as a Service.
https://www.webofscience.com/wos/woscc/summary/76568eb3-b10f-4da6-ae74-

Ghazy, S., Tang, YH., Mugumya, KL., Wong, JY., and Chan, A. (2022). Future-proofing Klang Valleys veins with REBET: A framework for directing transportation technologies towards infrastructure resilience.
https://www.sciencedirect.com/science/article/pii/S00401625220019 86

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Chapter 1

1. Introduction

1.1 Overview

Any musician can play alone, but it takes additional skills to be able to play well in an orchestra" (Cottet, 2021).

Integration of mobility providers is like putting an orchestra together. Envision the modes of transport as the musical instruments and the operators or providers as the musicians. While musicians can perform solo, in an orchestra, each musician must learn to play their own instrument in a way that fits seamlessly among others. The services of the transport providers are heterogeneous, from the data fueling them, to their varying business rules, their unique ticketing and payment systems, and their incompatible organisational goals. To integrate these heterogeneous elements, the transport providers need an orchestrator to harmonize their individual modes, services, and offers into a seamless experience for the customers. This led to the emergence of a Mobility-as-a-Service (MaaS) provider to act as the conductor of the transportation orchestra.

One might argue, why should we even bother to integrate transportation? Non-integrated transport systems precipitate the following inconveniences (Mrníková et al., 2017): (1) Non-synchronous timetables and connections between different mobility providers resulting in inaccurate Estimated Time of Arrival (ETA), (2) Multiple ticket purchases required, most likely using different ticketing systems, causing confusion and inconvenience to the users, and (3) Lack of an easy-to-understand information system that covers all mobility opportunities. This leads to difficulty in planning out a trip individually. These points delineate that a lack of integration mainly neglects the customer experience hence driving them towards individual automobiles and spatially inefficient modes.

By decreasing the ridership of sustainable modes, public transport operators are bleeding money and problems such as congestion and environmental pollution are augmented hence deteriorating the quality of life. Building upon modern day technologies, the concept of Mobility as a Service (MaaS) was proposed as a solution to integrate transportation with an aim to move people away from car ownership. However, the implementation of MaaS faces a number of challenges stemming from the lack of interoperability at a semantic, a technical, an organisational, and a legal level of the different stakeholders needed to participate in actualising the concept.

A review of the state of development of existing MaaS data ecosystems showed that a development of a unified standard will not be a suitable solution for MaaS (MaaS Alliance Working Group 3, 2021), instead, the focus should be on aligning current standards. The European Commission initiated Mobility Data Spaces, a method for regulating Multimodal Digital Mobility Services (MDMS). A Data Space is defined as *"a decentralised infrastructure for trustworthy data sharing and exchange in ecosystems based on commonly agreed principles"*. The IDS Association (IDSA) put together a position paper to define the design principles of an IDS which include a) Data sovereignty, b) Data level playing field, c) Decentralised soft infrastructure, d) Public-private governance (International Data Spaces Association, 2021a). While these principles provide high-level characteristics, there is no guidance specific to each domain. Further review identified a gap in standardising the entry of operators into a Mobility Data Space which would lead to silo-ed MaaS data ecosystems. Designing a solution to fill this gap is required, yet, there are no clear interoperability requirements for Mobility as a Service. To identify, understand, and devise a solution for standardisation, we must first be able to clearly define the interoperability requirements of MaaS.

This introductory chapter begins by discussing the problem statement behind this research followed by the aim and objectives. The scope of the research is outlined through the understanding of this research to MaaS and the term interoperability within the context of this work. Furthermore, an overview of Semantic Web Technologies is added to provide the reader with a brief explanation of the technology explored to improve the interoperability of the MaaS data ecosystem. The research questions are then covered followed by an summary of the contributions of this work to the field of knowledge. References to the following chapters are presented throughout, in addition to a section describing the arrangement of the thesis at the end of this chapter.

1.2 Problem statement

In the transportation domain, each mobility service generates data. The data is commonly stored in a certain structure, with inherent semantics that describe the data, and different access rules. Mobility-as-a-Service aggregates data from heterogeneous sources, not only transport data of varying types of mobility, but also factors affecting the success of a user's trip. Every time a MaaS provider integrates a transport operator, they are expected to merge their data into the MaaS ecosystem.

With the development of Data Spaces, better governance exists for designing data ecosystems for MaaS, however, there are no domain specific guidance that outlines the semantics, syntax, or data exchange specifications to adhere to. Therefore, the process of on-boarding a transport operator into a MaaS ecosystem is not standardized as operators commonly follow different standards better suited for their own services and business rules.

Consequently, the current approach to setting up a Data Space is to impose a specific standard and specifications which is done independently for each Data Space. While this allows the development of MaaS solutions, it will lead to silo-ed Data Spaces that increases the diameter of the current walled gardens from a single operator's database to a single MaaS Data Space.

Therefore, a solution is required to standardise the entry of stakeholders into a MaaS data ecosystem. However, there are no clear interoperability requirements set out for MaaS. Therefore, to design a solution that meets the needs of the ecosystem, we must first define the interoperability requirements of MaaS.

1.3 Aim

The aim of this research is to design a solution that standardises the entry of transport operators into a MaaS data ecosystem. To design a solution that meets the needs of the ecosystem, the research aims to first define the interoperability requirements of MaaS according to which the solution will be proposed.

1.4 Objectives

In pursuit of achieving the research aim, the following objectives were sketched out to guide the research plan:

1. To investigate reasons why stakeholders disagree over the implementation of MaaS, identifying the rationale behind different approaches to MaaS.

2. To examine the maturity of MaaS business and data interoperability, defining a set of requirements for each.

3. To propose a solution for standardising the entry of transport operators into a MaaS data ecosystem that meets the defined data interoperability requirements.

4. To demonstrate the practicality of applying the proposed solution in a data exchange process.

1.5 Research scope

1.5.1 Mobility as a Service

Mobility as a Service (MaaS) promises to dissolve the boundaries of todays transport network through the integration of transport modes. To date, several definitions have been developed for the term MaaS, as elaborated on in subsection 2.1.2, however, MaaS remains a blurry concept. The most comprehensive definition in light of this research is defined by Hensher et al. (2021) as *A framework for delivering a portfolio of multi-modal mobility services that places the user at the centre of the offer. MaaS frameworks are ideally designed to achieve sustainable policy goals and objectives. MaaS is an integrated transport service brokered by an integrator through a digital platform. A digital platform provides information, booking, ticketing, payment (as PAYG and/or subscription plans), and feedback that improves the travel experience. The MaaS framework can operate at any spatial scale (i.e., urban or regional or global) and cover any combination of multi-modal and non-transport-related multiservice offerings, including the private car and parking, whether subsidised or not by the public sector. MaaS is not simply a digital version of a travel planner, nor a flexible transport service (such as Mobility on Demand), nor a single shared transport offering (such as car sharing). Emerging MaaS best describes MaaS offered on a niche foundation. This relates to situations where MaaS is offered on a limited spatial scale, to a limited segment of society or focused on limited modes of transport. The MaaS framework becomes mainstream when the usage by travellers dominates a spatial scale and the framework encompasses a majority of the modes of transport.*

As demonstrated in the definition above, MaaS is a complex realm that demands the active involvement of and cooperation between multiple stakeholders such as transport operators, public transport authorities, and end-user routing application developers. The progress towards the seamless vision of MaaS, which provides users with a carefree experience of planning, booking, and payment of transport services, requires integration at multiple levels of the MaaS ecosystem. These include data integration for journey planning, ticketing and payment integration, and the integration and alignment of stakeholder's commercial goals.

1.5.2 Interoperability

The term interoperability can have a broad understanding. With regards to MaaS being a set of densely interconnected and heterogeneous firms and resources, its interoperability scope must cover elements beyond the technological aspect. This was best expressed by the European Commission (2010) definition for interoperability, within the context of European public service delivery as *"the ability of disparate and diverse organisations to interact towards mutually beneficial and agreed* ***common goals****, involving the* ***sharing of information and knowledge*** *between the organisations, through the* ***business processes*** *they support, by means of the* ***exchange of data between their respective ICT systems****."*

Highlighted in bold are the key areas for which interoperability must exist between MaaS stakeholders in order to integrate their services. Yet, a few questions remain:

1. Does interoperability already exist in any of these areas between MaaS stakeholders?
2. To what extent is interoperability developed in each area?
3. To what extent is interoperability required in each area?
4. Which area should be prioritized in order to push MaaS forward?

For the scope of this research, the interoperability requirements of MaaS is first explored as there exists no prior investigation specifically focusing on the maturity of MaaS interoperability. Only the maturity of the business interoperability and data interoperability are investigated with a focus on conceptual, technological, and organisational barriers according to (Leal et al., 2019). Defining a set of interoperability requirements is a prerequisite to designing a solution to improve the interoperability in the ecosystem. Subsequently, the research focuses on developing a data solution that meets these defined requirements to fill the gap of standardisation. Semantic Web Technologies (SWTs) are explored as a set of tools with the potential to shape the proposed data solution given their inherent characteristics of improving interoperability.

1.5.3 Semantic Web Technologies

The Semantic Web is a machine-readable Web being built through Semantic Web technologies. Similar to how traditional Web technologies define and interconnect **web pages**, Semantic Web Technologies aim to define and interconnect **data** (Lyngdoh, 2013). Semantic Web Technologies facilitate the integration and linking of data from heterogeneous sources, in addition to, querying and retrieving information across these sources (Khan et al., 2011). The core operation of the Semantic Web relies on rich computer languages that are used to encode knowledge for processing (Hitzler et al., 2010). Beyond enabling a seamless integration and exchange of data, Semantic Web Technologies can be leveraged for two further purposes. The first is to develop *abstract models* that reflect the complexity of the world in the form of simpler ideas (Hitzler et al., 2010). The second is *reasoning* over encoded knowledge to infer new and meaningful information (Hitzler et al., 2010). Fundamental to the encoding languages is the Resource Description Framework (RDF) which is a graph-based data model that can disambiguate data by providing assertions about each resource. This is made possible through its reliance on IRIs that gives each resource a globally unique ID on the Web. Defining *classes and subclasses, properties and subproperties, domains, and ranges* is predominantly done following the *RDF Schema (RDFS)*[1] standard. More complex assertions and statement constructs are supported by the *Web Ontology Language (OWL)*[2]. OWL supports better machine interpretability and hence, it is more strongly employed for reasoning over knowledge (Lyngdoh, 2013). Multiple other technologies are applied for particular uses including SHACL for validation[3], the query language SPARQL[4], the RDF Mapping Language (RML) [5], and others. The characteristics of Semantic Web Technologies offer an opportunity to improve the interoperability of MaaS data ecosystems and hence, achieve the research aim of this project as described in section 1.3.

[1]Full documentation of RDFS at w3.org/TR/rdf-schema/
[2]Full documentation of OWL at w3.org/TR/owl2-overview
[3]Full documentation of SHACL at w3.org/TR/shacl
[4]Full documentation of SPARQL at w3.org/TR/rdf-sparql-query
[5]Full specification of RML at https://rml.io/specs/rml/

1.6 Research Questions

From the objectives of this research, 6 questions were derived to address the problem statement.

RQ-1: What are the disagreements over the implementation of MaaS and what is causing them?

RQ-2: What are the current and desired levels of business and data interoperability?

RQ-3: What are the business and data interoperability requirements of a MaaS ecosystem?

RQ-4: What characteristics must the data exchange process possess in order to meet the requirements?

RQ-5: What data solution would meet the defined characteristics?

RQ-6: How does the proposed data solution fit within the current data ecosystems?

1.7 Research Significance

The significance of this research lies in its comprehensive approach to addressing the multifaceted challenges hindering the realization of MaaS ecosystems. By defining clear interoperability requirements for MaaS and classifying the maturity levels of both business and data interoperation elements, this research will serve as a guidance for the development of MaaS ecosystems. The expected contribution of this research can be seen through two complementary lenses. Firstly, it offers an interoperability roadmap that provides MaaS stakeholders with actionable insights on how to design their ecosystems based on their current levels of integration and its corresponding interoperability requirements. This roadmap, grounded in the findings from the qualitative research involving experts from diverse backgrounds, addresses key dichotomies surrounding MaaS and identifies the critical barriers that must be overcome for a sustainable MaaS ecosystem to emerge. Secondly, the data solution classifies the different cases of transport operations offering a method for standardising the entry of transport operators into a MaaS data ecosystem.

As this solution is designed according to the characteristics derived from the interoperability requirements, it guarantees an improvement in interoperation between stakeholders. The demonstration of its use along with the incorporation of Semantic Web Technologies provides a practical example that enables the direct application of the data solution. Together, these contributions not only advance the academic understanding of MaaS but also provide invaluable guidance for policymakers, industry players, and technologists working to shape the future of urban mobility.

1.8 Thesis Organization

The report begins with a literature review in chapter 2 which is divided into four main sections. Section 2.1 covers a thorough exploration of the MaaS literature and provides a partial answer to **RQ-1** by identifying the areas of disagreement over the implementation of MaaS. Next, section 2.2 encapsulates a complete picture of the current industry status of data exchange in the MaaS ecosystem. It begins by laying down the context of data and interoperability within this research followed by a detailed description and comparison of the current industry practices in MaaS data sharing.

To provide a preamble of Semantic Web Technologies, section 2.3 delineates a brief overview of the main technologies that serve as pillars of the Semantic Web Stack. The next section, section 2.4, is closely related as it examines the existing implementations of SWTs in the field of transportation, specifically focusing on the relevant applications to MaaS data exchange.

Subsequent to the literature review, an outline of the methodology is describe in Chapter 3. The research is divided into two main chapters: chapter 4 and chapter 5. The first chapter presents the qualitative research which investigates MaaS Dichotomies and MaaS Interoperability maturity leading to a defined set of interoperability requirements. The second chapter presents the development of the data solution for a standardised entry of transport operators into a MaaS Data Space. Each of these chapters presents its own brief background, methodology, results, discussion, and conclusions.

The research is summed up in the final chapter: chapter 6. This presents a summary of the key findings, the main research outcomes and contributions, the implications of the outcomes in practice and their relation to existing theory, the limitations of the study, and future research recommendations.

Chapter 2

2. Literature Review

2.1 Introduction to Mobility-as-a-Service

2.1.1 The mobility challenge

It is commonly misconceived that the rising number of mobility solutions, such as e-hailing platforms, bike-sharing, and microtransit services, brought along nothing but the betterment of transportation. Such solutions were expected to reduce traffic congestion, environmental pollution, and improve the quality of life, however, they ended up rather compounding these problems in addition to introducing nuances of their own.

Schaller (2021) investigated the impact of ride-hailing and car-pooling in the United States on vehicle miles travelled (VMT)[1] through both Uber and Lyft's pre-pandemic data. Results show that VMT at least doubled when compared to passengers' previous modes. This is mainly a consequence of the increase in dead-headed miles before each pick up, as well as, the switch of users to pooling from more efficient and sustainable modes (public transport/walking/cycling). Multiple studies across the globe have shown the same results besides increased congestion delays (Tirachini et al., 2020; Agarwal et al., 2019; Erhardt et al., 2019; Tirachini and Gomez-Lobo, 2019; Henao and Marshall, 2018). In addition to such negative effects, new mobility opportunities compete with rather than complement spatially efficient modes (Shi et al., 2020; Regina R. Clewlow, 2017). *"Spatial efficiency is defined as passengers per vehicle/train consist (or per unit road space equivalent) whilst temporal efficiency can be considered as the proportion of time a vehicle spends on the road (in revenue service for public transport)"* (Wong et al., 2020).

[1]Vehicle Miles Travelled (VMT) - the sum of the number of miles traveled by each vehicle over a given period of time.

Hensher et al. (2020) states that replacing public transport through service price and quality is a declared objective by many transport network companies (TNCs). TNCs are commonly technology providers which coordinate rides through connecting passengers to drivers.

However, competition between private mobility companies and public transport is nowhere near a level playing field. Firstly, TNCs are not bound to paying minimum wages as the drivers are not employees. Secondly, the commercial goals of public and private transport operators differ. On one hand, public transport is more concerned with government objectives for a city and as a result, commonly limited by fare regulations and the allocated funding. On the other hand, private mobility is profit and hence customer-oriented, providing better quality for a higher price. The misalignment of goals and lack of cooperative competition is the main driver against the possible integration of transport.

Nevertheless, emerging mobility providers and transport operators possess the required resources to tackle the challenges of transportation in urban environments. But the intrinsically fragmented ecosystem of these stakeholders, as well as the contradicting goals between public and private sides, brings about the main barrier to identifying and exploiting synergies between them. In order to harmonize the existing chaos in transport systems, there is an urgent need for an orchestrator. Governments have long sought to integrate transportation services while keeping the competition thriving. Attempts include master transport plans to institute city/region wide policies in transport operations (Ülengin et al., 2007) as well as the adoption of vertical and horizontal integration models for railways (Cui and Besanko, 2016). Vertical integration is where a specific party builds and maintains the rail tracks while other companies run the day-to-day operations, with competition taking place between the operators of the lines. Whereas a horizontally integrated model has the same company maintaining and operating the lines and competing with other companies doing the same. But with a multitude of TNCs and private mobility companies coming into the picture, a new form of integration is required that orchestrates all available mobility opportunities in a city and allows for a non-monopolistic market. This led to the rise of Mobility-as-a-Service (MaaS), an emerging concept that is anticipated to play the role of the orchestrator.

2.1.2 Conceptualisation of MaaS

> *"**Ownership is shifting away.** Pretend you live inside the world's largest rental store. Why would you own anything? You can borrow whatever you need within arm's reach. Instant borrowing gives you most of the benefits of owning and few of its disadvantages. You have no responsibility to clean, to repair, to store, to sort, to insure, to upgrade, to maintain."* (Kelly, 2016)

Recently, technology has pushed forward a new trend that promotes selling the functionality of a product rather than the product itself (Örsdemir et al., 2019). This move of servitization is now common to most of our households, whereby rather than buying products we just subscribe to have them as a service. If you feel like watching a movie or a TV show, Netflix is your first go-to. You no longer need to own any CDs or music albums as you get them all through your Spotify subscription. And now almost 800,000 books are at your access through Amazon's Kindle Unlimited. Transportation, as well, could not escape this trend. Uber, the well renowned on-demand taxi service, is a main disruptor of legacy transport business models. Not only for the convenience it brought about to users through its service, but also for the fact that Uber does not own any of its vehicles, providing one of the most successful examples of platform-based business models. Platform business models facilitate the connection between two or more user groups (Zhao et al., 2020) such as drivers and riders, in the case of Uber, or buyers and sellers, in the case of Amazon. Such platforms gave birth to the sharing economy which is defined by Botsman and Rogers (2010) as *an economic system based on sharing underused assets or services, for free or for a fee, directly from individuals*. Servitization, platform business models and the sharing economy inspired a new direction in transportation nowadays referred to as *"Mobility-as-a-Service"* (MaaS).

The first mention of the term Mobility-as-a-Service, henceforth referred to as MaaS, in the literature appeared in 2014. Only two publications mentioned the term in that year. Heikkilä (2014) described MaaS as *a system in which a comprehensive range of mobility services are provided to customers by mobility operators*. Hietanen (2014), who is commonly referred to as the father of the MaaS concept, laid out a vision for MaaS to be the road to replacing a private car. He referred to MaaS as a distribution

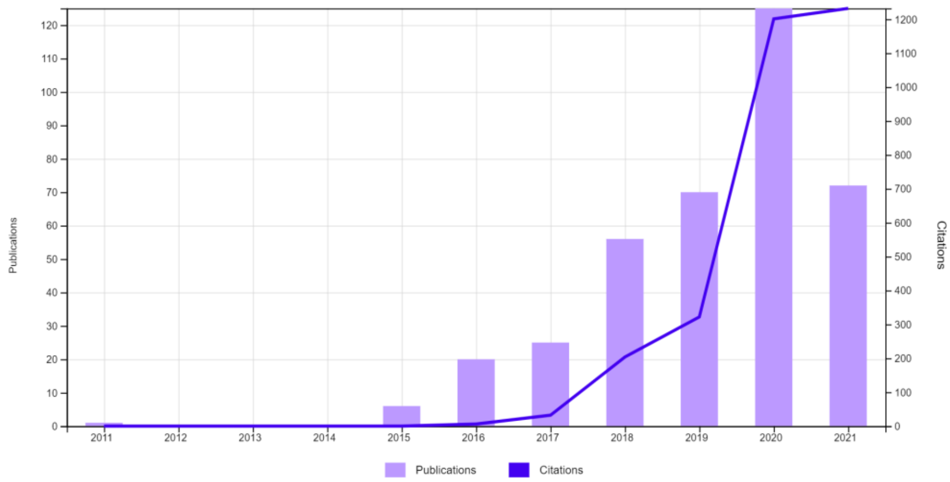

Figure 2.1 Growth of the literature on MaaS across the years. The bars show the number of publications while the line shows the number of citations (Web of Science query) [2]

model, hence implying that MaaS is a restructure of the manner in which transport services go from the point of manufacturing to the outlet through which they are offered to customers (Tobler-Rohr, 2011). Distribution models can range from a simple direct channel to more complex channels incorporating a wholesaler, distributors, brokers, etc. Hietanen (2014) went on to shape MaaS as a single interface offered by a service provider that caters for the customer's transportation needs, commonly including various transport services bundled into packages. The idea of bundling transport services into packages is analogous to monthly mobile packages offered by the telecommunications sector.

In subsequent years, the term's frequency in the literature has exponentially grown as shown in Figure 2.1 which is extracted through an in-depth bibliographic analysis of the full record of 347 articles on MaaS, extracted through the query `ALL=("Mobility as a Service")` from Web of Science. The query[2] was performed on July 20th, 2021. Sochor et al. (2018) presented a topology of MaaS, consisting of five levels of integration, to aid in the comparison of different services. The levels are described as follows:

Level 0: No integration

Level 1: Integration of information - A platform which provides information about a trip. At this level, the information is centralised and only helps users identify the best route for their trip through a multi-modal journey planner. *E.g. Google maps, Qixxit, Waze, etc.*

[2]https://www.webofscience.com/wos/woscc/summary/76568eb3-b10f-4da6-ae74-7f851a6ac50b-01778e8

Level 2: Integration of booking and payment - A platform that allows users to plan, book, and pay for a journey/trip. This level does not promise a replacement to car ownership as it is only used on a trip-by-trip basis. *E.g. HANNOVERmobil, Smile, etc.*

Level 3: Integration of the service offer - At this level, the platform focuses on providing an offer that caters for the complete mobility needs of a customer, hence, promising an alternative to car ownership. The platform offers mobility packages, possibly on a subscription-basis considering the customer's experience throughout the day, across different seasons and conditions, rather than on a trip-by-trip basis. Hence, this level offers a truly unified Mobility-as-a-Service solution. *E.g. Whim, UbiGo, etc.*

Level 4: Integration of societal goals - At this level, a platform operates beyond providing a service to its customers. A few examples of achieving this level include incorporating incentives that shift users towards sustainable and efficient modes, balancing demand on different modes, reducing congestion and carbon emissions, and working towards the improvement of a city's transportation network. *At the time of this writing, there are no examples of MaaS platforms that operate at this level.*

Kamargianni et al. (2016a) also presented a method for defining the level of integration achieved by MaaS solutions. They developed a scoring system based on 5 attributes that add up to a *"MaaS Integration Index"*. These attributes are: **(1) ticket integration** - one access method for all modes using a smartcard for example (higher score for a higher number of accessible modes), **(2) payment integration** - a single invoice, **(3a) Journey Planner (ICT integration)** - platform offers a journey planner to the users, **(3b) Booking function (ICT integration)** - a user can book a trip through the platform, **(4) Mobility package integration** - platform offers mobility packages. Unsurprisingly, the highest MaaS Integration Index was achieved by Whim followed by UbiGo, similar to the results of Sochor et al. (2018). This signifies some evidence towards an underlying consensus on what Mobility-as-a-Service represents. However, a further investigation of the ever-growing literature on the concept of MaaS revealed new definitions and contradictions. While the definition of MaaS remains in-explicit to date, there are some specific areas of consensus as highlighted below:

(a) **Single Platform with aggregated transport modes** - There seems to be a consensus regarding the necessity of a MaaS system to provide various transport/mobility options through a single interface:

> *...a customers major transportation needs are met through the use of one interface..."* (Hietanen, 2014)

> *a system, in which a comprehensive range of mobility services are provided by customers to mobility operators.* (Heikkilä, 2014)

> *...personalised on-demand service that integrates all types of mobility opportunities..."* (Atkins Ltd, 2015)

> *MaaS, a multi-actor environment that provides seamless door-to-door services for end users by combining several modes of transportation.* (Ghanbari et al., 2015)

> *...consumers can buy mobility services that are provided by the same or different operators by using just one platform and single payment"* (Kamargianni et al., 2015)

> *MaaS relies on a digital platform that integrates end-to-end trip planning, booking, electronic ticketing, and payment services across all modes of transportation, public or private."* (Goodall et al., 2017)

> *...where all mobility service providers offerings are aggregated by a sole mobility provider the MaaS provider, and are supplied to users through a single digital platform"* (Kamargianni and Matyas, 2017)

> *...which offer an individualised one-stop access to several bundled travel services, based on customers needs"* (Stopka et al., 2018)

> *uses a digital platform to bring all modes of travel together into a single on-demand service..."* (Ho et al., 2018)

> *combining transportation services from public- and private-transportation providers through an integrated mobility platform'"* (Audenhove et al., 2018)

> *MaaS systems offer customers personalised access to multiple transport modes and services, owned and operated by different mobility service providers, through an integrated digital platform for planning, booking and payment.* (ITS Australia, 2018)

Multiple definitions picture MaaS as a mobility aggregator that combines various modes of transport, however, there exists very few definitions which imply that the use of many interfaces still satisfies MaaS, such as the definition by Transport Committee (2018) stating *MaaS is a term used to describe digital services, often smartphone apps, which people use to access a range of public, shared, and private transport, using a system that integrates the planning, booking and paying for travel."*. Despite the large consensus on the use of a single application that provides multiple transport options, there is a lack of agreement on **whether MaaS should present an open platform for all mobility opportunities in a region or rather a selection of the possible options.** For example, should a MaaS provider form exclusive relationships with mobility operators of each mode or rather provide a one-stop-shop for any mobility opportunity in a region?

(b) Journey Planner/Routing - The second characteristic of MaaS which achieved a wide consensus is the need for the single platform to be supplemented with a journey planner/routing function to aid the user in determining the optimum route for their trip. Examples of definitions which identify this function are by Goodall et al. (2017) *"...end-to-end trip planning..."*, Kamargianni and Matyas (2017) *"...integration of the currently fragmented tools and services required by a traveller for a trip (planning, booking, real time information, payment, and ticketing)"*, Transport Committee (2018) *"...integrates the planning, booking and paying for travel."*, and more. However, there are a number of unclear characteristics of the routing function. These are described below:

Type of modality - there is no clear requirement on whether the journey planner should be capable of producing inter-modal trips (i.e. a single trip with many modes but each leg of a trip can be under a different operator/provider)

Level of routing intelligence - there is no emphasis on the accuracy of the routing function. For example, should the route optimization algorithm take into account real-time factors? produce context-aware recommendations? consider user preferences? balance demand on all the modes in a region?

Scheduling Type - while some definitions explicitly denote that MaaS should provide an on-demand service, there is a lack of evidence on whether a pre-scheduled service is equally representative of MaaS.

(c) Ticketing & Payment Integration - To achieve Mobility-as-a-Service, it is important to provide a seamless experience to the user. This demands the integration of currently fragmented elements in the transportation network as described below:

Payment method - At this time, different mobility services such as public transport, bike-sharing, car-sharing, ride-hailing, etc. each have different payment methods. Some support using online banking, your VISA or MasterCard, or their own e-wallets. To provide a truly integrated service for MaaS users, a unified payment method must be supported by all modes on the platform.

Access method - To pass the Transit Fareboxes, to unlock the shared car you booked, or to take an e-scooter for a ride, you need a method of access. This can be a smartcard, scanning a barcode through your application, or even using a bracelet or ring. To achieve a seamless user experience, it is important for the MaaS application to grant its users access to all available modes through a unified access method. This presents a major ticketing integration challenge for actualizing MaaS.

Single invoice - if a user were to embark on a trip that combines multiple modes, there are different payment interfaces for each mode. This leads to multiple invoices per trip. In a truly unified MaaS system, a single invoice is generated and paid for the entire trip, regardless of the number of mode switches a trip includes.

While these three unification elements are requirements of a MaaS system, it is unclear whether one or the other is more important for MaaS to achieve.

(d) Mobility Packages - A significant number of MaaS definitions and explanations emphasize on the necessity of including personalized mobility packages. Some examples include *"Typically, services are bundled into a package similar to mobile phone price-plan packages"* by Hietanen (2014) and *"A concept which allows households to purchase packages of mobility that provide an alternative to car ownership."* by Cox (2015). In developing the five levels of integration, Sochor et al. (2018) stated that adding personalised packages to a MaaS application is the key to providing a system with a potential of replacing private car ownership. However, multiple sources also state the need to offer a pay-as-you-go service. The difference between these schemes is similar to prepaid and post-paid schemes. In a pay-as-you-go service, consumers pay for every trip as they make it, while if they subscribed/purchased a mobility package, a certain amount is paid by the user for a bundle of customized services. For example, paying a fixed amount per month for unlimited access to public transport, 5 car sharing rides, and a season pass for bikes.

(e) **Multi-Services** - In addition to transport services, some definitions emphasize the need for a MaaS system to provide additional services such as shopping and delivery of groceries and other goods. Take for instance the definition by Mukhtar-Landgren et al. (2016) which states MaaS is *"...perhaps also involving other service components such as goods delivery or bicycle repair services."*. In reviewing sustainable MaaS business models, König et al. (2016) included pilots and projects that purely offered delivery of goods. Therefore, recognizing applications for logistics and deliveries as part of the MaaS realm. In conclusion, there is no consensus on which is more representative of a MaaS system (1) the transportation of goods being revolutionized by MaaS similar to passenger transport or (2) the transportation of goods will only be an add-on to passenger MaaS applications.

(f) **User Preferences** - Heavily emphasized on by most definitions is the user-centricity of MaaS. Some research was conducted to understand a user's perspective and expectations of MaaS in different regions of the world.

As discussed, the term *Mobility-as-a-Service* is still shaping. There are multiple definitions in the literature with varying elements and directions for what MaaS should and shouldn't be. The most recent and comprehensive definition of MaaS was offered by Hensher et al. (2021) where they stated that *MaaS is a framework for delivering a portfolio of multi-modal mobility services that places the user at the centre of the offer. MaaS frameworks are ideally designed to achieve sustainable policy goals and objectives.*

MaaS is an integrated transport service brokered by an integrator through a digital platform. A digital platform provides information, booking, ticketing, payment (as PAYG and/or subscription plans), and feedback that improves the travel experience. The MaaS framework can operate at any spatial scale (i.e., urban or regional or global) and cover any combination of multi-modal and non-transport-related multiservice offerings, including the private car and parking, whether subsidised or not by the public sector. MaaS is not simply a digital version of a travel planner, nor a flexible transport service (such as Mobility on Demand), nor a single shared transport offering (such as car sharing). Emerging MaaS best describes MaaS offered on a niche foundation. This relates to situations where MaaS is offered on a limited spatial scale, to a limited segment of society or focused on limited modes of transport. The MaaS framework becomes mainstream when the usage by travellers dominates a spatial scale and the framework encompasses a majority of the modes of transport. This definition aligns with the direction of this research, yet the contradictions or dichotomies identified above are further explored in a mixed method study to develop a clearer understanding of MaaS interoperability requirements. Figure 2.2 shows a summary of the discussed MaaS characteristics. The outer circle is a representation of the aforementioned elements with each of them being equally representative at the moment as there is no prior investigation of their relative importance in the constitution of MaaS. The inner circle is yet to be defined after the completion of the mixed method study which will look into the relative importance of each characteristic as well as the reasoning behind the existing dichotomies under each element.

2.1.3 Mobility-as-a-Service Implementation

Despite the appeal towards the potential of MaaS in making transportation more convenient and sustainable, the current implementations of MaaS continue to face barriers hindering their scalability. Karlsson et al. (2019) investigated the factors driving and slowing the development and implementation of MaaS with a focus on Finland and Sweden for the case study. The findings of the research highlight legislation and political will as key factors for driving MaaS. These denote the need for a shared vision in order to push MaaS forward. At a secondary level, the collaboration of stakeholders is a key enabler which will promote the development of an equitable business model, which to date is still struggling to be formed. At a micro level, Karlsson et al. (2019) indicate the effects of the passengers

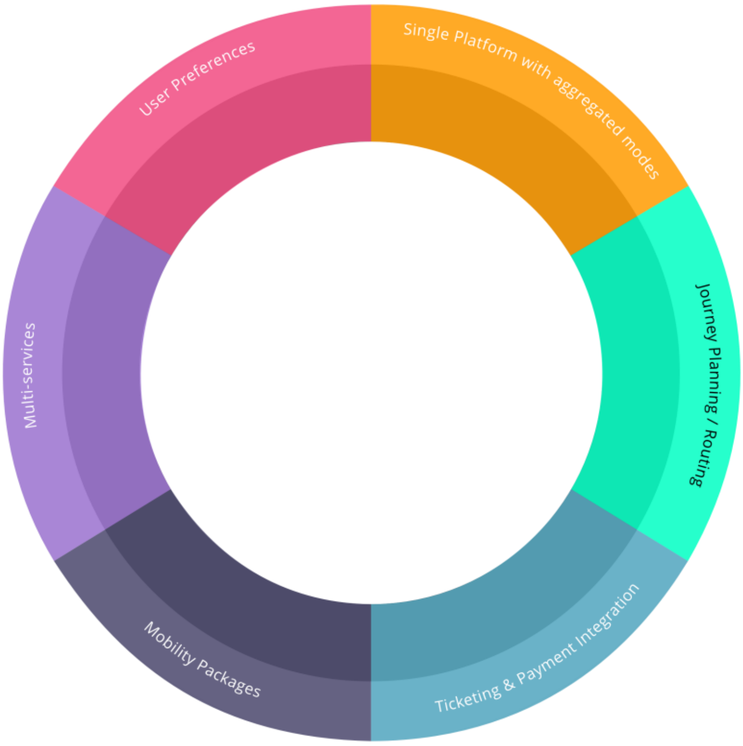

Figure 2.2 The Mobility-as-a-Service Donut: A premature representation of the service requirements of MaaS

perception and travel habits to be of significant importance to the success of MaaS.

In 2019, the MaaS Alliance Governance and Business Models Working Group publish a report highlighting the main challenges associated with MaaS along with their recommended approaches towards overcoming them (MaaS Alliance, 2019). The challenges were articulated in 7 questions as follows:

1. How to gain Market Access and overcome Integration Barriers?
2. How to build successful Public-Private-Partnerships?
3. How to overcome Sales Channel Restrictions and achieve payment Integration?
4. How to achieve Scalability?
5. How to develop Trust and Collaboration?
6. How to define Principles in Data Sharing and Data Access?
7. How to overcome the Lack of Knowledge and Understanding?

A more recent study by Butler et al. (2020) further elaborate on the barriers to the actualization of MaaS through a detailed literature review. The paper divides the barriers into supply driven and demand driven barriers. On the supply's side, Butler et al. (2020) summarise the factors to be (1) Lack of collaboration, (2) Lack of business support, (3) Lack of coverage, (4) Lack of shared vision, and (5) Lack of security. On the demand's side, the factors are (1) Appeal to older generations, (2) Appeal to public transport users, (3) Appeal of platform, (4) Willingness-to-pay, (5) Tradition of private vehicle. To date, MaaS is still hindered by the same problems, but the different implementations are striving to overcome them in their own ways. The following sections will narrow the focus on the barriers at the data level of MaaS.

2.2 Integration of Mobility Providers

2.2.1 Data Preamble

- This is an object.
- The object has a maximum capacity of 12 people.

What is it?

Coming across these observations, it is quite difficult to guess what the object is referring to. Perhaps, an elevator? a helicopter? Now if we connect these observations to more observations:

- This is an object.
- The object has 4 wheels.
- The object can move.
- The object can transport people.
- The object has a maximum capacity of 12 people.
- The object is of a white glossy color on the outside.
- It is colder inside the object during summertime.
- The object has seats inside it.

Reading through this list of observations, one can deduce that the object is a 12-seater vehicle. A single piece of observation can be referred to as data, but as demonstrated, a datum on its own doesn't give you much context. Ackoff (1989) presented 5 progressive levels of the content of a human's brain, starting with (1) ***data*** which are merely symbols that denote properties of objects, people, events, and their environments, (2) ***information*** where data is given context through connecting data to each other, however, information is not always useful. But to achieve (3) ***Knowledge***, information is put together with an intent of being useful. The next level would be (4) ***Understanding***, which is a process of analyzing the existing knowledge to infer or deduce new knowledge. The difference between the level of *understanding* and the level of *knowledge* is analogous to the difference between "learning" for the former and "memorizing" for the latter. And lastly, reaching a level of ***wisdom*** which requires a mental function we call *judgement*. This level utilizes special types of human programming such as morals, ethics, etc. that are inherently connected to one's thoughts, ideals, and personal beliefs of right and wrong. Hence, it is believed that machines can never achieve a level of Wisdom (Ackoff, 1989; Bellinger et al., 2004).

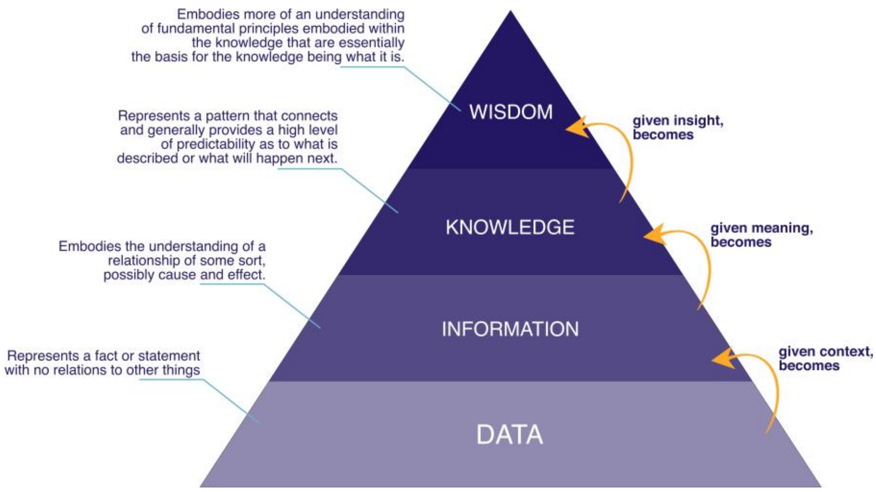

Figure 2.3 A representation of Data, Information, Knowledge, and Wisdom (Adapted from Bellinger et al. (2004))

Bellinger et al. (2004) redefined these 5 levels by extracting *understanding* as an independent level and including it as part of the transition between each of the levels as shown in Figure 2.3 and Figure 2.4. As demonstrated by the chart in Figure 2.4, the connectedness of data increases the level of understanding we have of a given dataset. Humans have since developed different ways of documenting data in a manner

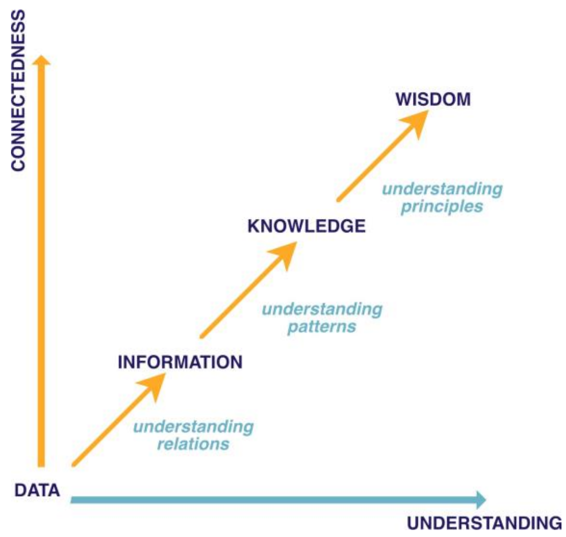

Figure 2.4 The relationship between the connectedness of data and the level of its understanding (Adapted from Bellinger et al. (2004))

where they are connected to each other. These data formats are commonly referred to as *serializations*. A common and basic form of serialization is using *Comma-Separated Values (csv)*. In a csv file, values are separated by commas. Take for example a representation of a list of participants:

```
"id", "name", "age"
 "1235", "John Doe", "31"
 "1236", "Marie Jane", "25"
```

This is an example of how a csv file can be arranged, which if imagined in an excel sheet would have the first line represent column headings and the subsequent lines represent rows of data. But csv files can be arranged in other ways depending on a higher-level specification. CSV, as well as other formats such as *Javascript Object Notation (json)* or *Extensible Markup Language (xml)* only specify a certain *syntax* which defines the structure of separating the different data elements. Every system is developed by human beings, which characteristically have their own ways of thinking. A very intuitive form of serialization that is as close to how a brain thinks is modeling data in a graph. A graph consists of nodes and edges which individually represent human sentences. For example, the participants above will be named: `Participant` $\xrightarrow{name}$ `“John Doe”`. A statement like this is called a *triple* which consists of a `Subject` $\xrightarrow{predicate}$ `Object`. Formal serializations of triples are *Turtle* and *N-triples* but triples can also be encoded within the aforementioned serializations. Nonetheless, the data structure in a specific system is always subject to the human setting up this system. Therefore, in order to share data across different systems, interoperability issues take place at different levels of data integration. The term interoperability and its different layers are discussed in the next section.

2.2.2 Interoperability

If you were to look up the term interoperability on the internet, the first definitions that show up are mostly related to computer systems. Undoubtedly, the communication of such systems falls under interoperation, but the concept is not limited to that. Having been a subject of concern for over 30 years, *interoperability* refers to the ability of different systems and organizations to work together (Rezaei et al., 2014). This is an eminently broad understanding leading to questions like *"What systems are we talking about here?", "What does it mean for them to work together?"*

Towards laying a deeper understanding of the term interoperability, multiple definitions have been established. Institute of Electrical and Electronics Engineers (IEEE) (1990) defined it as *"The ability of two or more systems or components to exchange information and to use the information that has been exchanged."* ISO/IEC (1993) specified it as *"The capability to communicate, execute* programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units."* Similarly, The Open Group (2006) described it as *"The ability of systems to provide and receive services from other systems and to use the services so interchanged to enable them to operate effectively together."* The definition that resonated most with the direction of this research was one that looked at interoperability beyond just technology systems, which is a definition by European Commission (2010):

> *"**Interoperability**, within the context of European public service delivery, is the ability of disparate and diverse organisations to interact towards mutually beneficial and agreed **common goals**, involving the **sharing of information and knowledge** between the organisations, through the **business processes** they support, by means of the **exchange of data** between their respective ICT systems."*

In pursuit of achieving interoperability, we are faced with ***different barriers*** that affect different levels in a system. Chen (2017) provided a comprehensive definition of these *interoperability barriers* in the literature, dividing them into three categories, as outlined below.

1. **Conceptual Barriers** - encapsulates syntactic and semantic barriers to interoperability as defined below. These are focused on the representation of information at a high-level of abstraction. Information here does not only refer to data, but also business models, process models, and others. Conceptual barriers are the major barriers that lead to interoperability issues (Chen, 2017).

    a) Syntactic Interoperability - is derived from the compatibility of data syntax, described in subsection 2.2.1, and therefore concerned with data formats and the ability to exchange data (Veer and Wiles, 2008).

    b) Semantic Interoperability - *Semantics* refer to the underlying meaning of the data. Hence, achieving semantic interoperability is concerned with the ability to operate on data according to agreed-upon semantics (Lewis, 2006). This means that the people exchanging data have a common understanding regarding the definition of that data (Veer and Wiles, 2008).

2. **Technological Barriers** - are barriers that exist due to the involvement of computers is an interoperation. These barriers occur during the communication and exchange of information between communications-electronics systems and their users (Kasunic, 2001). Examples of these barriers are:

    a) Communication barriers - incompatibility of the protocols adopted for information exchange.

    b) Content barriers - different methods in representing information as well as incompatible tools used in encoding/decoding that information.

    b) Infrastructure barriers - incompatibility in the middleware platforms used by different applications/systems.

3. **Organizational Barriers** - revolve around the management and organizational structure of the involved enterprises. This is connected

to their organizational culture and alignment of processes and goals. In the case of incompatibility, these will require mappings before operational interoperability can be achieved. In an interoperation between enterprises, responsibilities, authorities, and harmonization of organizational structures is important. This includes legal interoperability as defined below:

a) *Legal Interoperability* - is concerned with the incompatibility of legislation governing the legal weight or validity of information being exchanged (European Commission, 2010). Such incompatibilities occur when exchanges take place across borders, where different countries/states have different rules governing data management and privacy.

In addition to the above, European Commission (2010) emphasizes on the role of political support in enabling a high level of interoperability across the different layers. There are four areas of interoperation between enterprises within which these barriers can be faced. These are referred to as *interoperability concerns* by Berre et al. (2007), namely, a) *Business level* - this is concerned with the harmonization of business vision, culture, and ICT infrastructure support between organizations who might have different organizational structures, methods of work and legislation. Business interoperability focuses on the connection points of a business rather than harmonizing the business as a whole, which would only be required in a business integration scenario. b) *Service level* - is concerned with the interoperation of applications that were designed and implemented independently. The issues faced include the syntactic and semantic description sof the services, the methods of searching and discovering a service provider, the ICT support system of service discovery, as well as the organizational incompatibilities of service exchange. (c) *Process level* - processes define the order and relationships between the different services. Interoperability of processes is concerned with making such processes work together, which also faces similar issues with regards to incompatible descriptions of processes, different organization mechanisms, and incompatible IT systems. d) *Data level* - concerns the interoperation of different data models and the use different query languages. Data can be stored on different machines, with different database management systems and different operating systems. It is, hence, a challenge to enable the sharing, access, and seamless integration of data from heterogeneous sources. Interoperation at this level is affected by the different ways people model their data (syntax and semantics), different IT infrastructure and database technologies, and different organisational policies/legislation regarding data management and privacy. The three interoperability barriers can be related to their possible effects on the interoperability levels through a matrix. This helps pinpoint the exact sources of complication in an interoperation process between enterprises. A sample matrix showing high-level descriptions is shown in Figure 2.5.

Concerns \ Barriers	Conceptual	Technological	Organizational
Business	visions, strategies, cultures, understanding	IT infrastructure	organization structures, legislations, busines rules
Service	syntax and semantics of processes	process interfaces and supporting tools	procedures of work, processes organization
Process	semantics to name and describe services	interface, architecture	responsibility /authority to manage services
Data	data representation and semantics, data restriction rule	data exchange formats	responsibility/ authority to add/delete, change/ update data

Figure 2.5 An example matrix demonstrating the connection between interoperability Barriers and Concerns (Adapted from Leal et al. (2019))

2.2.3 Data Sharing Standards and Mechanisms

A main area of concern within emerging transportation technologies is the representation of data, syntactically and semantically. In Figure 2.5, this is the intersection of the first column: Conceptual Barriers, and the last row: Data level. The digitization of transportation data led to the development of a standard, called General Transit Feed Specification (GTFS), for public transit agencies in 2015. This standard, as described later in this section, has been widely adopted since by public transport operators who want to connect their services to Google Maps. But with the rise of technology, public transport was no longer the only focus for the consumer. The surge in other transport modes and mobility innovations, meant the need for new standards specifically designed for the new use cases. As a result, various standards emerged for various use cases with the aim of "facilitating" interoperability and integration between modes.

When a standard is developed, it is common to define it up to a certain level of granularity, leaving certain issues open (Veer and Wiles, 2008). The knowledge of how a system holistically functions is expected to be understood by the standardization community rather than reside within the standard itself. An escalation in interoperability issues, such as incompatibility of protocols, syntax, and other basic building blocks, occurs when the source of the different standards stems from different standards bodies, each with their own approach to doing things (Veer and Wiles, 2008). The data islands, formed by the so called *multi-organizational standardisation*, represents the current situation of data standards in the realm of mobility. It is a viable question to ask *"So what if we have standards created and managed by different people?"* As outlined by Veer and Wiles (2008), the answer to that question lies in compounding the issues hindering interoperation as a result of:

> **Lack of an overview of the system** - If the standards are not well-specified and cross-referenced, the implementer of the standards will not have a clear overview of the system, particularly a Mobility-as-a-Service provider who is required to work with a combination of the existing standards to actualize their service.

> **Using standards beyond their original purposes** - It is no longer surprising to face a case where a standard is being used out of its original context. This can occur due to the lack of inclusion of particular use cases or newer scenarios in the specification of a certain standard.

> **Inconsistency in quality** - Each standard defines its own rules and culture for its implementation, which may significantly vary from those of another standard. For users working with multiple standards, this might be a tricky situation that leads to mistakes and confusion in digesting different concepts.

To illustrate the current situation of data standardization within the transportation network, a comprehensive review covering the major standards related to the implementation of MaaS solutions is covered in this section.

General Transit Feed Specification (GTFS) *static*[3]

In 2005, the public transit agency in Portland, Oregon, called TriMet, came together with Google Bob (2000) to form a standard for sharing transit data. To date, GTFS is the most renowned and widely-adopted open data format, allowing public transit agencies to publish static operational data in 17Comma-Separated Values (CSV) files, demonstrated in detail by figure 2.6. GTFS is designed for transit agencies with generally fixed routes and

[3]developers.google.com/transit/gtfs

timetables. The standard supports the following modes of transport under the field `route_type` which indicates the type of transportation used on a route:

1. Tram, Streetcar, Light rail - Any light rail or street level system within a metropolitan area.
2. Subway, Metro - Any underground rail system within a metropolitan area.
3. Rail - Used for intercity or long-distance travel.
4. Bus - Used for short- and long-distance bus routes.
5. Ferry - Used for short- and long-distance boat service.
6. Cable tram - Used for street-level rail cars where the cable runs beneath the vehicle, e.g., cable car in San Francisco.
7. Aerial lift, suspended cable car (e.g., gondola lift, aerial tramway). - Cable transport where cabins, cars, gondolas or open chairs are suspended by means of one or more cables.
8. Funicular - Any rail system designed for steep inclines.
9. Trolleybus - Electric buses that draw power from overhead wires using poles.
10. Monorail - Railway in which the track consists of a single rail or a beam.

Designed by both software developers and a transit agency, the GTFS standard has proven to be very convenient for adoption by transit agencies worldwide, with over 1300 datasets published (OpenMobilityData, 2021). An open-source validation tool is also provided by its developers for transit agencies to test their data prior to publishing. However, this standard only allows agencies to publish static data i.e. does not cover realtime data. Furthermore, as delineated, the specification is curated for public transit with fixed routes and schedules, therefore, it is difficult to adopt by providers of micromobility, microtransit, on-demand services, and other tech-dependent transport services.

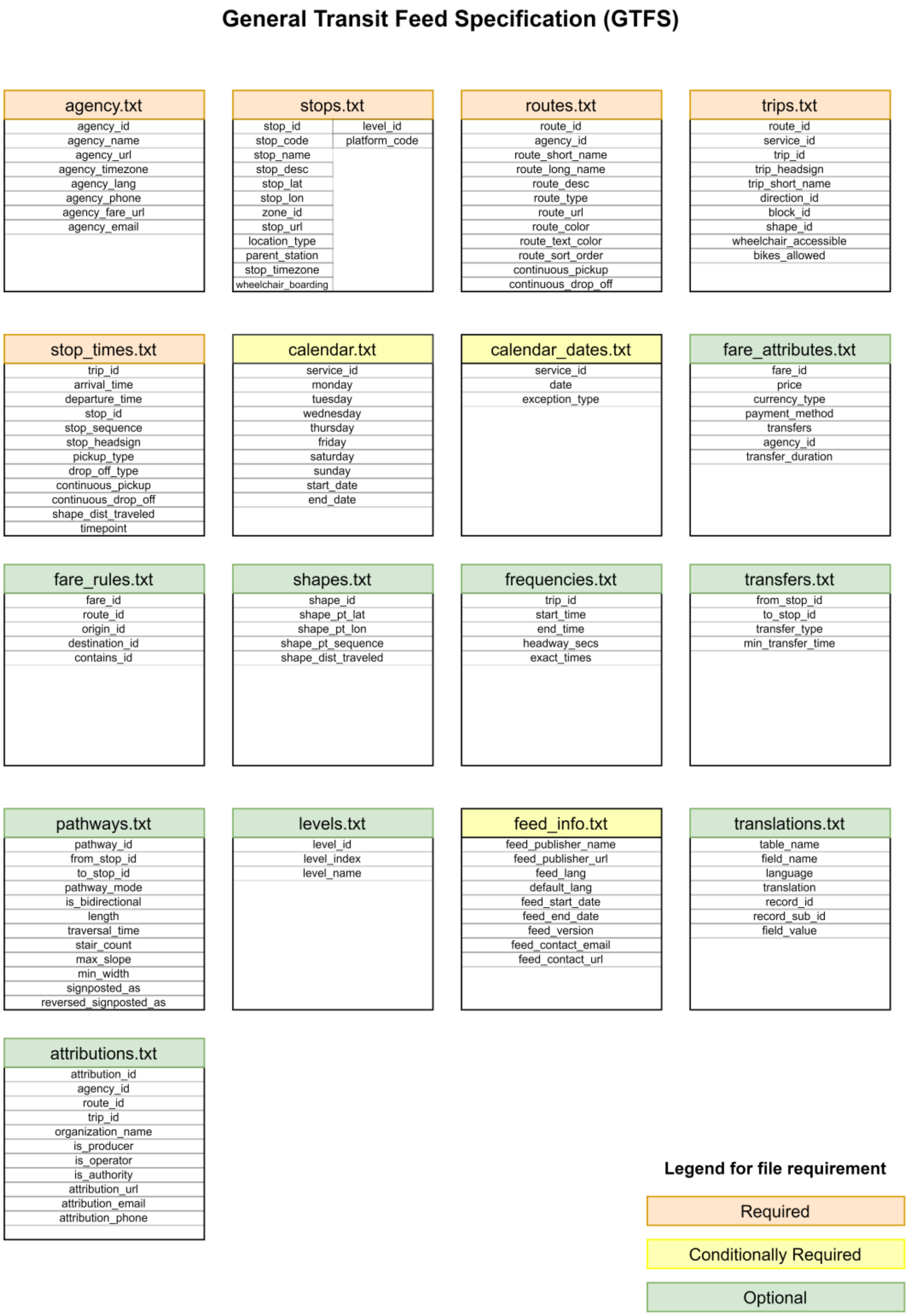

Figure 2.6 General Transit Feed Specification (GTFS) summary For the full definitions of fields and terms, refer to developers.google.com/transit/gtfs

GTFS *realtime* [4]

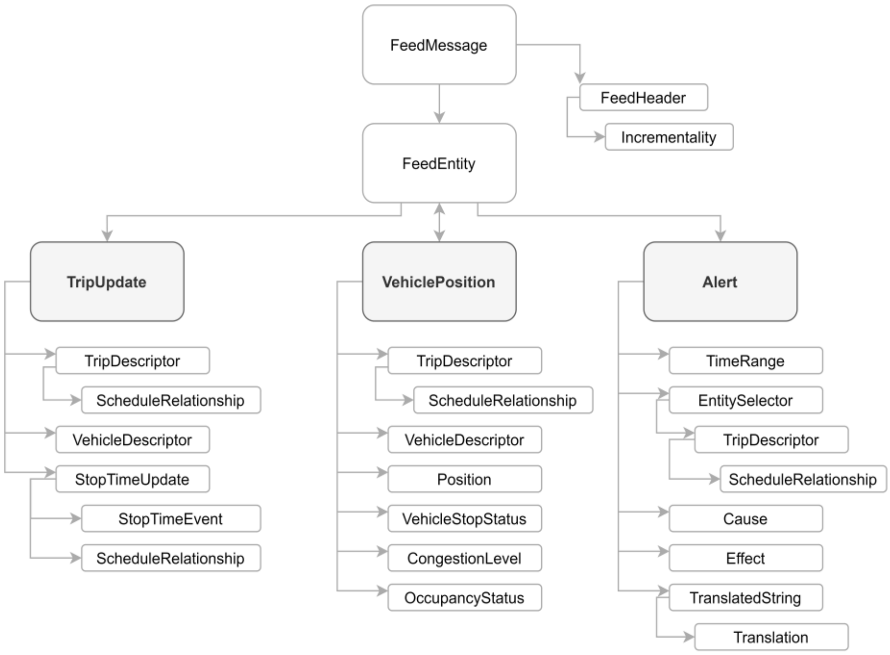

Figure 2.7 GTFS Realtime summary
For the full definitions of fields and terms, refer to
developers.google.com/transit/gtfs-realtime

To support the publishing of realtime data by transit agencies, Live Transit Updates partner agencies along with Google and other transit developers came together to develop an extension for GTFS. GTFS realtime supports three feed entities. These are types of realtime data namely: **(a) Trip Updates** - represent fluctuations in the timetable e.g. *"Bus X is delayed by 5 minutes"*, **(b) Service Alerts** - represent a problem with a particular entity in the form of a textual description e.g. *"Station Y is closed due to construction"*, and **(c) Vehicle Positions** - represent basic information about a specific vehicle within the network. The data model of GTFS-realtime is presented in figure 2.7.

General Bikeshare Feed Specification (GBFS) [5]

In 2014, Mitch Vars initiated the development of GBFS as an open data standard for shared mobility, with contributions from public and

[4]developers.google.com/transit/gtfs-realtime
[5]github.com/NABSA/gbfs

private shared mobility providers, including Motivate International LLC, now known as Lyft. In 2015, the North American Bikeshare Association (NABSA)[6] endorsed the GBFS and promoted its adoption. In 2019, MobilityData was chosen by NABSA to lead the improvement and maintenance of the GBFS standard. GBFS data is published in JavaScript Object Notation (JSON) format with currently over 294 bikeshare and scooter systems adopting the GBFS standard (NABSA, 2021). The specification is designed for real-time, read-only data that provides the status of the system at the current moment. GBFS does not allow a backward flow of communication where data is written back to individual shared mobility systems. Furthermore, GBFS is not intended for historical nor personal information (NABSA/gbfs, 2021). Despite being named as a "Bikeshare" specification, GBFS supports various shared mobility vehicles including bicycles, cars, mopeds, scooters, and others.

Mobility Data Specification (MDS) [7]

MDS is a set of Application Programming Interfaces (APIs) curated to provide access by regulatory agencies to data of mobility service providers, allowing these agencies to state regulations and policies in a machine-readable format. MDS is specifically designed for dockless shared mobility vehicles including scooters, bicycles, mopeds, and carshare. This project was initiated by Los Angeles Department of Transportation (LADOT) and passed on to Open Mobility Foundation in 2019, while remaining an open-source project. Commonly misconceived as a duplicate specification to GBFS, MDS was developed for a distinct use case from GBFS. GBFS is a specification for publishing shared mobility data and is developed for public sharing with a goal of enhancing passenger trip-planning. On the other hand, MDS is a set of APIs that are intended for use by cities and agencies, with the data being privately shared as it can contain sensitive location information and historical data. It is a requirement to expose a public GBFS feed for any organization sharing an MDS Provider feed. Currently, there are over 115 cities and public agencies utilizing MDS.

To illustrate MDS on a technical level, it constitutes of three primary APIs.

[6] For more information on the North American Bikeshare Association (NABSA), visit nabsa.net/

[7] github.com/openmobilityfoundation/MDS

These APIs are data sharing protocols that provide a secure channel for data exchange between cities and mobility providers. The three APIs are described as follows:

(a) Provider API - An API hosted by the mobility provider to communicate data with agencies. The data provided is generally composed of historical data and vehicle status information. Mobility providers share data with agencies that utilize data for planning and compliance. However, this API comes with its drawbacks specifically on scalability. Agencies need to query data from each provider individually and the API does not provide real-time data about events in the right-of-way.

(b) Agency API - An API hosted by agencies and cities for real-time data collection from mobility providers in the region. However, it requires a high degree of technical capacity on the agency's side in order to run and maintain the API.

(c) Policy API - An API hosted by agencies and cities that supports the publishing of policies and regulations within a certain geographical location, allowing a dynamic and automated update of systems when policies are updated. So far, the API only supports high level policies with no complex rules and also requires a high technical expertise on the agency's side.

The TOMP-API [8]

In the term TOMP, TO stands for Transport Operators, and MP stands for MaaS Providers. The Dutch Ministry of Infrastructure and Water Management in the Netherlands initiated the TOMP Working Group (TOMP-WG) to facilitate the communication between Transport Operators and MaaS Providers. The major development by the TOMP-WG is an Application Programming Interface (API) that standardizes exchange of data between TOs and MPs, called the TOMP-API. A summary of the API parts is shown in figure 2.8. The TOMP-WG are extending their work in two other directions. 1) **City Data Standard – Mobility (CDS-M)**[9] - An API that facilitates communication between transport operators and cities returning origin-

[8]github.com/TOMP-WG/TOMP-API

[9]github.com/TOMP-WG/CDS-M

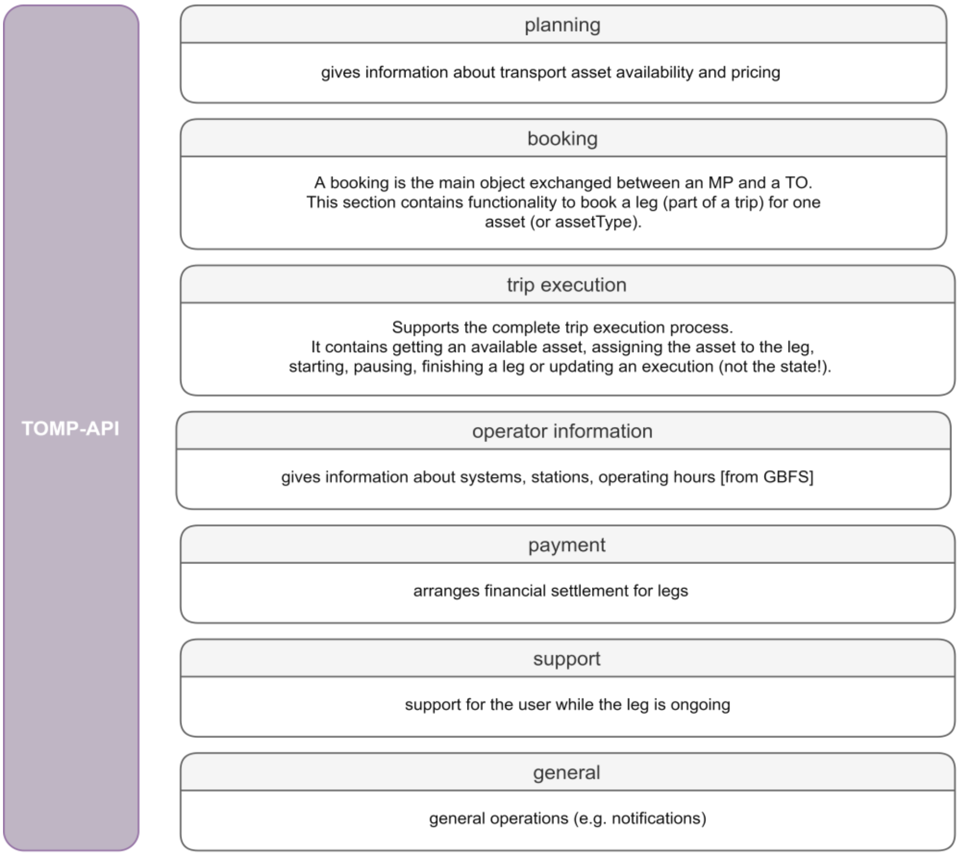

Figure 2.8 Summary of TOMP-API endpoint categories For the full API documentation, refer to app.swaggerhub.com/apis/TOMP-API

destination data about a specific region, and 2) **Personal Data Storage API for Mobility (PDS-M)** [10] - An API specifically for communication of user information between TOs and MPs, providing information required for routing, booking and logging of travel behaviour and preferences.

Transmodel[11]

Short for the European Standard Public Transport Reference Data Model, Transmodel was developed to provide a common language for public transport. Transmodel is divided into 8 parts, each for a specific representation of data as shown in Figure 2.9. While largely comprehensive of the public transport domain and its related data structures, Transmodel is characteristically granular. Granularity refers to the level of detail considered by the model.

[10]github.com/TOMP-WG/PDS-M

[11]transmodel-cen.eu

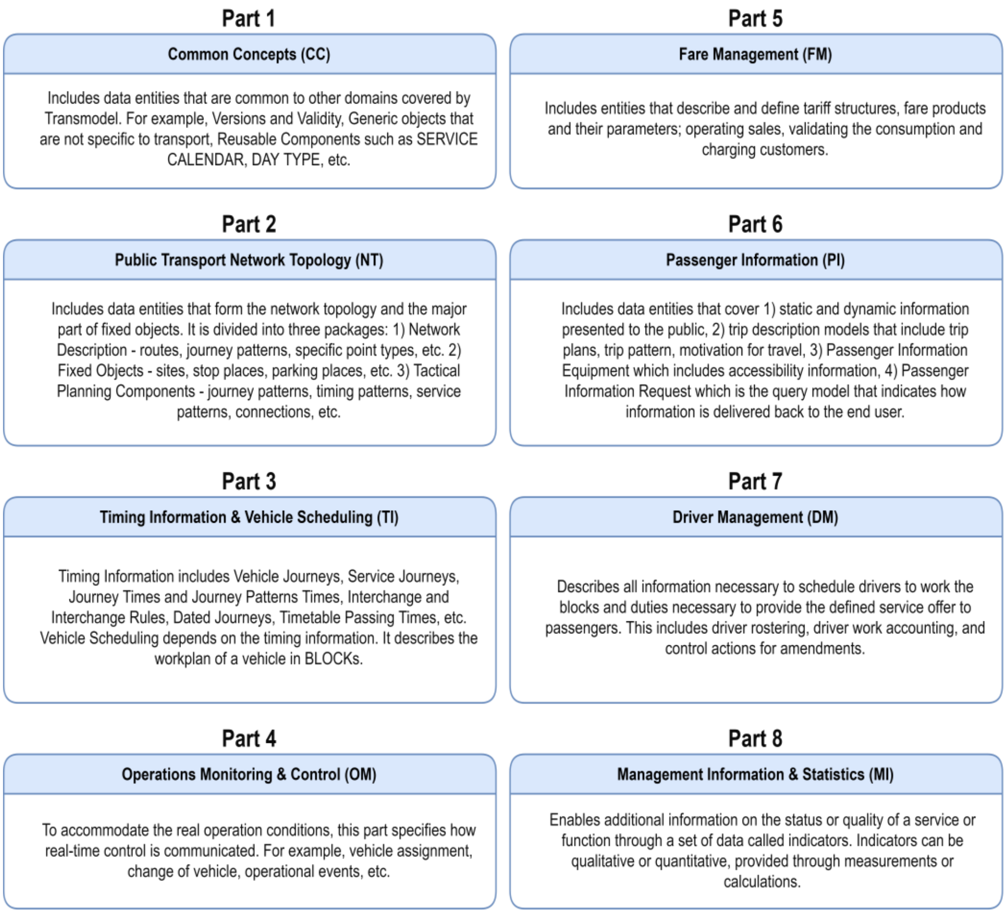

Figure 2.9 Summary of the 8 parts of Transmodel for the full model definition in UML, refer to transmodel-cen.eu/model

Data model granularity can be advantageous in precisely representing the domain, however, when implemented in practice, a high level of granularity affects the performance of the service offered to the user (Haesen et al., 2008). The high level of complexity of Transmodel makes its implementation a non-trivial task (Benvenuti et al., 2017) considering it constitutes of 371 classes, arranged into 14 core modules and 61 sub-modules, and it continues to grow to accommodate new developments in transportation. Based on Transmodel, different standards have evolved utilizing Transmodel as input. Some of the most widely used are:

Network Timetable Exchange (NeTEx) [12] - is the CEN Technical Standard for exchanging Public Transport data in four specific parts: 1) Public Transport Network topology, 2) Scheduled Timetables, 3) Fare information, and 4) Passenger Information European Profile. Transmodel is a fundamental input to the NeTEx standard, where NeTEx inherits from Parts 1, 2, 3, 5, and 6 of Transmodel. Currently, Part 5 of

[12]netex-cen.eu

NeTEx is being developed which will cover alternative modes.

Standard Interface for Real-time Information (SIRI) [13]

- an interface standard for exchanging structured real-time information including transportation schedules, vehicles, connections, and other information related to the operations of the services. SIRI inherits from part 4 and part 6 of Transmodel.

National Access Points (NAP) [14]

With the vision of integrating transportation across the entire European continent, the European Union (EU) initiated the National Access Points (NAPs) as a digital architecture that facilitates access, exchange, and reuse of transport-related data. The NAPs can be present in various forms such as databases, repositories, data marketplaces, web portals, and others, depending on the type of data. It is important that data access is unbiased and conforms to the necessary standards for exchange and reuse. The NAPs are currently developed for the following 5 domains, encouraging each Member State to develop an Access Point for each domain.

(a) Multimodal Travel Information (MMTIS)
(b) Safety-Related Traffic Information (SRTI)
(c) Real-Time Traffic Information (RTTI)
(d) The interoperable EU-wide eCall
(e) Safe and Secure Truck Parking (SSTP)

Other standards and APIs

GTFS-Flex [15] is an extension to the GTFS static schedule standard, where GTFS-Flex allows operators to model Demand Responsive Transportation (DRT). **General On-Demand Feed Specification (GOFS)** is a standard, under development by MobilityData, which will incorporate GTFS-Flex and extend it to include descriptions of real-time and transaction data. **MaaS Transport Service Provider Booking API (MaaS-TSP-API)**[16] is an API developed by Whim, a MaaS Provider that originated in Finland, to enable any transport service providers to be integrated into their application.

[13] vdv.de/siri.aspx
[14] ec.europa.eu/transport/nap_en
[15] github.com/MobilityData/gtfs-flex
[16] github.com/maasglobal/maas-tsp-api

DATEX II [17] is the European standard for electronic exchange of traffic related information. **Open Charge Point Interface (OCPI)** [18] is an interface that facilitates the connection between mobility service providers who incorporate electric vehicles in their services and Charge Point Operators who manage charging stations. In the United Kingdom, the Department for Transport (DfT) developed the **Bus Open Data Service (BODS)** [19] to promote travel by bus anywhere in England. BODS enables bus operators to publish their data following TransXChange, NeTEx, and SIRI-VM. **TransXChange** [20] is a UK National XML standard for exchanging bus schedules and related information.

More standards continue to be developed to complement, optimize, or extend the existing standards, as well as, to standardize new areas that have not been modelled previously. However, in pursuit of breaking silos through standardization, the multitude of standards have created new data islands based on their preferred standards. This is due to the lack of alignment of the definitions of key concepts, the language dependency of standards, and the challenges of aggregating data from different feeds (ODIN, 2019). The data models developed for specific use-cases are required to interoperate when offered in a singular service to travellers as in the case of MaaS. As a result, a major gap stands in the face of integrating heterogeneous data which is the interoperation of the data standards and models behind the data. In the field of data engineering, however, there is an uprising technology which can be leveraged as a solution for the delineated problem. The next section introduces Linked Data and Semantic Web Technologies, sketching out the opportunity for investigating this tool as a solution for the de-silo-fication of MaaS data.

2.3 Introduction to Linked Data

"***A vision encompassing the decentralized, organic growth of ideas, technology, and society.*** *The vision I have for the Web is* about anything being potentially connected with anything. It is a vision that provides us with new freedom and allows us to grow faster than we ever could when we were fettered by the hierarchical classification systems into which we bound ourselves." (Berners-Lee, 1999)

[17]datex2.eu/datex2

[18]evroaming.org/ocpi

[19]gov.uk/government/bus-open-data-service [20]gov.uk/government/transxchange

Created by Tim Berners-Lee in 1989, the design of the World Wide Web was a puzzle to professionals. Not because of how it worked but because of how it broke out of its preceding conventions. There was no central computer storing the information, no organization owning the Web, and no dedicated single network through which its protocols worked. The Web was constructed by only three core elements: (1) Universal Resource Identifiers (URIs), (2) Hypertext Transfer Protocol (HTTP), and (3) Hypertext Markup Language (HTML). Hypertext documents and resources are published and accessed by users of the internet. These resources can be linked together by containing hyperlinks to other documents through their unique IDs (i.e. their URIs). The Web was simply a space of linked documents within which information existed. However, the extensibility and flexibility of the Web began to lead to a fragmentation in standards (Berners-Lee, 2021). This led to the formation of the World Wide Web Consortium (W3C) in 1994, to oversee the development of the Web. Sir Berners-Lee's vision for the Web was partly meant to unlock boundaries in communications, collaborations, and innovations of, and between, people. But the vision also included empowering machines to take part in analyzing data on the Web, which would allow machines to handle a major part of our daily lives. This meant the development of a Web of data, nowadays termed as the *Semantic Web*.

However, in actualizing a machine-understandable Web, a significant issue of incompatibility occurred in how data was being published on the Web (Bizer et al., 2009). Data was commonly provided as raw dumps in formats such as CSV or XML or marked up in HTML tables. Such formats sacrifice both the structure and the semantics of the data. Semantics of the data refer to the underlying meaning of the data. For example, a data entity
`apple` might refer to an apple fruit or to the technology company Apple. Annotating data with semantics that describe the data is essential to enable machine-understandable data. Data about other data is commonly referred to as metadata. *The term metadata addresses data attributes that describe, provide context, indicate the quality, or document other object (or data) characteristics* (Greenberg, 2005). In addition to the data publishing methods, large databases were opening up access to their data through Web APIs. While this provides access to a wealth of information, each Web API has its own method of data identification. Similar to how each human has a unique fingerprint and DNA strand to identify them, Identifiers (IDs) are given to each data entity to provide them with a unique identity through which they can be retrieved from a database. As data entities from heterogeneous sources are not assigned globally unique identifiers (IDs that are unique across the entire Web), any process of combining

data from various sources faces interoperability issues. As a result, instead of breaking barriers to data access, unstandardized Web APIs have led to the silofication of data on the Web (Bizer, 2009).

To overcome the fragmentation of data, a set of principles for publishing and interlinking structured data on the Web was developed: the *Linked Data principles*. Linked Data is built upon standard Web technologies such as URIs and HTTP. The four principles of Linked Data are outlined below (Bizer et al., 2009):

1. Use URIs as names for things.
2. Use HTTP URIs so that people can look up those names.
3. When someone looks up a URI, provide useful information, using the standards (RDF, SPARQL).
4. Include links to other URIs. so that they can discover more things.

In summary, Linked Data uses the RDF data model (Refer to subsection 2.3.1) to publish structured data on the Web and uses RDF links to interlink data items from heterogeneous sources. Linked Data opens up the possibility to crawl the data on the Web through their links, merge data about entities from various sources, and query the data space in a similar manner to querying a local database Bizer (2009). The Resource Description Framework (RDF) provides the foundation technology upon which Linked Data and the Semantic Web are built.

2.3.1 The RDF Data Model

The majority of devices surrounding us generate data in an automated fashion. The quantity of data produced on a daily basis is beyond our levels of consumption. This led to the emerging concept of *big data*. Big data refers to quantities of data that are too large and complex for conventional data processing applications (Sagiroglu and Sinanc, 2013). In addition, big data is characterised by three qualities (1) Volume - amount of data which can range from terabyte to zettabyte, (2) Velocity - the speed at which the data is generated, ranging from live streams to static batches, and (3) Variety data can have various structures and formats of modeling. While both Volume and Velocity are key concerns, Variety of the data is the main factor behind data integration and interoperability issues (Gayo et al., 2018). A graph-based data model, called Resource Description Framework (RDF), was proposed as a solution to aid in data interoperability. RDF is intrinsically a model that disambiguates data by providing assertions about each resource.

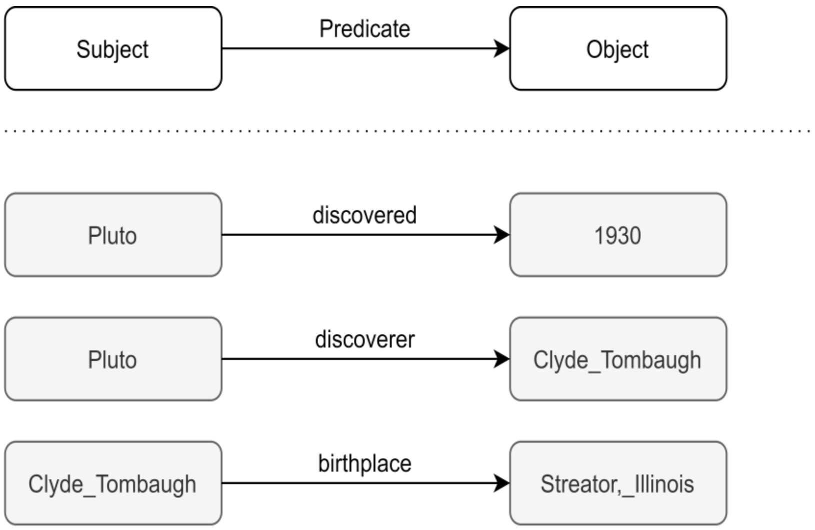

Figure 2.10 Example of the RDF triple structure

This is made possible through its reliance on IRIs that gives each resource a globally unique ID on the Web. As a result, machines are able to understand the data and furthermore, heterogeneous data modeled in RDF can be instantly merged from various sources (Gayo et al., 2018). These advantages are wholly due to the underlying data structure of RDF. The term *resource* in Resource Description Framework (RDF) can refer to any object/human/entity/thing that exists in the world, with a requirement to identify or reference every defined resource via a URI (Miller, 2005). This means that across the entire Web, there will always only be a single URI that refers to each entity. Knowledge represented in RDF is composed of a list of statements that follow a very simple schema, called *triples*, close in nature to the structure of a sentence in the English language as shown in Figure 2.10. The triple has three parts: (1) Subject, (2) Predicate, and (3) Object. Each of these three components are given URIs, however, an Object can be a *literal*. Literals are used for string values (with or without language tags) or to denote different datatype values such as integers or dates (Beckett et al., 2014). For instance, representing the first example from Figure 2.10 in a simple format, it would be:

```
<http://dbpedia.org/resource/Pluto> <http://dbpedia.org/ontology/
```

If we were to dissect this example into a Subject-Predicate-Object triple, the Subject of the triple is <http://dbpedia.org/resource/Pluto>. This is a URI that points to the resource Pluto. The URI begins with dbpedia.org which is one of the largest multi-domain ontologies. The DBpedia project extracts information from Wikepedia pages and makes them accessible in a structured format using the dbpedia ontology. The Predicate <http://dbpedia.org/ontology/discovered> is also a URI following a similar structure denoting the verb `discovered`. Lastly, the Object of the triple is `"1930"`, which is a string literal value. Therefore, the statement reads Pluto discovered 1930. The example above is given using the Turtle [21] syntax which also allows us to abbreviate the URIs by providing the ontologies or vocabularies that the resource is under as a list of prefixes at the beginning of the document. Therefore, for this example it can be summarized as:

```
@prefix dbo:  <https://dbpedia.org/ontology>
```

RDF also allows us to have blank nodes, these are anonymous nodes that are not assigned an identifier. This allows us to include nodes in the graph that represent information that is not yet known or determined. This is advantageous in representing and documenting incomplete knowledge graphs, which is the common state of knowledge especially at the initial development stages. To further illustrate, classical database follow a *Closed World Assumption (CWA)* which assumes that the existing data is a complete representation of the world and hence, in situations where a data entity is missing, the default assumption will be that it does not exist/is not true. For example, in a database of different destinations and flights between them, asking the database a question like "Is there a flight between Cairo and Casablanca?" might return negative simply because the data does not exist in this particular database. On the other hand, an *Open World Assumption (OWA)* rather assumes an "I do not know" answer to missing information. While OWA can be beneficial, a common pitfall is when the database is required to assume completeness of what it has rather than of the whole world. This indicates that in the previous example of a database of flights, a tourism agency's database will commonly only represent the flights the agency has access to. Therefore, the sweet spot between CWA and OWA is the Local Closed World Assumption (LCWA) which assumes that certain parts of the graph are complete while others can remain open. To instate such an assumption, a data schema is required. A data schema is the structure that the data follows. When modeling data in graphs, a major advantage is the ability to forgo or delay the definition of a schema (Hogan et al., 2020).

Nevertheless, it is common to design a high-level schema that a graph follows or should follow. There are three types of graph schemata (Hogan et al., 2020):

1. **Semantic Schema** - describes high-level terms and concepts, commonly referred to as the *vocabulary* or *terminology* of the graph. For example, when designing a schema for a transportation knowledge graph, we may notice high-level groups under which instances fall. We

[21] Full documentation of the Turtle syntax at w3.org/TR/turtle

can then identify these groups as the *classes* in a schema, e.g. `Mode`, `Passenger`, `Operator`, `Location`. These classes can also have *subclasses* which inherit properties of their parent classes. For example, under the class `Mode`, we can have a subclass of `Active Mode` for modes such as walking, cycling, etc, that have their own properties. Having a semantic schema for the graph allows reasoning and inference over the existing knowledge. The graph can automatically infer that if walking is an `Active Mode`, then walking is also a `Mode`. Speaking of *properties*, these can also be defined in the semantic schema and can have a hierarchy of `sub-properties`. The properties are the edges in the graph that connect between the nodes, for instance, `Bicycle A` $\xrightarrow{maxSpeed}$ `"6mph"`. When defining properties, we can define their *domain* and *range*. The *domain* is what the property points out from, so for a property $\xrightarrow{maxSpeed}$, we can define that it points out from the class `Mode`. The range is what the property is directed to and so for a property $\xrightarrow{maxSpeed}$, we can define that it points to a literal with a numeric data type. Defining *classes and subclasses*, *properties and subproperties*, *domains*, *and ranges* is predominantly done following the *RDF Schema (RDFS)*[22] standards. More complex assertions and statement constructs are supported by the *Web Ontology Language (OWL)*[23].

2. Validating Schema - In a graph modeling a transportation network, we may want to ensure that every mode of transport at least has a property $\xrightarrow{maxSpeed}$ and a property $\xrightarrow{maxCapacity}$. To define such constraints, we design a validating schema that validates existing graph data and lists any violations to the constraints. Constraints are applied to a graph by defining what is called *shapes*. A shape can *target* a specific class, domain or range of a property, or even the *target* of another shape. Constraints are therefore applied to the specified target of the shape to restrict number or types of values on a certain property, for example, in a graph about families, we can apply a constraint that restricts every individual to have only one mother and only one father. The *shapes graph*, formed from the interconnected shapes, is represented in a similar diagram to a UML class diagram. It is important to note that when designing shapes, there can be two types of shapes: (a) *Closed Shape* - this limits the node to have only the properties defined by the shape, and (b) *Open Shape* - allows the node to have properties not defined by the shape. A closed shape can enable the local completeness of certain parts

[22]Full documentation of RDFS at w3.org/TR/rdf-schema/

[23]Full documentation of OWL at w3.org/TR/owl2-overview

of the graph but it might restrict inference of new knowledge. The two most common shape languages are *Shape Expressions (ShEx)*[24] and *SHACL (Shapes Constraint Language)*[25]. In their book, Gayo et al. (2018) provide a comprehensive comparison between both shape languages and their use cases. Distinguishing between the two schema types, semantic schema is mainly to allow for the inference of new data whereas a validating schema checks existing data. These schema types are not exclusive and can be used together to complement each other.

3. Emergent Schema - while both semantic and validating schema need to be designed for data graphs, every data graph will intrinsically form latent structures which can generate a summary for the graph called an *emergent schema*. This schema is most commonly defined through a *quotient graph* framework. A quotient graph will merge nodes from the original graph into a single node, provided that these nodes follow precisely the same structure, i.e. have the same relationships/properties. In the process of defining semantic and validating schemata, an emerging schema can provide a useful human-understandable summary of a graph to facilitate the definition of the other schemata.

Aside from schemata, a core characteristic of RDF data models is the use of URIs as seen in previous examples. W3C (2008) published a note on the best practices of naming or assigning URIs to the nodes in a graph. The first recommendation is to use HTTP URIs. These would allow the retrieval of machine-readable (i.e. RDF) and human-readable representations (e.g. HTML) over HTTP protocol with content negotiation. Content negotiation allows you to specify the specific representation when sending a request for a resource. The second recommendation emphasizes on the disambiguation in naming. For instance, there should be a clear difference between a URI denoting a non-web resource *thing* (e.g. an iPhone) and the URI of the web resource describing the *thing* (e.g. the web page of iPhone specifications). The different types of URIs and their optimal use-cases are outlined in detail in the Cool URI report (W3C, 2008).

2.3.2 Vocabularies and Ontologies

To resolve syntactic interoperability, the RDF data model may be sufficient, however, semantic interoperability requires the underlying meanings behind the terms to be standardized or shared amongst interoperating parties.

[24]Full documentation of ShEx at github.com/shexSpec

[25]Full documentation of SHACL at w3.org/TR/shacl

This is commonly achieved by devising an *ontology* to be followed. *Ontologies*, in the field of Computer Science, have been attributed to multiple definitions which were summed up by Studer et al. (1998) - *An ontology is a formal, explicit specification of a shared conceptualisation*. Guarino et al. (2009) broke down this definition into three main components:

What is a *conceptualization*? - A conceptualization is described as an abstract model of a real world phenomenon. The model represents the different entities in an area or domain of interest such as the concepts, their relationships, and other modeling elements. According to the definition by Genesereth and Nilsson (1987), every knowledge base or knowledge-based system conform to a *conceptualization*, either implicitly or explicitly.

What is a proper *formal, explicit specification*? - This refers to the employment of a formal language. To elaborate, a formal language can be described as a machine-readable language that is constructed upon formal logics such as First-Order Logic (FOL) or Description Logic (DL). The type of formal logic used will affect the efficiency of using an ontology for reasoning about a domain of knowledge or inferring new information. Commonly, the design of the ontology will entail a compromise between how expressive and detailed the conceptualization is and how efficient it is for inference and reasoning. Majority of database schema languages are not suitable for a formal and explicit specification.

Why is *shared* of importance? - The main benefits attained from an ontology are observed when interoperating stakeholders *commit* to a mutually agreed upon ontology. By committing to an ontology, the intended user of the ontology, whether a human or a machine, should implement its vocabulary in a consistent way to how the terms are defined (Falquet et al., 2011). Therefore, any ontology developed for interoperability should be based on well-founded and easily understood meanings. This entails the *sharing* of human-readable examples and explicit formal constraints.

The terms *"ontology"* and *"vocabulary"* are used interchangeably, however, ontologies commonly refer to more complex vocabularies with a formal description of the terms while vocabularies are more likely to be a classification of terms where a strict formalism is not necessary (W3C, 2015).

In a web environment, ontologies based on Semantic Web Technology (SWT) are known as web ontologies. These ontologies commonly follow two main assumptions: (1) Open World Assumption (OWA), which was described in subsection 2.3.1, and (2) No Unique Name Assumption (NUNA), which allows multiple URIs to refer to the same real world entity (Hogan et al., 2020). This is necessary in a decentralized environment like the Web where there isn't a single organization defining vocabularies and URIs to be used. For ontologies, specifically ones based on Description Logic, it is common to distinguish between three types of axioms (Krötzsch et al., 2014): **(1) Assertional (ABox) axioms** - consist of concept assertions and role or properties assertions, for example, in a vehicle dataset, the ABox can include `BMW` $\xrightarrow{type}$ `Brand` or `BMW` $\xrightarrow{hasMode}$ `Car`, **(2) Terminological (TBox) axioms** - are statements which define formal feature types and relationships between concepts, for example, `Car` $\xrightarrow{subclass}$ `Vehicle` or `Car` $\xrightarrow{disjoint}$ `Train`, and lastly **(3) Relational (RBox) axioms** - consist of statements on roles or properties including the type of property and its relationship with other properties or concepts, for example. `hasMode` $\xrightarrow{domain}$ `Train`, `hasSpeed` $\xrightarrow{range}$ `Train`, or `hasSpeed` $\xrightarrow{range}$ `Train`. Ontologies or Vocabularies commonly refer to the *TBox* or *RBox*, excluding *ABox*. This is likely due to the ABox layer commonly including data instances which are specific to a closed environment, for instance, the ABox of a university dataset would include the actual names of the students and staff in the university and their information.

Ontologies can be used to model any domain of knowledge or interest, and hence, there exists many that are available online for usage and reference. The Linked Open Vocabularies (LOV)[26] is an online repository that houses a number of such vocabularies. Some examples of very well known ontologies/vocabularies are: *Friend of a Friend (FOAF)*[27] - is a representation of social networks describing humans and the connections between them as well as other types of networks, *Data Catalog Vocabulary (DCAT)*[28] - is a vocabulary that describes datasets in catalogs to facilitate the interoperability between them. Specifically in the field of civil engineering: *Building Topology Ontology (BOT)*[29] - is an ontology describing the core topological features of a building, *ifcOWL* [30] –

[26] lov.linkeddata.es/dataset/lov

[27] Find the full documentation of FOAF at xmlns.com/foaf/spec

[28] Find the full documentation of DCAT at w3.org/TR/vocab-dcat-2

[29] Find the full documentation of BOT at w3c-lbd-cg.github.io/bot

[30] Find the full documentation of ifcOWL at standards.buildingsmart.org/IFC

The Industry Foundation Classes (IFC) schema is a standard for describing Architectural, Engineering, and Construction (AEC) industry data. *ifcOWL* provides a Web Ontology Language (OWL) version of the IFC schema.

2.3.3 Mapping and Alignments

Now that the technical potential of RDF and Linked Data has been explained, one might ask *"How do we get to this enhanced level of interoperability from the technologies that are ubiquitous today? What are the steps in that roadmap?"*

The first step to consider is perhaps how can we convert legacy data into RDF. For that, there have been **RDF Mapping** techniques developed which map data from their original format to RDF. To map or convert data to RDF, multiple factors need to be considered with regards to the original format the data is in. Mapping Relational Databases (RDB) to RDF is one of the actively developed areas of research (Hert et al., 2011). Hert et al. (2011) conducted a comparison of different RDB-to-RDF mapping languages and highlighted the applicability of 9 mapping languages under various use cases. A mapping language, currently supported as a W3C recommendation, is **R2RML**[31]. R2RML produces customized mappings from relational databases only, based on one or multiple Triples Maps.

The online documentation of RML[32] demonstrates how a mapping is done for a CSV data source, a JSON data source, and an XML data source. Another extension of R2RML, with some RML concepts, is a language designed to map non-relational databases to RDF, called **xR2RML**. xR2RML supports the mapping of XML databases and some NoSQL databases, given the large variety (Michel et al., 2017). Aside from the mentioned mapping languages, multiple other languages were developed for various use-cases, for example, **Triplify**, a lightweight approach to publishing Linked Data from RDBs (Auer et al., 2009), **R3M**, a language that allows both reading and writing access to a relational database (Hert et al., 2010), **XLWrap**, maps spreadsheets to RDF (Langegger and Wöb, 2009), **Mapping Master** (M^2), a language that maps spreadsheets to OWL (O'Connor et al., 2010), **ShExML**, a language based on ShEx that maps and merges heterogeneous data formats into a single RDF representation , **JSON-LD**, maps JSON to RDF graphs (Kellogg et al., 2019). In addition to mapping languages, more complex frameworks and platforms were also developed to aid in the process of conversion to RDF such as the **Datalift** platform (Scharffe et al., 2012). Despite the developments in the field of RDF mapping languages, there are still cases where converting a non-RDF dataset into RDF is inefficient. In such cases, an annotation of the dataset with RDF triples is

[31] Full specification of R2RML at w3.org/TR/r2rml

[32] Find the full documentation of RML at rml.io/specs/rml

considered as an alternative, specifically when working with unstructured data such as images, videos, text in natural language, and audio.

With this understanding of how we can go to RDF, and assuming we can overcome the complexity of mapping various legacy data to RDF while ensuring that process is lossless, one might think "Well, Perfect! Now RDF will magically merge everything effortlessly." But unfortunately, there still is a caveat. One of the main strengths of RDF is the utilization of Internationalized Resource Identifiers (IRIs) instead of plain strings which enables effortless merging of data from heterogeneous sources (Gayo et al., 2018). The IRIs in an RDF dataset should be persistent, i.e. the IRI should last at least as long as the resource it identifies lasts (Hakala, 2010), and are meant to disambiguate resources where any entity should only have one unique IRI. This precipitates a need for everyone to agree on the identification and semantics of common entities and relationships. Indeed, it can be argued that the representation of knowledge is unique to every human's thoughts and the way they interpret it, perhaps with correlation to a human's background, culture, native language, and other factors. Therefore, working out a universal single vocabulary for each domain of knowledge to be used on the Web seems impractical. To overcome semantic heterogeneity, different vocabularies representing the same information are aligned through *Ontology Matching* (Shvaiko and Euzenat, 2013). This is a process where corresponding entities in different ontologies are matched to produce an alignment i.e. a set of correspondences (Shvaiko and Euzenat, 2013). This allows data with aligned ontologies to interoperate. There are various methods to align ontologies which were meticulously reviewed by Otero-Cerdeira et al. (2015).

Within the realm of Linked Data, it is common to use formally defined terminology to make the alignments, e.g. RDFS or OWL. When generating an alignment with formal terminology, reasoning or inference can be done across both aligned ontologies. Therefore, an in-depth understanding of both ontologies is required to avoid the introduction of contradictions. Alignments can be both one-directional and bi-directional. One-directional alignments attribute one ontology to another for example through `rdfs:subClassOf` and `rdfs:subPropertyOf`. Bi-directional alignments attribute both ontologies to each other for example through `owl:equivalentClass`, `owl:equivalentProperty`, or `owl:sameAs`. In some cases, however, alignments are required between ontologies without affecting inference and reasoning. In such cases, less formal links are used for example `rdfs:seeAlso` as well as `skos:closeMatch` and `skos:broaderMatch` from the SKOS[33] terminology. There are both manual and (semi-)automatic

[33]Full documentation of SKOS at w3.org/TR/skos-reference

processes to produce the alignments (Shvaiko and Euzenat, 2013; Algergawy et al., 2018) yet automated processes should be checked by an ontology engineer. When alignments are made between two ontologies, it is best practice to separate the alignments into its own dataset so that users can ignore the alignments if they do not need them.

2.3.4 Validation

When working with RDF, the ontologies defined are commonly used with *instance data*, which refer to data of a situation at a particular point in time (Gayo et al., 2018). RDF validation is used to check if instance data conforms to an ontology. Validation can be done over an entire dataset, a selection of nodes, or even a single node. There might be a need to validate properties of a node (e.g. A `Human` must have a `Name`) or more complex axioms (e.g. The `Child` of a `Person` should not be the `Parent` of the same `Person`). Various technologies have evolved to validate RDF data including query-based approaches (Steer and Miller, 2004; Knublauch, 2011; Labra Gayo and Rodriguez, 2013), inference-based approaches (Sirin and Tao, 2009; Patel-Schneider, 2014), as well as languages for implementing constraints on RDF data. This section will briefly describe two of these languages with an example : (1) **Shape Expressions (ShEx)**[34], published as a W3C Community Group Report, and (2) **Shapes Constraint Language (SHACL)**[35], published as a W3C Recommendation.

ShEx was developed as an RDF validation language that is human-readable and intuitive (Labra-Gayo et al., 2019). The language takes a schema-based approach while adopting Turtle and SPARQL syntax, in addition to, XML-inspired validation (Labra-Gayo et al., 2019). A demonstration of ShEx is shown in listing 2.1 with explanation comments after each `#` symbol:

```

prefix : <http://example.org/>
prefix xsd: <http://www.w3.org/2001/XMLSchema/>

<Student> IRI {                              # A <Student>, which is identified by an IRI, has:
    :name           xsd:string+;             # at least one givenName.
    :familyName     xsd:string;              # one familyName.
    :age            xsd:integer?             # optional property age of an integer value
    :enrolledIn     @<Course>+;              # one major that they are enrolled in
}
<Course> {                                   # A Major has:
    :subject     xsd:string+                 # at least one subject
    :students    @<Student> {1,150}          # with a number of enrolled students between 1 and 150
}
```

listing 2.1: ShEx example

[34]Full documentation of ShEx at shex.io

[35]Full documentation of SHACL at w3.org/TR/shacl

On the other hand, SHACL defines Shapes as groups of constraints with two types of SHACL shapes: (1) node shapes - apply constraints to the values of a specific node, and (2) property shapes - apply constraints to a specific property or path (Labra-Gayo et al., 2019). In comparison to ShEx, SHACL can define the *target* nodes or properties that are to be validated by the shape, which is only achievable in ShEx through a *shape map*. If we were to represent the example in listing 2.1 using SHACL instead, the validation would be as shown in listing 2.2:

```
<Student>   a   sh:NodeShape;
    sh:nodeKind sh:IRI;
    sh:property [ sh:path :name;
        sh:minCount 1;
        sh:datatype xsd:string;
    ];
    sh:property [ sh:path :familyName;
        sh:maxCount 1;
        sh:datatype xsd:string;
    ];
    sh:property [ sh:path :age;
        sh:maxCount 1;
        sh:datatype xsd:integer;
    ];
    sh:property [ sh:path :enrolledIn;
        sh:node <Course>;
    ];

<Course>   a   sh:NodeShape;
    sh:property [ sh:path :subject;
        sh:minCount 1;
        sh:datatype xsd:string;
    ]
    sh:property [ sh:path :students;
        sh:minCount 1; sh:maxCount 150;
        sh:node <Student>;
    ]
}
```

listing 2.2: SHACL example

2.3.5 Evaluation

The quality of ontologies relies on various criteria including its complexity and granularity, coverage of a certain domain, specific requirements or applications it was developed to address, and formal properties such as completeness and modeling language (Obrst et al., 2007). Therefore, the evaluation methods of ontologies target specific criteria to validate. Because this research is investigating the development of a vocabulary which is tightly integrated with application tasks, only a few of the existing methods
are discussed which are the methods considered for evaluation under this research.

Commonly when developing an ontology, a set of objectives are outlined for the ontology to meet. These objectives are often in the form of

Competency Questions. Competency Questions (CQs) are natural language questions outlining and constraining the scope of knowledge represented in an ontology (Wiśniewski et al., 2019)." Incorporating CQs in the development life-cycle of an ontology enables its evaluation through checking the ontology's compliance (ability to accurately answer) with its predefined CQs. For example, an ontology that describes vehicle features should be able to answer questions like "*What is the speed range of a 4x4 vehicle?*" or "*What are the common components across all kinds of vehicles?*". As sketched out, competency questions are a useful method in circumscribing an ontology in a way that allows its developers to ensure the ontology can satisfy its purpose of development. It must be noted that these questions are not a necessary step for developing an ontology but rather a practical way to evaluate them.

Aside from CQs, there are other techniques to evaluate ontologies. As ontologies are usually abstract models reflecting a certain domain of discourse, an expert or a group of experts within the designated domain can evaluate the accuracy of the domain's representation through a consensus-based method, for example, the Delphi technique. The Delphi technique is a mixed method technique which is effective in evaluating the semantic agreement of the ontology's users over its structure and definition. In addition, ontologies can be evaluated through application. As mentioned in subsection 2.3.2, a trade-off is made between the representation's expressivity and its computational efficiency. Through applying the ontology in a knowledge management system, an evaluation of the ontology can be done based on different performance metrics, such as its *soundness* (the results of a query over the knowledge base is logically implied by the ontology's rules), *completeness* (expressions which are logically implied by the ontology can be queried or derived from the knowledge base), *decidability* (a characteristic of being both sound and complete), *consistency* (whether contradictions can be derived from a knowledge base), and *complexity* (the time and memory required to compute a result).

2.3.6 Linked Data for Interoperability

In its essence, Linked Data was developed to power interoperability. When introduced by Tim Berners-Lee, it was accompanied by a 5-star rating that influences data managers to publish their data as Linked Open Data. The 5-star rating is classified as follows:

1. **One-star** - Making data available on the web, in whatever format, under an open license.

2. **Two-star** - Making data available in a machine-readable format that allows easy re-use of data.

3. **Three-star** - Ensuring data is available in an open format that does not require proprietary software to run.

4. **Four-star** - Publishing data in an open standard, incorporating URIs as identifiers. This points towards the adoption of RDF as the base technology.

5. **Five-star** - Advocates linking data to each other by re-using existing URIs and vocabularies.

The five stars of Linked Data promote an improved interoperation with every star, however, interoperability in itself should be an adaptive process at its best as sketched out within the Maturity Model for Enterprise Interoperability (MMEI) (Guédria et al., 2015). So while it can be argued that two or three stars are sufficient, information management systems continue to evolve and that evolution will require interoperability to become a matter of continuous improvement. Therefore, the goal is to be as interoperable as possible. The following paragraphs delineate how an additional star can make a difference through an example case.

The domain of Urban Civil Engineering has been using ontologies to categorize and describe many of its concepts (Falquet et al., 2011). Some of such use-cases were able to fill in interoperability gaps in the industry. Similar to the transportation industry, the building and urban design industry suffers from heterogeneous data, specific to the different stages of projects from planning and feasibility, to facility management. Through these stages, the Building Information Modeling (BIM) approach has been developed to facilitate the documentation and exchange of building information. The Industry Foundation Classes (IFC) is an open data model used for representing building information. However, the IFC schema being mainly in XML is not feasibly interoperable with the heterogeneous data of the building industry. Therefore, ifcOWL[36] was developed as an ontology representing the entire IFC schema. ifcOWL enables IFC data to be available in RDF which results in a more convenient linking of building data to material data, sensor data, GIS data, weather data, product manufacturer data, and so on. This powers a web of linked building data that has brought major opportunities for data management within the Architecture, Engineering and Construction (AEC) sector (Pauwels and Terkaj, 2016).

Although ifcOWL raises the interoperability of IFC files by making them available in RDF, the broadness of IFC covers concepts of time, location, units, etc., which are previously covered by existing ontologies. Due to its volume, ifcOWL is difficult to maintain and its redefining of existing concepts raises new interoperability gaps, where the redefining of existing concepts hinders ontologies from being easily aligned and understood in integration with other ontologies. To improve the deficiencies in ifcOWL, simpler and modular ontologies were developed for small specific representations, for example, the Building Topology Ontology (BOT) which defines the the core topology of a building (Rasmussen et al., 2017).

2.4 Linked Transport Data

Having discussed the characteristics of Linked Data and the opportunities it offers for resolving the data exchange barriers within MaaS, this section outlines the previous work done related to incorporating semantic web technologies in MaaS. While there exists various ontologies dedicated to the transportation domain, the discussion here is limited to the implementations which can improve the interoperability of the existing standards.

Linked GTFS[37]

Linked GTFS is a mapping to RDF of the General Transit Feed Specification (GTFS) discussed in subsection 2.2.3. Similar to how ifcOWL raises the interoperability of IFC files, Linked GTFS enables the GTFS CSV feeds to be mapped to an RDF graph representation. However, Linked GTFS is currently not up to date with the latest GTFS specification.

Open Network of Public Transport (ONETT)[38]

ONETT leverages Semantic Web Technologies to generate a knowledge graph representation in the transportation domain. ONETT performs a mapping using RML of GTFS feeds to a Transmodel-based Ontology[39], generating a knowledge graph of GTFS CSV feeds (Chaves-Fraga et al., 2019). Furthermore, ONETT is meant to utilize Ontology-Based Data Access (OBDA) which is an approach aiming to link data sources to ontologies (Poggi et al., 2008).The implementation of ONETT as a conversion platform is inactive at the moment.

[36]https://technical.buildingsmart.org/standards/ifc/ifc-formats/ifcowl/

[37]https://github.com/OpenTransport/linked-gtfs

[38]https://osoc-es.github.io/onett/index.html

[39]https://github.com/oeg-upm/transmodel-ontology

Open Mobility Vocabulary (MobiVoc)[40]

MobiVoc is an open vocabulary developed for mobility solutions that are future-oriented. The vocabulary covers various mobility aspects such as bike stations, electric vehicle charging stations, and parking management.

Linked Connections[41]

Linked Connections is a specification for publishing transport data in a form that is ready to be consumed by route planning algorithms. It is structured into departure-arrival pairs between stations which are arranged by departure time. It functions with an underlying vocabulary which is aligned to the GTFS specification. Linked Connections showed a significant potential in being a lightweight solution for route planning as it incurs less load on the server (Colpaert et al., 2017). However, the bandwidth needed is three times larger in magnitude. Nevertheless, Linked Connections opens a door towards a new ecosystem of public transit route planners through allowing to be processed over flexible cached data fragments.

Semantic Transformations for Rail Transportation (ST4RT) [42]

The ST4RT project presented an approach towards raising the interoperability of systems relying on different transportation standards through semantically annotating the data representation which aligns it to a reference ontology. The reference ontology is then used as a medium to convert between two standards based on their ontological annotations (Carenini et al., 2018). The testing prototype proved the semantic conversion to be successful, however, the development of a commercial solution will require extending the reference ontology to accommodate the needs of the industry (Hit Rail, 2018).

(Semantics for PerfoRmant and scalable INteroperability of multimodal Transport (SPRINT)

Building on top of the ST4RT project is the SPRINT project which aims to improve and automate the conversion process achieved by ST4RT. It specifically focuses on the annotation phase by utilizing a neural network, *word2vec* by Mikolov et al. (2013), which is machine-learning tool that can be trained using text corpus.

[40] https://www.mobivoc.org/index.html

[41] https://linkedconnections.org/

[42] http://www.st4rt.eu/

The approach aimed to automate the annotation process so that it is no longer done manually which is time-consuming and requires expertise. The challenges faced through this approach is outlined by Hosseini et al. (2019).

2.5 Mobility Data Exchange

The field of transportation data interoperability and API development has undergone extensive exploration and investigation, with numerous studies and scholarly works focusing on the intricacies of integrating data models and establishing seamless connectivity. In a significant contribution, the MaaS Alliance Working Group presented a position paper (MaaS Alliance Working Group 3, 2021) that provided a comprehensive overview of the state of data exchange processes in Mobility-as-a-Service (MaaS). This paper aimed to compare different existing data models, formats, and API specifications at a high level. The ultimate goal was to identify a minimal set of common elements among these specifications, enabling the development of a versatile API for MaaS.

Contrary to the expectation of the need for a new standard for MaaS, the comparison in the paper concluded that the focus should be on aligning existing standards to achieve interoperability. The research highlighted that this alignment and mapping process is challenging and would require a significant amount of time and detailed knowledge about each standard. It suggested that the organizations responsible for originating or maintaining the standards should take up this task. Alongside its conclusions, the paper offered valuable insights into the exploration of data interoperability. It defined data interoperability as "an alignment of data semantics sufficient to enable the remote exchange of products and services." Considering the extensive number of stakeholders and complexity within the industry, the establishment of robust open standards and rules of engagement becomes essential.

To guide the comparison of standards, the paper proposed a shift in perspective, emphasizing a focus on where the individual wants to go rather than simply tracking the vehicle's movements. Accordingly, the paper identified several stages in a journey where data flows between the operator and the user, including user registration, planning, booking, traveling, fare collection, payment, support, and after-sales services.

Additionally, the paper highlighted the importance of global standardization rather than local approaches. As an increasing number of operators deploy their services across different countries, adopting a global perspective becomes crucial to ensure harmonization and interoperability.

The European Commission has put together a new initiative to regulate Multimodal Digital Mobility Services (MDMS). These services can be defined as systems providing information about, inter alia, the location of transport facilities, schedules, availability and fares, of more than one transport provider, with or without facilities to make reservations, payments or issue tickets (e.g. route-planners, Mobility as a Service, online ticket vendors, ticket intermediaries) (European Comission, 2022). The objectives of this initiative are outlined below:

1. "Provide certainty and transparency for business-to-business commercial agreements for services reselling mobility products for land-based modes, waterborne and maritime transport, as well as for agreements on journey continuation."
2. "Prevent harmful market effects which may arise from discriminatory behaviour of MDMS against operators, and ensure that the deployment of MDMS is not hampered by discriminatory practices."
3. "Ensure that MDMS enhance the efficiency and sustainability of the transport system."

The commission opened the initiative for feedback in 2021 and conducted public consultation in 2022. The adoption of the initiative is planned for 2023.

The MaaS Alliance recently published a White Paper on Mobility Data Spaces (Maas Alliance Working Group, 2022). Mobility Data Spaces are built on top of the International Data Spaces (IDS), established in 2019, which sets a Reference Architectural Model built on Open Standards. It specifies the terms and conditions in the European data economy, promoting FAIR (findability, accessibility, interoperability, and reusability) principles (International Data Spaces Association, 2019). A data space is defined as *"a decentralised infrastructure for trustworthy data sharing and exchange in ecosystems based on commonly agreed principles"*. The IDS Association (IDSA) put together a position paper to define the design principles of an IDS which include a) Data sovereignty, b) Data level playing field, c) Decentralised soft infrastructure, d) Public-private governance (International Data Spaces Association, 2021a). Building on IDS, Mobility Data Spaces would act as a trusted aggregator of mobility data between a set of mobility stakeholders. An example of a Mobility Data Space Topology is shown in Figure 2.11.

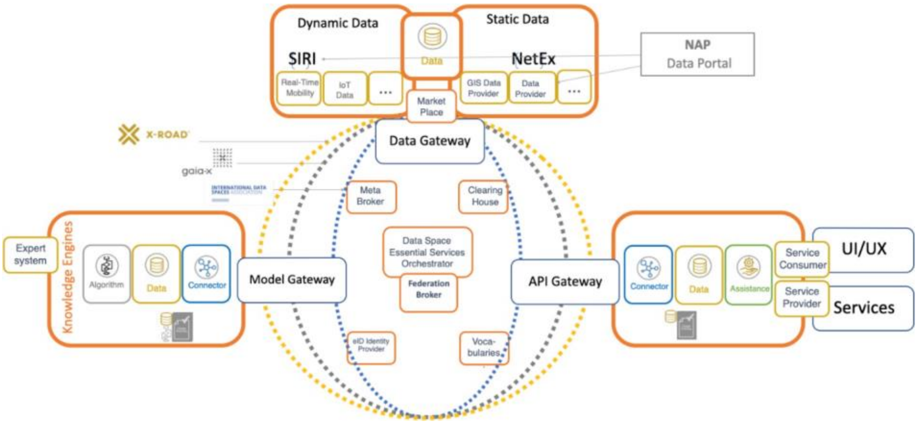

Figure 2.11 Example Topology of a Mobility Data Space (Olaf-Gerd Gemein, 2022)

In order to establish a Mobility Data Space, a collaborative entity is formed by the stakeholders with the following objectives (Maas Alliance Working Group, 2022):

- Formulate and establish participation rules.
- Define a shared set of policies.
- Develop a trust model and serve as a trusted authority.

This entity assumes responsibility for the registration and onboarding process of new members into the Mobility Data Space. Some of the subsequent steps involve creating a comprehensive list of data sources, constructing a federated catalogue of services for data users, defining a description and semantic integration of datasets, a common ontology, and a reference semantics to be adopted by all members, among others.

Although there are design principles in place for setting up a data space (International Data Spaces Association, 2021b), the principles are not domain-specific. There is an emphasis on standardisation, but there are no specifications set out for each domain. As a consequence, independently developed data spaces may lack interoperability as there is no global specification for data models. To address this challenge, the MaaS Alliance recommends the use of Transmodel as the reference semantics for any Mobility Data Space (Maas Alliance Working Group, 2022). However, it is difficult to impose a specific standard on operators, especially if they already adhere to a different standard, such as GTFS.

2.6 Summary

Through this chapter, a complete background is provided for the research problem statement, establishing grounds for the motivation behind proposing a data solution. The chapter first explores the evolving paradigm of ownership and consumption in the context of emerging technologies and changing consumer behaviors. It introduces concepts like servitization, platform business models, and the sharing economy, illustrating their impact across various sectors, notably in transportation. Central to this discussion is the concept of Mobility-as-a-Service (MaaS), which aims to offer users comprehensive mobility solutions through integrated digital platforms. The development of MaaS is traced from its inception to its current state, highlighting key features such as single-platform access, journey planning, and integrated ticketing and payment systems. However, the lack of consensus on certain aspects of MaaS, such as the scope of services and user preferences is highlighted. Despite these uncertainties, recent efforts have sought to define MaaS more precisely, emphasizing its user-centric nature and potential for achieving sustainable policy goals. The literature underscores the need for further research to address existing contradictions and to refine our understanding of MaaS interoperability requirements, through which this research aims to address by answering **RQ-1:** *What are the disagreements over the implementation of MaaS and what is causing them?*
The following areas of disagreement were identified through the literature:

1. Market Model
2. Modality
3. Features of Intelligent Routing
4. Ticketing and Payment Integration
5. Booking Features
6. Geographical Coverage
7. User Priorities
8. Payment Model
9. Auxiliary Services

These areas of disagreement will be further investigated through qualitative research presented in chapter 4 to understand the rationale behind each. Subsequently, 6 elements that can hinder or facilitate interoperability were identified in this chapter according to the definition of interoperability by European Commission (2010) and the interoperability matrix by Leal et al. (2019) which formed the questions in the qualitative research in chapter 4 addressing **RQ-2:** *What are the current and desired levels of business and data interoperability?*. The 6 elements are:

Business Barriers

1. **Conceptual:** Business Model
2. **Technological:** IT Infrastructure
3. **Organisational:** Common Goal

Data Barriers

1. **Conceptual:** Data Model
2. **Technological:** Data Storage and Access
3. **Organisational:** Data Management

Furthermore, the literature emphasized how, in the domain of Mobility as a Service (MaaS), there's a notable obstacle: the merging of various data types. Despite efforts to standardise transportation data, the result has been the creation of separate data entities due to differing definitions and language usage, as well as challenges in combining data from diverse sources. This division prohibits the smooth provision of services to travelers. A key research gap lies in making these data standards and models work together seamlessly, a crucial step in creating unified MaaS systems. However, emerging technologies like Linked Data and Semantic Web Technologies offer hope for overcoming this challenge and integrating diverse datasets within the MaaS framework.

The literature has shed light on critical gaps in the integration of transportation data models and the establishment of seamless connectivity within Mobility-as-a-Service (MaaS) frameworks. Despite extensive exploration in the field, including a thorough examination by the MaaS Alliance Working Group, it is evident that the emphasis should be on aligning existing standards rather than creating new ones. However, this alignment presents significant challenges, necessitating comprehensive understanding and coordination among stakeholders. Moreover, the absence of domain-specific specifications within current design principles for data spaces poses risks of interoperability issues among independently developed systems. To mitigate this challenge, the adoption of a common reference semantics, such as Transmodel, is proposed, although implementing such standards may face resistance from operators already adhering to different protocols.

In summary, this thesis aims to address these gaps by first investigating the areas of disagreement and identifying barriers to interoperability through qualitative research. Furthermore, it seeks to tackle the challenge of integrating diverse transportation data models within the MaaS framework through developing a data solution. By addressing these gaps, this research endeavors to contribute to the advancement of interoperable and unified MaaS systems, ultimately enhancing mobility experiences for users.

Chapter 3

3 Methodology

The methodology employed in this study serves as the backbone for understanding and addressing the research questions posed in this thesis. This chapter outlines the systematic approach taken to collect, analyze, and interpret data, ensuring the rigor and reliability of the findings. By delineating the research design, data collection methods, and analytical techniques utilized, this chapter provides insight into how the research objectives were pursued.

The flow diagram in Figure 3.1 demonstrates an overview of the research methodology, highlighting the research questions driving each step. The study begins with a literature review that defines the elements investigated in the qualitative research. The qualitative research follows a structured questionnaire which is analysed to provide insights on the areas of disagreement and the maturity of the business and data interoperability in MaaS. The results of the qualitative study define a set of interoperability requirements which are used to shape the data solution. An analysis is conducted on prominent data standards and exchange specifications to derive the different possible cases of transport operations. A taxonomy is built based on these cases to provide a method of standardising entry of transport operators into a data ecosystem. Finally, the applicability and implementation of the data solution is explored through a prototype which offers a demonstration of a step-by-step process for on-boarding transport operators. The next section explains how each method is applied to address the research questions outlined in Section 1.6. Following this, a detailed description of the qualitative study approach is provided, outlining its design and execution. Finally, the chapter concludes with an explanation of the methodology used to develop the taxonomy, which is based on the findings gathered from the qualitative study on interoperability requirements.

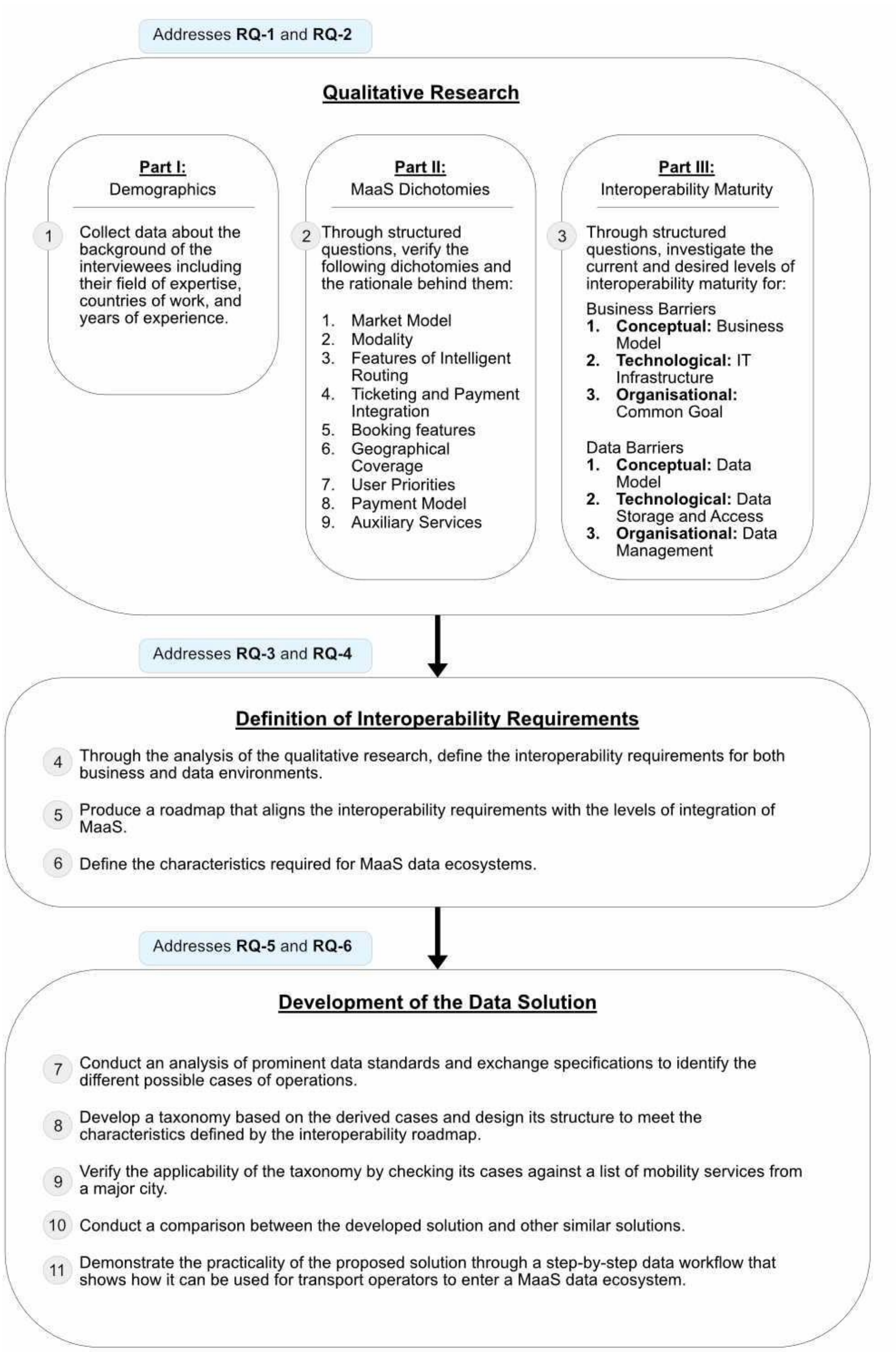

Figure 3.1 Summary of the research methodology specifying the corresponding research questions of each step

3.1 Alignment to Research Questions

RQ-1: What are the disagreements over the implementation of MaaS and what is causing them?

Prior to establishing the interoperability requirements of MaaS, an exploration of the literature is required to determine a thorough understanding of the concept. As outlined in subsection 2.1.2, the literature on Mobility as a Service delineates apparent dichotomies causing a disagreement over the definition and implementation of MaaS. To verify each dichotomy and the rationale behind it, a qualitative study is designed to explore these areas of disagreement through a structured interview. By providing an understanding of the varying and core characteristics of implementing MaaS, a better formulation of the interoperability requirements of the MaaS ecosystem will be possible.

RQ-2: *What are the current and desired levels of business and data interoperability?*

No prior investigation has been conducted to explore the level of maturity of interoperability in MaaS. Understanding where we are and where we need to be for a sustainable MaaS ecosystem is crucial in defining the interoperability requirements. In the same qualitative study addressing **RQ-1**, a section of the interview is designed to identify the current and desired levels of interoperability maturity. The maturity of both data and business interoperability is explored due to the major role the business requirements play in shaping data ecosystems.

RQ-3: *What are the business and data interoperability requirements of a MaaS ecosystem?*

Through the results of the qualitative study addressing **RQ-1** and **RQ-2**, a set of interoperability requirements are defined which are formulated into a roadmap based on the level of integration of the MaaS ecosystem.

RQ-4: *What characteristics must the data exchange process possess in order to meet the requirements?*

Based on the defined data interoperability requirements, a set of characteristics are deduced as the core features required to enable the data ecosystem to meet the interoperability requirements.

RQ-5: *What data solution would meet the defined characteristics?*

A data solution is designed based on the defined characteristics with the aim to standardise the entry of transport operators into the data ecosystem. This involves an analysis of prominent data standards to identify the different possible cases of transport operations.

RQ-6: *How does the proposed data solution fit within the current data ecosystems?*

An experimental platform or prototype is built to examine the applicability of the solution into the current data ecosystem. This involves data experiments leading to a proposed step-by-step process for on-boarding transport operators into a MaaS Data Ecosystem. The steps of the process are trialled using both conventional and Semantic Web Technologies, exploring the benefits of incorporating the latter.

3.2 Qualitative Study

A comprehensive review was undertaken to analyze different approaches for defining interoperability requirements and assessing their maturity levels. While several rigorous methods exist for quantifying interoperability, they primarily focus on ICT systems and measure factors such as data loss or computational efficiency during transactions (Ford, 2008). However, the objective of this study was to qualitatively understand the interoperability requirements specific to Mobility as a Service (MaaS) and endeavor to quantify their maturity levels.

Among the existing frameworks in the literature, the Maturity Model for Enterprise Interoperability (MMEI) (Guédria et al., 2015) was found to be the most suitable for achieving the study’s objective. Maturity models are frameworks that outline various levels of complexity at which activities in a particular domain can be executed (Alonso et al., 2010). Interoperability can be approached in two ways: a priori, where the potential for a system to be interoperable is assessed assuming future partnerships without specifying their identity, or a posteriori, where interoperability measures the compatibility of two or more systems that are willing to interoperate.

The MMEI is an a priori method for measuring interoperability. It encompasses three interoperability barriers (Conceptual, Technological, Organizational) and four areas of concern (Business, Service, Process, Data), as previously demonstrated in the literature in Figure 2.5. In this study, only the areas of Business and Data are explored. The model defines five maturity levels, as highlighted in Figure 3.2. The subsequent section will elaborate on the methodology employed to assess the maturity of interoperability.

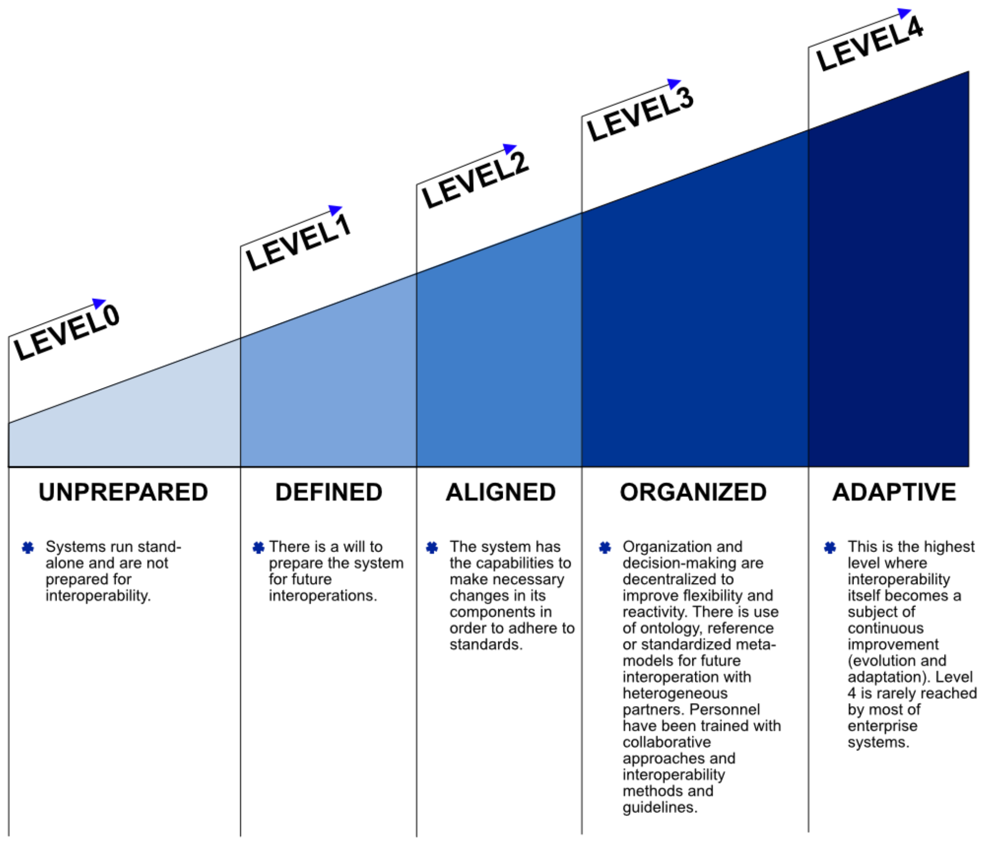

Figure 3.2 Five levels of maturity for Enterprise Interoperability (Guédria et al., 2015)

This investigation took a structured approach by integrating a qualitative interview with a survey. The survey questionnaire comprised three parts: **Part I**: Demographics and Background, **Part II**: MaaS Dichotomies, and **Part III**: Maturity of MaaS Interoperability.

To ensure the questionnaire's efficacy, a pilot study was initially conducted with seven participants, using only the survey format. Feedback from the pilot study revealed that the question structure was perceived as complex, requiring participants several minutes to answer each question. Additionally, it became evident that a purely survey-based approach lacked qualitative data, and the quantitative results alone were insufficient to fulfill the research objectives.

Consequently, the methodology was modified to an interview-based study, where participants underwent a structured questionnaire during the interview process. A total of **65 participants**, including the seven participants from the pilot study, were involved in the study. The questionnaire used in the interviews is attached in the appendices.

In this study, qualitative data was collected through interviews, allowing participants to provide rich and detailed information about their perspectives. The interviews also provided an opportunity to explore participants' reasoning for their choices in the questionnaire. For each question, the participants were asked to clarify why they picked a certain answer. On the other hand, quantitative data was obtained through the questionnaire, enabling the extraction of statistical values for the different questions. By employing both methods, the study could capture a broader range of insights and perspectives.

The qualitative data from the interviews and the quantitative data from the questionnaires were analyzed and compared to gain a deeper understanding of the barriers, challenges, and opportunities related to MaaS interoperability. The qualitative analysis involved a thematic analysis approach, where interview transcripts were coded to identify overarching themes related to the challenges and opportunities of MaaS interoperability. The quantitative analysis was only comprised of a basic statistical extract for each question. As the sample size is not statistically significant, it is only considered as supplementary insights to the qualitative data. By integrating and presenting both qualitative and quantitative findings, the study provides meaningful indications of the current state and desired directions of MaaS interoperability.

The subsequent sections will provide a detailed description of each part of the questionnaire, elucidating the research design and the specific questions posed to participants.

3.2.1 Part I: Demographics and Background

A total of 65 participants took part in the study. Initially, a pilot study was conducted with 7 participants, which helped refine the questionnaire. Subsequently, interviews were conducted with each participant to gather qualitative data. The final version of the questionnaire used in the interviews is included in Appendix A. Data collection concluded with a sample size of 65 participants. The participants in the study were primarily from the USA, European countries, Australia, and Malaysia, as depicted in Figure 3.3. They represented various stakeholder groups involved in MaaS, including:

- **Transport** (MaaS provider, Mobility-service provider, Transport operator, etc.) - 11 participants.
- **Regulation & Planning** (Public Authority, Policy Director, Enabler Group, City Planners, etc.) - 18 participants
- **Research** (Academic & Research institutes, universities, etc.) - 9 participants.
- **Technology & Data** (IT infrastructure, Third-party routing, Payment solutions, Data provider, etc.) - 19 participants.
- **Other** (Management Consultants, Non-Government Organisations, Non-Profit Organisations) - 8 participants.

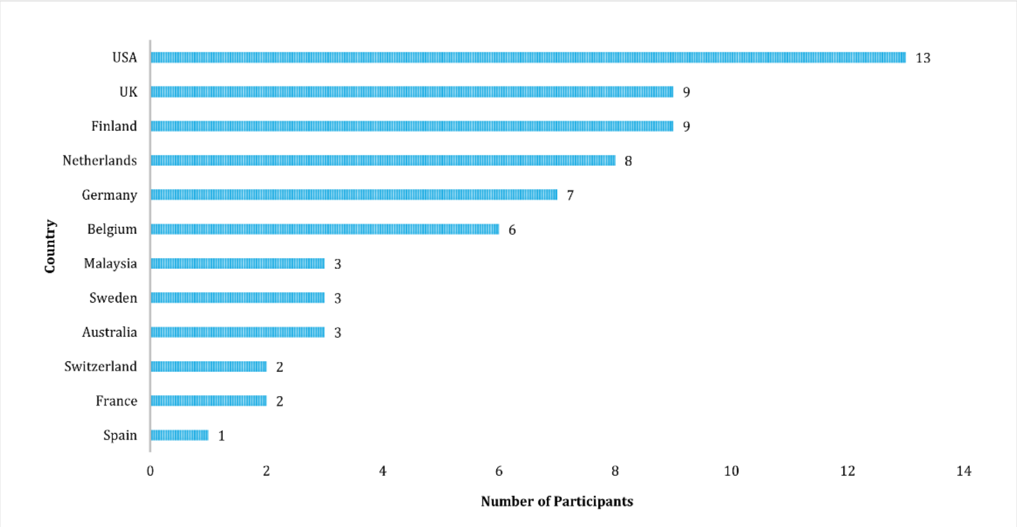

Figure 3.3 Geographical Background of Participants

The sampling approach employed in this study can be characterized as purposive sampling or expert sampling. Participants were selected based on their extensive experience and expertise in the field of Mobility as a Service (MaaS) and their active involvement in leading the transformation towards MaaS. The selection process involved identifying individuals with a strong background and thought leadership in MaaS through research and recommendations from other participants.

This sampling approach was deemed suitable for the research objectives for several reasons. First, by intentionally targeting highly experienced individuals in the field, the study aimed to capture valuable insights and perspectives from experts who possess in-depth knowledge of MaaS and its challenges. These experts are likely to have a deep understanding of the interoperability issues surrounding MaaS, which aligns with the research focus on analyzing MaaS interoperability maturity.

Second, purposive sampling allowed for a focused investigation of the research topic. By selecting participants who are actively engaged in the development and implementation of MaaS, the study sought to obtain rich and comprehensive data that can contribute to understanding the key factors influencing interoperability in MaaS systems. The expertise and thought leadership of these participants offer valuable insights that may not be readily available from a random sample.

However, it is important to acknowledge that the sampling approach employed in this study may introduce some biases, such as overrepresentation of specific perspectives or potential limited generalizability to the broader population. The focus on experts in the field may limit the diversity of perspectives and may not fully capture the experiences and challenges faced by other stakeholders in the MaaS ecosystem. Nevertheless, given the research objectives of exploring MaaS interoperability and leveraging insights from leading experts, the purposive sampling approach was deemed appropriate and beneficial for achieving the intended research outcomes.

The sample size of 65 participants was determined based on the principle of data saturation within the context of purposive sampling. As the study aimed to capture insights from leading experts and stakeholders in the field of Mobility as a Service (MaaS), the focus was on obtaining in-depth and comprehensive data rather than achieving statistical representativeness. Through the iterative process of conducting interviews and analyzing the qualitative data, it became evident that the insights and perspectives began to converge around the 60th participant. This convergence indicated that the key themes and patterns related to MaaS interoperability had been consistently observed in the data. The subsequent inclusion of five additional participants allowed for further validation and reinforcement of the emerging findings. By reaching the point of data saturation, where no new significant information was obtained, the sample size of 65 participants was deemed appropriate for fulfilling the research objectives and capturing the depth of expertise and experiences among the participants. The focus on data saturation, rather than achieving a specific target sample size, ensured that the study yielded rich and nuanced insights into MaaS interoperability from a range of perspectives, providing a comprehensive understanding of the research topic.

3.2.2 Part II: MaaS Dichotomies

Following the collection of demographic and background data from the participants, the study progressed to the first primary section of the questionnaire which explores areas of disagreement among stakeholders regarding the concept and constituents of Mobility as a Service (MaaS). This section aimed to comprehensively investigate these disagreements and their implications for interoperability, thus providing valuable insights to inform strategies for addressing the identified challenges. The study solicited both qualitative and quantitative data from each participant, specifically focusing on their perspectives regarding the opposing sides of the disagreements and their rationale behind their chosen stance. The following areas of disagreement were explored in this study based on finding from the literature discussed in subsection 2.1.2:

1. **Market Model** - Stakeholders' perspectives on two contrasting market models were examined:
    - **Broker Model** - This model entails MaaS providers having exclusivity over a series of transport service providers, thereby exerting control over the market. Exclusivity contracts, rather than acting as intermediaries, form the basis of this model.
    - **Open Market** - In contrast, an open market allows any transport operator, irrespective of size, to share their services through standardized data, facilitating inclusion in the MaaS system.
2. **Modality** - Disagreements centered around two modal approaches:
    - **Unimodality** - This approach involves offering travelers various modes of transportation but lacks integration to enable multimodal journeys from point A to B.
    - **Intermodality** - In contrast, intermodality provides passengers with the capability to utilize multiple modes of transport within a single journey, facilitated by a journey planner.
3. **Intelligent Routing Features** - Stakeholders expressed varying opinions on the following features and capabilities of intelligent routing for MaaS:
    - **Balancing demand** - MaaS needs to balance supply and demand across different modes of transport, recommending alternative options if a particular mode is at full capacity.

- **Generating insights** - MaaS should generate data on multimodal travel behavior that can be utilized by various MaaS stakeholders.
- **Context-aware routing** - Incorporating real-time factors such as weather and network disruptions, MaaS provides travelers with context-aware routes to optimize their journeys.

4. **Ticketing and Payment Integration** - Different integrated features for ticketing and payment were compared:

    - **Unified payment method** - Enabling payment for all services through a unified gateway, accommodating various payment options like online banking, credit cards, and QR codes.
    - **Unified access method** - Allowing users to access different modes of transport using a single validation method, such as entering a station or unlocking a bike.
    - **Single invoice** - Integrating transaction processing to provide users with a single invoice for their payments.

5. **Booking Features** - Comparison of stakeholders' views on the importance of on-demand booking versus scheduling rides in advance.
6. **Geographical Coverage** - Comparison of different extents of geographical coverage for MaaS.
7. **Features for Users** - Comparison between the importance of providing different features for users of MaaS.
8. **Payment Model** - Comparison of pay-as-you-go model with personalized bundles and subscriptions.

    - **Pay-as-you-Go** - Passengers pay for trips post-use, based on a request-and-pay model.
    - **Subscriptions and Personalized Bundles** - Passengers pay a fixed fee for a certain duration, granting access to a set amount of services.

9. **Auxiliary Services** - The inclusion of auxiliary services, such as food delivery, package deliveries, and hotel bookings, within the same application or platform as the passenger transport application was assessed for its importance.

To investigate these areas of disagreement, structured interviews were conducted with the 65 participants selected through purposive sampling. The interviews were designed to capture participants' perspectives, insights, and experiences related to MaaS and its constituent elements. The qualitative data obtained from the interviews were analyzed thematically to identify patterns, commonalities, and differences in stakeholders' viewpoints.

In addition to qualitative analysis, the quantitative data collected during the interviews were subjected to statistical analysis. Although the quantitative results of this study do not reach statistical significance, they still provide valuable insights into the prevalence of certain perceptions within the sample. These insights shed light on which side of the disagreements holds greater influence or whether there is a neutral stance among participants.

It is important to acknowledge that the areas of disagreement explored in this study may not encompass all possible dimensions of disagreement surrounding MaaS. However, delving into these specific areas serves as a foundational step in understanding the challenges associated with differing perceptions of MaaS. By doing so, the study contributes to the development of effective strategies to address these challenges, ultimately promoting enhanced interoperability in the MaaS ecosystem.

3.2.3 Part III: MaaS Interoperability

The second part of this study was concerned with assessing the maturity level of MaaS interoperability in terms of both business interoperability and data interoperability. The methodology aimed to extract different insights from the data through both quantitative and qualitative analysis regarding barriers to increasing interoperability, developing elements such as data model and business model, and understanding the current and desired maturity levels of interoperability.

The structure of the questions in the questionnaire followed the Maturity Model for Enterprise Interoperability (MMEI) (Guédria et al., 2015). After the pilot study, the feedback on this section of the questionnaire showed that the matrices were difficult to relate to MaaS due to the phrasing of the questions being theoretical. Therefore, the questions were re-worded to ensure they were less theoretical and more easily understandable for the participants.

For the assessment of business interoperability, the barriers to interoperability were categorized as follows:

a) **Conceptual** - maturity of the business models in a MaaS ecosystem

Level 0: Business model NOT explicitly modelled or documented

Level 1: Business model is explicitly modelled or documented

Level 2: Use of standards for alignment with other models

Level 3: Business models for multi partnership and collaborative enterprise

Level 4: Adaptive business model

b) **Technological** - maturity of the IT infrastructure used by MaaS transportation stakeholders

Level 0: No or unreliable IT infrastructure

Level 1: Basic IT infrastructure in place

Level 2: Standard and configurable IT infrastructures

Level 3: Open IT infrastructure

Level 4: Adaptive IT infrastructure

c) **Organisational** - standardisation and agreement over the objective of MaaS between stakeholders

Level 0: No common goal

Level 1: Common goal is not well defined

Level 2: Common goal is well defined but not agreed upon by stakeholders

Level 3: Some stakeholders agree and work towards common goal

Level 4: All stakeholders understand, agree, and work towards common goal

Regarding data interoperability, the barriers to interoperability were categorized as follows:

3. **Conceptual** - maturity and interoperability between data models required for the operation of MaaS

Level 0: Data models NOT explicitly modelled or documented

Level 1: Data model is explicitly modelled or documented

Level 2: Use of standards for alignment with other models

Level 3: Meta-modelling for multiple model mappings

Level 4: Adaptive data models (both syntax and semantics)

4. **Technological** - accessibility of data and maturity of data storage methods

   Level 0: No or closed data storage devices, manual exchange

   Level 1: Data storage devices connectable, simple electronic exchange possible

   Level 2: Automated access to data, based on standard protocols

   Level 3: Remote access to databases possible for applications, shared data

   Level 4: Direct database exchanges capability and full data conversion tool

5. **Organisational** - maturity of data management where roles and responsibilities of stakeholders are defined.

   Level 0: Data responsibilities and authorities not explicitly defined

   Level 1: Responsibilities/authorities defined and in place

   Level 2: Rules and methods for data management

   Level 3: Personalized data management for different partners

   Level 4: Adaptive data management rules and methods

For the qualitative results, a thematic analysis approach was employed. The qualitative data was collected during interviews conducted with the participants, providing rich and detailed information about their perspectives on MaaS interoperability. The interviews allowed for an exploration of the participants' reasoning for their choices in the questionnaire. The interview transcripts were divided into question specific documents and then coded where the overarching themes were related to the challenges and opportunities of MaaS interoperability for each of the questions.

In addition to the qualitative analysis, a quantitative analysis was conducted to extract statistical values for each level of interoperability. However, it is important to note that due to the limited number of participants (65) and the focus on interoperability within the specific regions/countries that the participants work in, the quantitative results are not supposed to possess statistical significance or generalizability for MaaS in any region. Therefore, they were primarily analysed to reveal any valuable patterns and trends between the responses, which would complement the qualitative results by providing meaningful indications of the current state and desired directions of MaaS interoperability.

The results are presented in section 4.5. Each interoperability element (e.g., data models, business models, etc.) has qualitative and quantitative results derived to represent the current and desired levels of its maturity with detailed insights on why these levels were chosen, geographical differences in maturity, challenges and opportunities in raising the maturity level, and more.

3.3 Taxonomy Development

Through the results of the qualitative study, the data interoperability requirements of MaaS are derived. Based on these defined requirements and a review of the standards, a taxonomy is proposed covering the different cases of transport operations. The approach taken to the steps in Figure 3.1 is described below:

1. Conduct an analysis of prominent data standards and exchange specifications to identify the different possible cases of operations.

    The approach to conducting the data standards analysis involves a comprehensive review of prominent data standards within the Mobility-as-a-Service (MaaS) ecosystem. Building upon the initial review conducted in subsection 2.2.3, a select set of data standards was identified, focusing on those commonly used across various MaaS operations. Each standard is carefully examined to understand its scope, purpose, and applicability to different phases of a journey within the MaaS framework. This analysis aims to identify the diverse cases of operations covered by each standard, including the types of data elements, formats, and exchange specifications they encompass. The review process involves studying the documentation, specifications, and guidelines provided for each standard to gain insights into their structure and functionality. Additionally, the analysis includes comparing and contrasting the features and capabilities of different standards to assess their suitability for integration within the MaaS ecosystem.

2. Develop a taxonomy based on the derived cases and design its structure to meet the characteristics defined by the taxonomy roadmap.

The approach taken to develop the taxonomy based on the derived cases involves a systematic analysis of the phases of a journey and the corresponding variations in operator data profiles. The analysis identifies the key phases of a journey, where each phase is carefully examined to understand the specific data interactions required between users and operators, considering variations in services and operational models. Through this process, a comprehensive breakdown of the journey phases and additional layers of variation is established, forming the core elements of the taxonomy. This structured approach ensures the development of a robust taxonomy that captures the diverse operational scenarios and data requirements encountered across different MaaS services and operators.

3. Verify the applicability of the taxonomy by checking its cases against a list of mobility services from a major city.

   To ensure the comprehensive coverage and applicability of the taxonomy developed in the previous step, a validation process is conducted by examining a list of mobility services in Moscow against the taxonomy layers. This validation aims to verify whether each layer of the taxonomy adequately captures the different types and elements comprising an operator's dataset necessary for facilitating passenger movement. For each mobility service, the taxonomy is scrutinized to determine the applicability of a case from each layer. By systematically comparing the characteristics of various mobility services with the taxonomy layers, this validation process provides insights into the taxonomy's effectiveness in categorizing and addressing the diverse operational scenarios encountered across different mobility service providers.

4. Conduct a comparison between the developed solution and other similar solutions.

   In order to assess the uniqueness and effectiveness of the developed taxonomy, a comparative analysis is conducted with existing taxonomies relevant to the field of mobility services. Notable taxonomies are identified from previous studies that offer distinct perspectives and classifications within the realm of shared mobility. Through this comparative study, different dimensions and classifications pertaining to shared mobility are explored, enriching the understanding of the field's complexities. The aim of this study is to verify the novelty and relevance of the Mobility Profiles taxonomy in addressing the specific challenges and needs within the realm of Mobility as a Service.

5. Demonstrate the practicality of the proposed solution through a step-by-step data workflow that shows how it can be used for transport operators to enter a MaaS data ecosystem.

   To practically demonstrate the applicability and usability of the proposed Mobility Profiles taxonomy within a MaaS data ecosystem, a step-by-step data workflow is developed. The workflow development is based on the characteristics defined through the qualitative study. This step-by-step approach aims to demonstrate the practicality and effectiveness of the Mobility Profiles taxonomy in facilitating seamless data exchange and interoperability within the MaaS ecosystem.

Chapter 4

4. Analysis of MaaS Interoperability Requirements

4.1 Overview

A lack of interoperability hinders the seamless integration of diverse transportation modes, preventing the realization of MaaS' full potential in providing convenient, efficient, and sustainable mobility solutions. Hence, the exploration of MaaS interoperability is a crucial area of research that holds great interest for policymakers, industry stakeholders, and researchers alike.

Limited research has explored the areas of disagreement among stakeholders regarding the concept and constituents of MaaS. The literature was studied where 9 areas of disagreement were defined as summarised in Section 2.6. However, there are no previous studies that explore the reasons behind these areas of disagreement and hence the reasons behind the difficulty in collaboration between MaaS stakeholders. Addressing the first research question of this thesis, **RQ-1:** *What are the disagreements over the implementation of MaaS and what is causing them?* the first part of this qualitative study investigates these disagreements and their implications for interoperability which provides a comprehensive understanding of the challenges that can be used to inform strategies to overcome them.

In addition, previous studies have highlighted the benefits of MaaS interoperability but there is a gap in identifying and examining critical factors that influence interoperability maturity, such as data models, storage, and access. The second section of this study addresses the second research question **RQ-2:** *What are the current and desired levels of business and data interoperability?* The methodology is described in Section 3.2. In this chapter, the results of the interviews are presented followed by the discussion and conclusion.

4.2 MaaS Dichotomies: Results

In this section, the results of the MaaS Dichotomies section of the questionnaire are presented. Each subsection will represent the qualitative and quantitative results for each question in the study.

4.2.1 Market Model

This question was set out to explore the different opinions on existing visions of implementing Mobility-as-a-Service. The first vision is where a MaaS provider has exclusivity over a series of transport service providers and the larger that series is, either in terms of size or quantity, the greater the control they have over the market. This vision is referred to as the broker model. Brokering here does not refer to a MaaS provider being an intermediary between operators and users, but instead focuses on the exclusivity of the contracts. The second vision is where MaaS is achieved through an open market. An open market enables any operator to put their services on the system, regardless of their size, through sharing their data in a standardized way.

The quantitative and qualitative results of the questions were aggregated into three different stances, where the first stance supports a Broker model market, the second supports an Open Market model, and the third stance is neutral. **Error! Reference source not found.** demonstrates the split in these three views as voted by 65 participants.

For each stance, the qualitative points, which encapsulate the reasons or thought process behind the participants' choices, were documented and categorised into positives and negatives for each view. In this case, where only two models are being compared, the negatives of one approach can be considered as the positives of the other.

Broker Model A summary of all the qualitative data collected during the interviews on the Broker Model is presented in Table 4.1. The table presents both positive points in favor of implementing a Broker Model for a MaaS provider as well as negative points against it.

Table 4.1: Summary of positive and negative points on a Broker Model for MaaS Operators

Positives	*Negatives*

+ Integrating medium and large players is easier through a broker model.	- The Broker model makes it difficult to include smaller local providers and reduce barriers to entry.
+ Many people in the MaaS industry follow a broker approach for their business.	- Profit-oriented broker models may exclude smaller operators.
+ The Broker model has the potential to build trust and relationships among players.	- Broker models appeal to MaaS providers for commercial benefits but may not align with MaaS goals.
+ Broker models can provide a unique value proposition for MaaS providers.	- Exclusive contracts in broker models create barriers for smaller operators as it will favour operators who can cover the most regions and hence higher profit.
+ Broker models enable local focus and drive innovation.	

Open Market A summary of all the qualitative data collected during the interviews on the Open Market is presented in Table 4.2. The table presents both positive points in favor of implementing an Open Market as well as negative points against it.

Table 4.2: Summary of positive and negative points on an Open Market for MaaS Operators

Positives	*Negatives*
+ Open markets focus on enabling any operator to put their services without being profit oriented.	- Open markets may require continuous funding or investment, which may not be sustainable or scalable.

+ MaaS platforms should have open APIs for integration by any size player. + Conditions for accessing the market should be non-discriminatory and fulfill basic requirements. + Open market encourages open data sharing, promoting innovation and achieving MaaS goals.	- Encouraging a one-stop shop in the name of an Open Market can lead to monopolization if only one platform has access to all the data. - Too many choices in an open market may make the app user-unfriendly. - Enforcing an open market can be costly for operators and providers.
+ Open market aligns with the financial model of subsidized public transport. + Transport operators can find an open market more interesting as their services are promoted on different platforms.	- The resources and transactions required to maintain an open market may lead to monopoly and diminish localized services.
+ True MaaS is achieved when all providers share data in a standardized way on a single app. + Open market with open data of larger players fosters competition and innovation. + Targeted data in an open market reduces noise and confusion for users.	

Neutral Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of both of the concepts being compared or a statement to consider when deciding on the market model that should be implemented for MaaS.

1. **Flexibility and Choice:**

   - Multiple platforms should compete, giving people the freedom to choose.

- Travelers need access to all options that suit their needs and preferences.
- Ideal MaaS involves decentralized broker models where everyone can join using the right standards.
- Multiple apps should cater to travelers with different needs.

2. Market Dynamics:

- The market currently consists of a mixture of both broker models and open markets.
- The choice between models depends on policy objectives and profitability/scalability considerations.
- Transition to an open market may occur over time, but opening a closed model can be challenging.
- Different cities/regions may have different transportation funding structures and legislation, leading to varied models.

3. Role of Government:

– The government may need to play a role in building the supply chain of partners, as the private sector alone may not be capable.
– In countries where the government is the primary public transport operator, they should also be the MaaS provider.
– Europe's emphasis on open data inherently supports the open market.

3. Integration and Interoperability:

– Optimal integration and interoperability can be achieved with both broker models and open markets.
– All transport operators should provide data in a standardized way to enable multiple aggregators.

4. Champions and Sustainability:

- The presence of a champion is crucial for MaaS success.
- Venture capital reliance may have limitations, and long-term sustainability is a concern.

- It is too early to determine which model is superior.

5. **Combination of Models:**

   – A combination of broker models and open markets can be used based on the mode of transportation.

   – An open market can coexist with multiple broker models competing against each other.

4.2.2 Modality

This question was set out to explore the importance of multimodality as a characteristic of MaaS.

The two concepts compared were a) a unimodal journey planner where the application or platform offers travelers a variety of modes of transportation but is not capable of integrating the modes into a single multimodal journey, and b) an intermodal journey planner where passengers can travel from point A to point B using multiple modes of transport in a single journey.

These concepts are only compared at an integration level to define the interoperability requirements of the journey planner. It is not to be confused with the contractual definitions of these terms where multimodal transport refers to a single contract with a carrier that covers the entire door-to-door journey regardless of how many modes of transport, and intermodal transport where a separate contract is present for each individual leg of the journey. The latter definitions are common in transportation logistics. The difference was clarified to participants with previous knowledge of these terms.

Unimodal A summary of all the qualitative data collected during the interviews on unimodal journey planners is presented in table 4.3. The table presents both positive points and negative points.

Intermodal A summary of all the qualitative data collected during the interviews on intermodal journey planners is presented in table 4.4. The table presents both positive points and negative points.

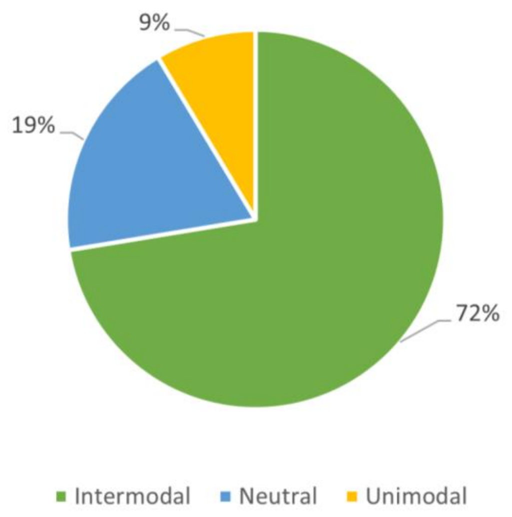

Figure 4.1 Percentage of participants supporting a unimodal MaaS platform, an intermodal MaaS platform, and a neutral stance

Table 4.3: Summary of positive and negative points on Unimodal Journey Planners

Positives	*Negatives*
+ Easier coordination and feasibility with a unimodal approach. + Strong value proposition even with a unimodal platform. + Commuting trips between home and work constitute a significant portion of travel journeys, making unimodal planning relevant. + Potential for significant improvement in unimodal planning with the introduction of MaaS. + Just having multiple modes on the same platform can bring a lot of value. Users do not need to switch between apps and payment accounts.	- Providing a lot of options with no capability to interchange between modes does not align with the concept of MaaS.

+ Feasibility of establishing a fee structure and contractual framework for a unimodal app compared to an intermodal app. + Adequacy of unimodality within urban areas where public transit is well-connected and first-mile/last-mile connectors are unnecessary.	

Table 4.4: Summary of positive and negative points on Intermodal Journey Planners

Positives	*Negatives*
+ To achieve environmental and sustainable goals, MaaS needs to address the first mile/last mile problem and help users connect to public transit networks. + The value of intermodal planning lies in facilitating access to and from transportation hubs, such as train stations. + Modes should not be treated independently; intermodal planning should focus on providing a seamless door-to-door experience. + Intermodality adds value to transportation for tourists. + Eliminating the need for users to navigate different apps, systems, and schedules to plan a trip is a fundamental promise of MaaS.	- It is very difficult to coordinate between modes there will be time delays, availability issues, payment and ticketing issues. - Does not add too much value to users who are mainly commuting. - We do not have rail cars that would allow bikes on board. Integrating micromobility with public transit will be challenging.

+ Intermodality offers flexibility to meet diverse traveler needs for different journeys.
+ Intermodal planning is crucial for connecting people to suburban areas lacking adequate public transit coverage.
+ Intermodal becomes particularly important in scenarios with seasonal variations or situations where walking to a station is less convenient.

Neutral Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of both of the concepts being compared or a statement to consider when deciding on the modality that should be implemented for MaaS.

1. **Unimodal as a Prerequisite for Intermodal:**
   - Recognition that a unimodal journey planner serves as a foundation for an intermodal planner
   - Acknowledgment of a continuum where unimodal planners are a starting point for gradually achieving interoperability requirements of intermodal planners
2. **Customer Perspective and Convenience:**
   - Customer viewpoint that multimodality may not matter as long as the MaaS service is convenient
   - Emphasis on the importance of seamless journeys, comprehensive coverage, and convenient payment methods
3. **Interoperability and Standards:**
   - Highlighting the need for discussions on interoperability requirements beyond technical barriers
   - Identifying the importance of open data and journey planner standards

to facilitate planning across different modes

4. **Integration and Coordination Challenges:**

   – Recognizing the difficulty of integrating and coordinating modes in journey planning, despite the potential for unified ticketing and payment methods

5. **Resilience and Flexibility:**

   – Acknowledging the necessity of multiple modes to ensure resilience in the face of disruptions or unexpected events

6. **Relevance to Vertical Service Providers:**

   – Indicating that the modality (unimodal or intermodal) may not matter for vertical service providers like parking apps

4.2.3 Features of Intelligent Routing

This question was set out to explore the features of intelligent routing that would influence the interoperability requirements of MaaS. The following three features were explored which tackled requirements on the MaaS providers end:

- **Balancing demand** This feature means that MaaS needs to balance the supply and demand between the different modes in the network. For example, if the trains are of full capacity, then the routing engine would recommend different modes to users.

- **Generating Insights** - This feature means that MaaS will generate data regarding multimodal travel behavior that can be utilized by the various stakeholders of MaaS.

- **Realtime factors and context-awareness** - This feature means that MaaS will incorporate real-time factors such as weather and network disruptions and provide travelers with context-aware routes. For example, if you are heading to the airport for travel with a large luggage, it will not recommend that you take a bike or a scooter.

Figure 4.2 presents the quantitative split between the participants for each of the three features.

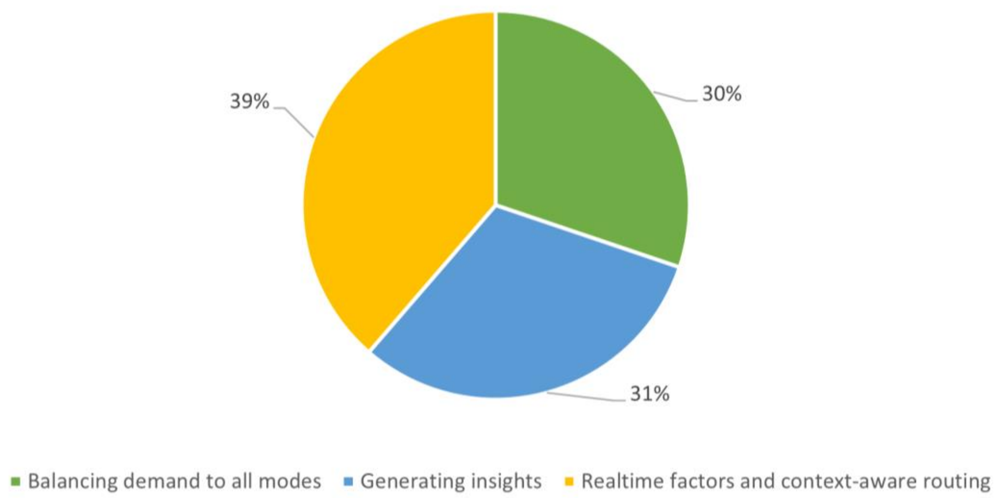

Figure 4.2 Percentage of participants supporting each of the three features of intelligent routing

Balancing demand to all modes A summary of all the qualitative data collected during the interviews on balancing demand to the different modes is presented in Table 4.5. The table presents both positive points and negative points.

Generating Insights A summary of all the qualitative data collected during the interviews on generating insights is presented in Table 4.6. The table presents both positive points and negative points.

Realtime factors and context-aware routing A summary of all the qualitative data collected during the interviews on Realtime factors and context-aware routing is presented in Table 4.7. The table presents both positive points and negative points.

Table 4.5: Summary of positive and negative points on Balancing Demand

Positives	*Negatives*
+ Balancing demand is important for policy, reliability, and social distancing, especially in a pandemic setting. + Providing alternative options to avoid peak hours, particularly for trains, is beneficial. + Balancing demand is crucial for the cost-effectiveness of MaaS and prevents underutilization of services. + It contributes to achieving policy objectives, such as environmental sustainability. + Balancing demand guides users toward better mode choices and addresses the lack of information for informed travel decisions. + Differential pricing based on supply and demand helps achieve a balance in demand. + Balancing demand optimizes asset utilization in MaaS operations.	- Some argue that balancing demand is unnecessary due to policy concerns, revenue considerations, optimization challenges, and equity issues. - Public authorities already make efforts to balance demand across different transportation modes. - Balancing demand may limit user control and flexibility by guiding them toward specific modes. - Public authorities may be hesitant to balance demand between public transport and other services. - Introducing balancing demand adds complexity to MaaS interoperability requirements, potentially contradicting its customer-focused nature. - Discussions about balancing demand as a requirement are considered premature since MaaS is not yet a planning tool.

Table 4.6: Summary of positive and negative points on Generating Insights

Positives	*Negatives*
+ MaaS has the potential to provide valuable multimodal data, making it important for public authorities and cities to pay attention to. + Generating insights from MaaS can support multimodal network management, enabling data-driven changes to improve schedules, routes, and services. + If the MaaS operator is from the public sector, generating insights becomes a priority to enhance the network through MaaS. + Generating insights would be of significant interest to cities and governments, aligning with their goals.	- Generating insights may be considered more of a byproduct of MaaS rather than a requirement, as insights are expected to be generated regardless. - The importance of generating insights may be higher for secondary stakeholders, such as researchers or city planners, rather than being a primary priority. - It might be premature to consider generating insights from MaaS at this stage. - Concerns about user privacy and the perception of being monitored may discourage users from embracing MaaS, necessitating careful regulation and privacy considerations. - Generating insights may not add much value unless it surpasses the existing data capabilities of public authorities. - Before focusing on generating insights, it is necessary to establish the MaaS system and address responsible data collection and privacy concerns as a prerequisite.

Table 4.7: Summary of positive and negative points on Realtime factors and context-aware routing

Positives	*Negatives*
+ Real-time factors and context-aware routing are important for on-demand services, enhancing their effectiveness. + They contribute to the reliability of MaaS by recommending alternative options based on trip preferences or network disruptions. + In geographical locations with constantly changing weather, real-time factors and context-aware routing are crucial to consider, such as avoiding booking a bike when it is going to rain. + Including individual preferences, such as CO2 emissions and other factors beyond time and cost, would be interesting for users. + Prioritizing the end-user is essential in MaaS, and real-time factors and context-aware routing directly benefit them. + Achieving real-time data is challenging but highly important for providing a better user experience in MaaS.	- Real-time factors and context-aware routing are less relevant when dealing with modes of transportation with fixed routes and schedules. - Allowing software to make travel decisions can be concerning, particularly in the context of optimization and the potential for bias or discrimination in decision-making. - Disruptions in the system may not be a significant concern for users, making the complexity introduced by real-time factors unnecessary. - The integration of real-time factors and context-aware routing is primarily a usability improvement rather than a critical requirement.

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when deciding on the features of intelligent routing that should be implemented for MaaS.

1. **Supplier's Perspective and User Flexibility:**
   – The requirements of MaaS differ for suppliers and users, with users prioritizing flexibility in transportation choices.
   – MaaS should be built to serve societal goals, regardless of whether the operator is public or private, and the sharing of insights should be considered accordingly.
2. **Interconnectedness of Balancing Demand and Real-time Factors:**
   – Balancing demand (matching supply and demand) and considering real-time factors (such as trip preferences, network disruptions, and changing weather conditions) are closely interconnected in MaaS.
3. **Core Requirements for MaaS Journey Planner:**
   – A comprehensive MaaS journey planner should enable users to discover intermodal routes, rank options based on individual preferences beyond time and price and offer comprehensive solutions.
   – The discussed items are desirable features for a MaaS journey planner but not considered core requirements for achieving MaaS.
4. **Societal vs. Individual Benefits:**
   – The importance of the discussed items varies depending on whether the focus is on benefiting society as a whole or individual customers.
5. **Business Case and Profitability:**
   – Convenience and user experience are crucial in MaaS and help differentiate it from established companies like Google, requiring the provision of incentives, whether financial or otherwise.
6. **Influence of Operator Type and Pandemic:**
   – The relevance and prioritization of the discussed items depend on the nature of the MaaS operator (public or private) and the impact of the pandemic on traffic patterns and work-from-home trends.
7. **Vertical Service Providers:**
   – The relevance of the discussed items for vertical service providers

depends on whether they already offer similar features or can benefit from collaborating with MaaS.

8. **Prioritization and Phased Approach:**
   – Enhancing the user experience through better routing is a priority in MaaS to attract more users, with a subsequent shift towards optimizing the network, generating insights, and achieving broader objectives.

9. **City-Specific Considerations:**
   – The desirability of the discussed features in MaaS varies based on city-specific challenges, such as congestion, real-time data availability, or demand balancing.

4.2.4 Ticketing and Payment Integration

This question was set out to explore the interoperability requirements for integrating ticketing and payment within a MaaS ecosystem. The question explored the following three integrations:

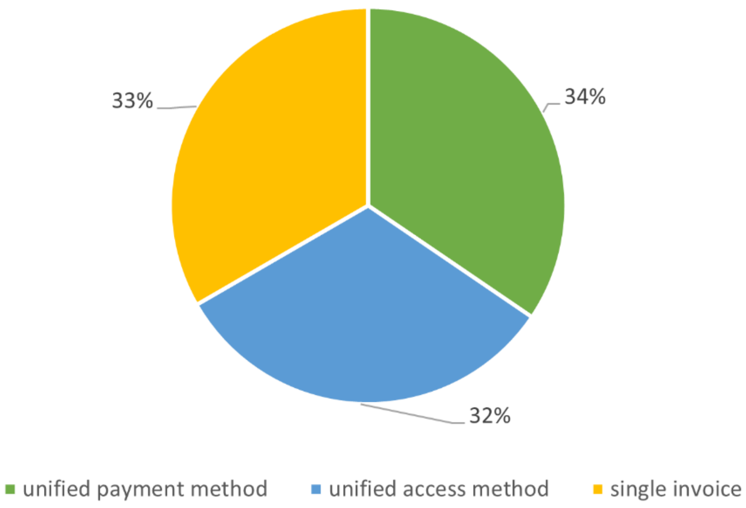

Figure 4.3 Percentage of participants supporting each of the three ticketing and payment integrations.

Unified Payment Method refers to enabling all services/modes of transportation to be paid for through a unified payment method. The method here refers to a single gateway that can include different payment options such as online banking, credit cards, QR codes, etc. A summary of all the qualitative data collected during the interviews on unifying the method or gateway of payment is presented in Table 4.8. The table presents both positive points and negative points.

Unified Access Method refers to enabling users to access different modes of transport through a unified method. This refers to the validation of the traveler that, for instance, allows them into a station or to unlock a bike. A summary of all the qualitative data collected during the interviews on unifying the method or gateway of access is presented in Table 4.9. The table presents both positive points and negative points.

Single Invoice refers to the processing of transactions being integrated where users only receive a single invoice for their payment. A summary of all the qualitative data collected during the interviews on single invoice is presented in Table 4.10. The table presents both positive points and negative points.

Table 4.8: Summary of positive and negative points on Unified Payment Method

Positives	*Negatives*
+ The unified payment method is a prerequisite for MaaS.	- Challenges may arise when certain operators do not support the payment method used by the MaaS operator or when travelers have existing subscriptions with specific operators.
+ It is important for brokers as it allows travelers to pay for their multimodal trip in a single transaction.	- Exclusive agreements between big payment companies and larger tech companies can hinder the achievement of unified payments accessible to all parties.
+ A middleware, such as a mobility wallet, needs to be engineered into the platform to facilitate unified payments.	- There is a risk of excluding users without bank accounts, so implementation should ensure inclusivity.
+ Users benefit from not having to worry about multiple payment tools, cards, or wallets.	

Table 4.9: Summary of positive and negative points on Unifying Access Method

Positives	*Negatives*
+ It is beneficial to simplify and make access more convenient for users by avoiding different access methods for different modes. + Using a smartphone as a universal access tool, with various methods like Bluetooth, QR codes, and contactless payments, would be ideal.	- Imposing a single access mechanism across different regions and services may not be feasible or practical. MaaS should rather be able to accommodate different access models. - The priority should be on integrating payments rather than unifying access methods. - The TOMP standard for access methods has proven to be complex, but alternative solutions like deep links can provide a seamless transition between different third-party apps for access. - Implementing the same access method for all modes may not be possible due to inherent differences in hardware and operational requirements. - There is a risk of excluding certain users if only digital access methods are used, so inclusivity should be ensured in the implementation.

Table 4.10: Summary of positive and negative points on Single Invoice

Positives	*Negatives*
+ The most important aspect of a single invoice is to provide users with a clear and easily understandable price for their entire trip. + A single invoice is crucial for enhancing user experience by eliminating confusion and the need to interact with multiple invoices from different transport providers. + On the operator's side, a single invoice can help reduce credit card fees associated with multiple transactions, especially for bike operators and small vehicle operators. + Providing a single invoice is a defining characteristic of the MaaS offering and determining the frequency of the invoice (per trip, per day, per week, per month) is an important consideration.	- While desirable, having a single invoice is not essential, and it is not a significant issue if a trip with multiple modes results in separate payments on the user's card. - Achieving a single invoice may require all modes to be provided by the same transport provider to streamline the invoicing process.

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when deciding on integration of ticketing and payment that should be implemented for MaaS.

1. **Convenience and Seamless Experience:**
   - All three integrations (ticketing, payment, and access) are necessary to create a convenient and hassle-free MaaS service for travelers.
   - The ideal scenario involves partnering with a single finance provider for unified payment and invoicing.

- MaaS should offer a seamless ecosystem that connects to users' bank accounts, automatically tracks and deducts payments based on travel choices, and provides regular summaries of trips.

2. **Integration and Subscription:**
   - The three integrations (ticketing, payment, and access) are essential for achieving a monthly subscription model in MaaS.
   - Payment and access methods are often interconnected, such as using contactless payments for both accessing turnstiles and paying for train trips.

3. **Mode-Specific Considerations:**
   - The importance of access methods varies depending on the mode of transportation. For example, buses require simple boarding, while bikeshare and rideshare services rely more on access methods.
   - Unified payment methods are typically associated with the generation of a single invoice, highlighting the close relationship between these two integrations.

4. **Customer Preference and Technical Feasibility:**
   - Customer preference and technical possibilities should be considered when deciding on integration approaches.

5. **Security and Liability:**
   - The services offered in a MaaS environment have varying liabilities, leading to differences in the security of payments.

6. **Ticket Unification:**
   - Avoiding separate tickets for each mode of transportation is seen as an important aspect to consider.

4.2.5 Booking Features

This question was set out to understand the perception of stakeholders on the requirement for MaaS to offer on-demand booking versus the ability to schedule rides in advance.

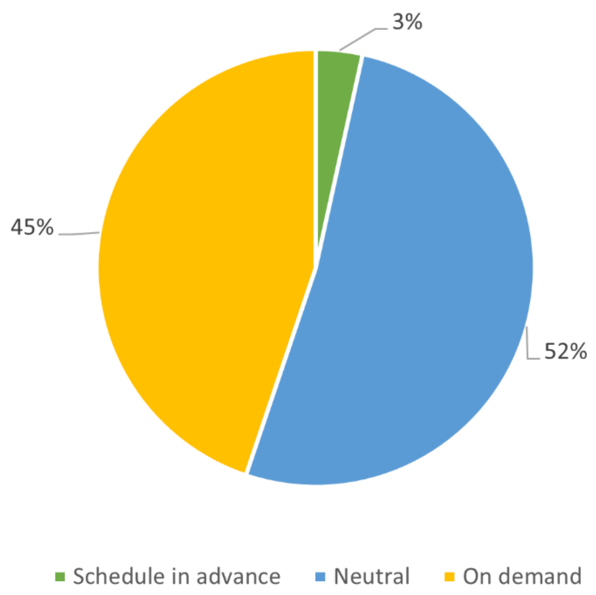

Figure 4.4 Percentage of participants supporting on-demand booking, scheduling bookings in advance, and neutral stance.

On-demand Booking A summary of all the qualitative data collected during the interviews on booking trips on-demand is presented in Table 4.11. The table presents both positive points and negative points.

Scheduling Trips in Advance A summary of all the qualitative data collected during the interviews on scheduling rides in advance is presented in Table 4.12. The table presents both positive points and negative points.

Table 4.11: Summary of positive and negative points on On-demand Booking

Positives	*Negatives*
+ On-demand booking is particularly beneficial for rural areas where trips are more likely to be ad-hoc.	- The capacity of public transport presents a significant challenge in achieving a fully on-demand MaaS system.
+ Providing on-demand booking is necessary for MaaS to replace or reduce reliance on private cars, as it should offer a similar level of availability and convenience.	- Building an intermodal and on-demand MaaS system is difficult due to the variation in the operation of each mode, making it challenging to guarantee reliability for each leg of a trip.

Table 4.12: Summary of positive and negative points on Scheduled Booking

Positives	*Negatives*
+ Scheduling trips in advance can ensure the availability of modes of transit and help manage capacity, which is important for offering reliable service.	- Most people will not use scheduled bookings frequently, except for occasional use cases like cross-country trips, which represent a small percentage of overall trips.
+ + It is more suitable in bigger cities where people have regular schedules and can plan their commutes ahead of time.	- It may not be very convenient to predict the exact departure time for a trip in advance, as schedules can change.
+ + Scheduled bookings can be offered at a cheaper price compared to on-demand options, as they guarantee transport operators their capacity.	
+ + Paratransit services and certain use cases, such as hospital appointments or long-distance trips, can benefit from scheduling in advance.	
+ Scheduled booking may be necessary to integrate transport operators with legacy technology systems.	

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when deciding on booking features that should be implemented for MaaS.

1. **Location and Demographics:**
   – The choice between on-demand booking and scheduling depends on the location and population demographics. Rural areas may benefit from on-demand booking, while bigger cities may find scheduling more optimal.

2. **Mode of Transport:**
   – The booking method may vary depending on the mode of transport. Multimodal trips involving ride-hailing could benefit from scheduling, while standalone ride-hailing trips are already oriented towards on-demand booking.

3. **Integration and Convenience:**

   - MaaS focuses more on integration than the moment of booking. Scheduling in advance may require less complex integration.

   – Users prioritize convenience in terms of travel time, frequency, and cost. Financial incentives can influence their booking behavior.

4. **Continuum and User Preferences:**
   – There is a continuum between scheduled and on-demand booking, where initial offerings can start with scheduled bookings and gradually transition towards a fully on-demand service.
   – MaaS should be capable of offering both booking options to cater to user preferences.

5. **Commuter Trips:**

   – MaaS may not play a significant role in commuter trips, as commuters often have established travel patterns and may already hold annual or season passes. MaaS would need to provide a compelling value proposition to attract commuters who primarily use public transport.

4.2.6 Geographical Coverage

This question was set out to understand the expectations of MaaS stakeholders on the extent of the geographical coverage of a single MaaS platform.

City-wide / State-wide Coverage A summary of all the qualitative data collected during the interviews on city-wide / state-wide coverage is presented in Table 4.13. The table presents both positive points and negative points.

National Coverage A summary of all the qualitative data collected during the interviews on national coverage is presented in Table 4.14. The table presents both positive points and negative points.

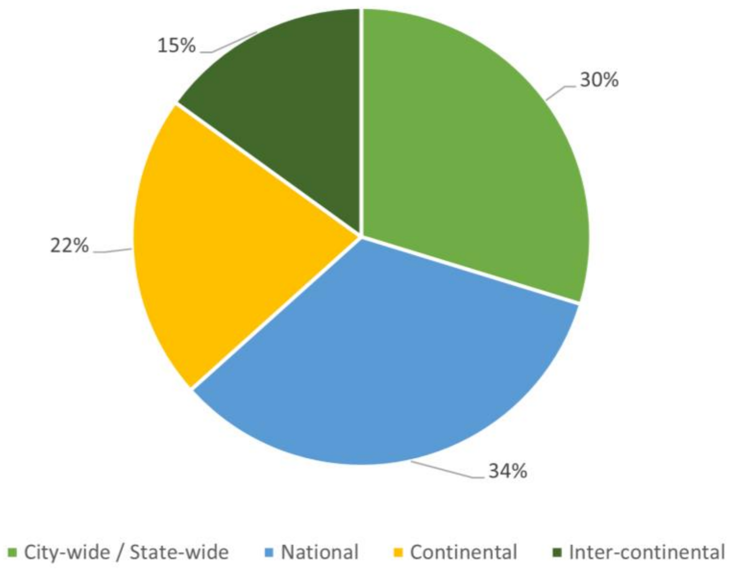

Figure 4.5 Percentage of participants supporting city-wide coverage, nationwide coverage, continental coverage, and intercontinental coverage

Continental Coverage A summary of all the qualitative data collected during the interviews on continental coverage is presented in Table 4.15. The table presents both positive points and negative points.

Intercontinental Coverage A summary of all the qualitative data collected during the interviews on intercontinental coverage is presented in Table 4.16. The table presents both positive points and negative points.

Table 4.13: Summary of positive and negative points on City-wide / State-wide Coverage

Positives	*Negatives*
+ City-wide coverage is suitable for Europe. + Regional solutions that enable interstate travel, rather than national or city-wide, may be more suitable for countries like the United States. + The majority of trips take place within one's city environment, making city-wide coverage more relevant.	- The industry's focus on city-wide solutions may lead to interoperability issues between different cities' MaaS platforms, requiring users to download multiple apps. - National coverage may be optimal for setting consistent authentication rules or regulations like disabled parking.

+ Local coordination and relationship-building with suppliers or mobility service providers are easier at a city-wide level. + Focusing on achieving a city-wide solution in the next five years is a priority. + + Connecting the city center to suburban areas would benefit passengers in terms of sustainability and reducing car ownership. + In small countries, local transportation is prevalent, while in larger countries, city-wide coverage may not be sufficient due to greater distances. + New operation models like car sharing are most suitable for city or state coverage due to practicality constraints.	- Achieving a statewide solution, especially in the United States, faces challenges due to autonomy and different regulations between states. - In cities where sustainable transportation is already prevalent, MaaS may have limited usefulness for local residents and be primarily beneficial for visitors.

Table 4.14: Summary of positive and negative points on National Coverage

Positives	*Negatives*
+ National coverage is relevant and in demand, especially in countries like Scotland and Australia. + National coverage is important to serve populations residing in suburbs and non-major cities. + Unifying transportation access cards across different regions can facilitate the transition from a regional to a national network.	- Providing MaaS at a national level may result in the loss of small local operators who may not have the same resources as larger city operators. - Implementing a national-level app in a country like the United States would need to consider a vast geographic area and a large number of transport services, posing significant challenges.

+ In countries with a well-operated transport network, such as Singapore, implementing a national MaaS platform can work effectively.	-

Table 4.15: Summary of positive and negative points on Continental Coverage

Positives	*Negatives*
- The concept of having a limited number of mobility operators running all mobility worldwide is a possibility for the future. - Continental coverage would be more relevant in Europe due to cross-border commuting and the potential value of a cross-border app between certain countries. - Continental coverage would be beneficial for businessmen and tourists, although it represents a small proportion of overall trips.	- It may not be necessary or realistic to have a single MaaS platform for an entire continent, such as Europe, due to barriers and differences between countries. - For continental trips, the focus shifts to long-distance transportation modes like planes or trains, making the first and last-mile connectivity less significant. - It may be reasonable to expect users to download separate MaaS apps when traveling to different continents for work or leisure.

Table 4.16: Summary of positive and negative points on Intercontinental Coverage

Positives	*Negatives*
+ The future vision of MaaS includes intercontinental coverage, where users can travel anywhere in the world using a single app without the need to download new apps.	- Implementing intercontinental coverage poses significant challenges from commercial and regulatory perspectives. - Achieving full intercontinental coverage is not expected in the near future.

+ Intercontinental coverage would offer great convenience to travelers, especially when visiting unfamiliar countries, by providing a consistent app experience. + There is interest among contributors to the Transport Operator Messaging Protocol (TOMP) standard in developing international capabilities. + Intercontinental coverage would likely be an evolutionary progression from the current state of MaaS.	- The mindset and preferences of international travelers differ significantly, making it a complex use case for MaaS to fulfill.

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when deciding on the geographical coverage of a MaaS Operator.

1. **Impact of Geographical Size and Boundaries:**
   - Depends on the size of the country.
   - Achieving coverage beyond city-wide introduces complexity, especially across regions with different languages.
   - Geographical boundaries have no impact on making MaaS functional; it depends on the willingness of suppliers/mobility providers to participate.
   - The radius of coverage affects the perception of value, with intercontinental coverage being more appealing than city-wide.
2. **Interoperability and Data Standards:**
   - Continuum of coverage from city-wide to intercontinental as interoperability improves.
   - Data standards should be interoperable at a global level regardless of the MaaS platform.

3. **Objectives and Target Audience:**
   - MaaS operator's goals and target audience influence coverage decisions.
   - Customization of MaaS solutions for each city may be necessary.
   - Different approaches required for tourists versus employees.

4. **Evolutionary Approach:**
   - Start with a viable proof of concept and expand coverage gradually.
   - Higher geographical coverage can be considered once initial stages are successful.

5. **Value and Financial Sustainability:**
   - Capturing the value of car ownership is crucial for financial sustainability.
   - City-wide coverage may not address the mindset and freedom associated with car ownership.

4.2.7 User Priorities

This question was set out to understand what do the MaaS stakeholders believe to be the main priority for the users of MaaS.

Data Privacy and Security A summary of all the qualitative data collected during the interviews on data privacy and security is presented in Table 4.17. The table presents both positive points and negative points.

Pricing and Packages A summary of all the qualitative data collected during the interviews on pricing and packages is presented in Table 4.18. The table presents both positive points and negative points.

Personalized Routing A summary of all the qualitative data collected during the interviews on personalized routing is presented in Table 4.19. The table presents both positive points and negative points.

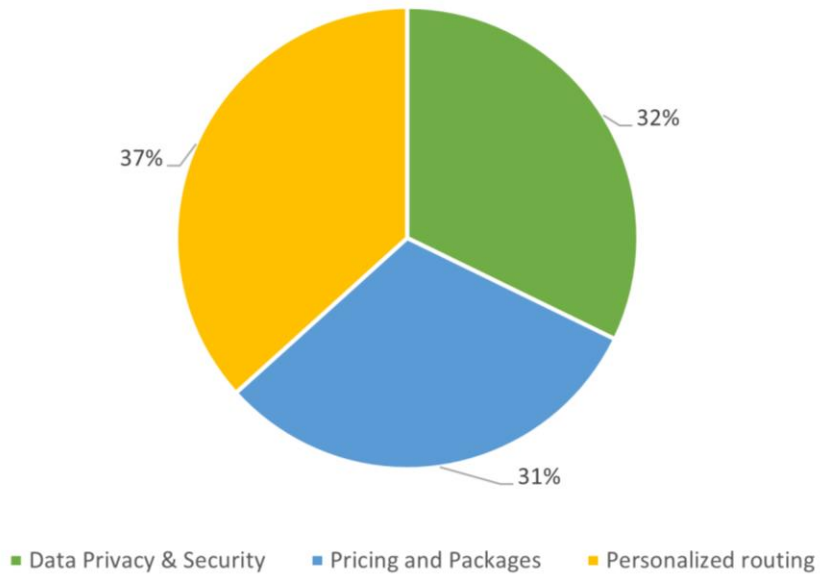

Figure 4.6 Percentage of participants supporting each of the three user priorities.

Table 4.17: Summary of positive and negative points on Data Privacy and Security

Positives	*Negatives*
+ Data privacy is a significant concern for users, and it is crucial to provide solutions that are secure and protect user data.	- Some argue that despite claims of being sensitive to data privacy, users' behaviors do not consistently support that claim.
+ Germans particularly prioritize data privacy.	- The average user may not pay much attention to data privacy and accept terms and conditions without reading them.
+ Due to the involvement of multiple stakeholders, personal data exchange in MaaS must be secure and limited to necessary instances.	- People generally do not mind sharing depersonalized data.
+ Security is crucial to maintain user trust, especially in the context of the automotive industry and people's cars.	- Data privacy is considered a hygiene factor, expected but not a unique attractor for users.
+ Data privacy is important from the government's perspective, and users care more about it if the MaaS provider is a government authority.	- With the ubiquity of mobile phones, privacy trade-offs are often made, as people rely on phones in the modern age.

+ Industry professionals tend to be more conscious of data privacy. + User awareness of the data being collected, and its use will make data privacy more important. + Sensitive data types like payment information and geographical locations are seen as sensitive, and people are conscious of protecting them. + Data privacy is a prerequisite for user trust, but once established, attention shifts to pricing and personalization.	

Table 4.18: Summary of positive and negative points on Pricing and Packages

Positives	*Negatives*
+ Pricing and packages are considered the primary driver for people to use MaaS. + Offering users the best price options quickly and without extensive searching across platforms is important. + Reasonable pricing is a minimum requirement, and users should feel that they are not overpaying for the services. + For the average user, pricing and suitable packages are crucial factors. + When the price is right, users may prioritize it over privacy	- Pricing may be considered a lower priority if public transit is already subsidized by national authorities.

and convenience.	
+ Packages and their pricing have the potential to change users' travel behavior and encourage the adoption of more sustainable modes of transport.	
+ The Dutch particularly value pricing considerations.	

Table 4.19: Summary of positive and negative points on Personalized Routing

Positives	*Negatives*
+ Personalization is a key aspect of MaaS, focusing on understanding users, their preferences, and travel behaviors.	- Personalized routing may be considered a future feature that is not necessary in the early stages of MaaS implementation.
+ Offering modes of transport that match users' preferences is important.	- Some users may prefer to manually choose the modes of transport they are interested in, making personalized routing less essential.
+ Providing a door-to-door experience is highly desired by many users.	- Commuters with fixed travel patterns may not derive significant value from personalized routing.
+ Personalizing routes for each mode of transport, considering factors like terrain for biking, is important.	-
+ The system needs to accommodate the diverse needs and constraints of users to encourage usage.	

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when perceiving the priorities of users in MaaS.

- The priorities will depend on the country and the culture and travel behavior of the people in that country.

- Having an ecosystem is important in this scenario so that you can have different MaaS platforms with different value propositions that suit different target audiences as there is a lot of diversity within the users of MaaS.

- Personalization is most important to users, be it through pricing or through routing. Data privacy is more of a necessary thing to have but it can be provided to a very minimum standard.

4.2.8 Payment Model

This question was set out to explore the disagreement of MaaS stakeholders over the payment model of MaaS platforms. The models compared were:

- **Pay-as-you-Go** This refers to post-paid payment models where passengers pay for trips as they request them.

- **Subscriptions and Personalized Bundles** - This refers to pre-paid payment models where passengers pay a fixed fee for a certain duration which gives them access to a set amount of services.

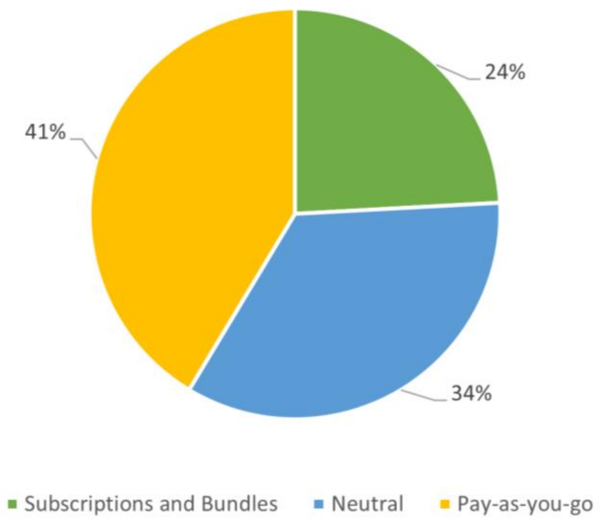

Figure 4.7 Percentage of participants supporting Pay-as-you-Go, Subscriptions, and neutral stance.

Pay-as-you-Go A summary of all the qualitative data collected during the interviews on Pay-as-you-Go is presented in Table 4.20. The table presents both positive points and negative points.

Subscriptions and Personalized Bundles A summary of all the qualitative data collected during the interviews on Subscriptions and Personalized Bundles is presented in Table 4.21. The table presents both positive points and negative points.

Table 4.20: Summary of positive and negative points on Pay-as-you-Go

Positives	*Negatives*
+ Pay-as-you-Go has the potential to promote the adoption of MaaS.	- Pay-as-you-Go often incurs high transaction fees. - Relying solely on Pay-as-you-Go may not fulfill the business or societal goals of MaaS, as it primarily adds convenience to users without necessarily supporting sustainable modes of transport. - MaaS operators emphasizing Pay-as-you-Go may steer customers towards less sustainable options, such as car-sharing and e-hailing, for higher revenue, which contradicts the desired societal objectives.

Table 4.21: Summary of positive and negative points on Subscriptions and Personalized Bundles

Positives	*Negatives*
+ Subscriptions have been successful in certain contexts, such as an offer in Switzerland that allows users to travel anywhere within the country for one year. + People are willing to pay for subscriptions if the price is right.	- The market may not be ready for certain package offerings, as they are not attractive enough to customers. - Customers may be hesitant to pay a large subscription fee for a new service. - The market may not be ready for certain package offerings, as they are not attractive enough to customers.

+ Subscriptions have been successful in certain contexts, such as an offer in Switzerland that allows users to travel anywhere within the country for one year.
+ People are willing to pay for subscriptions if the price is right.
+ The concept of "as-a-Service" aligns with the idea of MaaS, where users can pay for a mobility subscription instead of owning a car.
+ Bundles and subscriptions provide a guaranteed income for mobility providers and can include bonus systems to incentivize users.
+ Tailored packages, such as commuter or tourist packages, can influence user behavior and encourage advanced scheduling of transportation.
+ Subscriptions bring value to corporate organizations, especially for employees who travel frequently.

- The market may not be ready for certain package offerings, as they are not attractive enough to customers.
- Customers may be hesitant to pay a large subscription fee for a new service.
- Pricing of subscriptions has been a challenge, with some subscriptions being overpriced compared to the services consumed.
- Building bundles with shared mobility is difficult due to the varying frequencies and instability of demand for those modes.
- Offering clear discounts and reducing monthly expenses through subscriptions is challenging, especially if train operators are already subsidized.
- Subscriptions may have limited value for commuting trips taken with public transport, as season passes, and consistent routes already exist.
- Post-trip incentives, such as loyalty schemes, may be more effective than subscriptions in incentivizing users.
- It is still early to determine what needs to be included in an attractive package.
- Subscribing to packages with modes users do not usually take may lead to unnecessary usage, network overload, and increased CO_2

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when deciding on the payment model of MaaS.

1. **Continuum and Readiness:**
   - There is a continuum between pay-as-you-go and subscriptions/bundles, with the market gradually becoming more ready for the latter.
   - The choice between payment models depends on user preferences, mode of travel, and user profiles (e.g., commuters, tourists).
   - Lack of consensus within the MaaS community on the definition and payment model of MaaS.
2. **Mixture and User Choice:**
   - The payment model is likely to be a mixture of both pay-as-you-go and subscriptions/bundles, with users having the flexibility to choose.
   - The integration of different mobility options is more important than the specific payment model, providing convenience through a single interface for users.
3. **Bundles and Add-ons:**
   - Ideal bundles should accommodate the user's frequently used mode of transportation, such as public transit, with the option to add-on other services as needed.
   - Convenience is often prioritized in payment models, but considerations should also be given to financial, temporal, and ecological impacts.
4. **MaaS Operator as an Intermediate:**
   - The MaaS operator should act as a travel agent and recommend the best payment model for users, serving as an intermediary between users and transport operators.

4.2.9 Auxiliary Services

This question was set out to understand the expectations of MaaS Stakeholders on including auxiliary services on the same application or platform as the passenger transport application. Auxiliary services here refer to any service other than the transportation of passengers, such as food delivery, package deliveries, hotel bookings, etc.

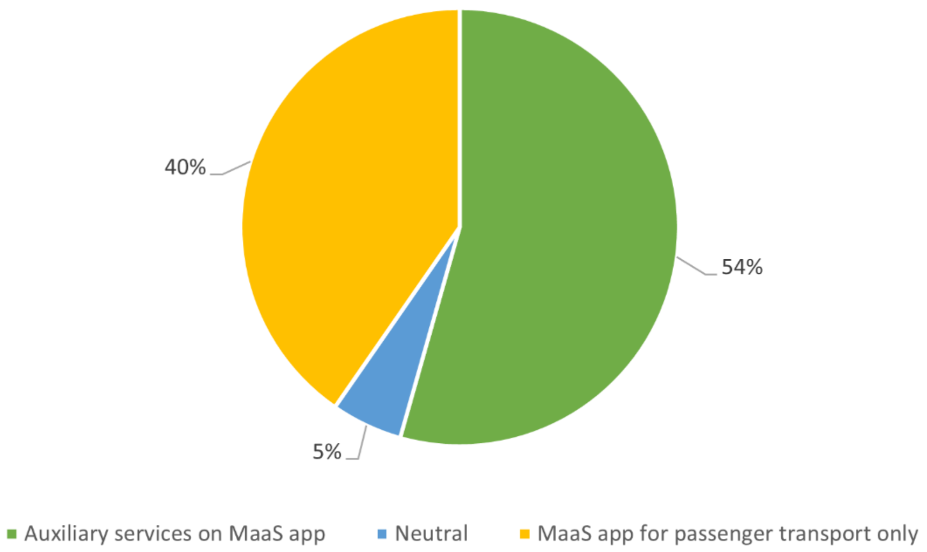

Figure 4.8 Percentage of participants supporting the integration of auxiliary services, separating them, and a neutral stance.

Separating Auxiliary Services A summary of all the qualitative data collected during the interviews on Separating Auxiliary Services is presented in Table 4.22. The table presents both positive points and negative points.

Including Auxiliary Services A summary of all the qualitative data collected during the interviews on Including Auxiliary Services is presented in Table 4.23. The table presents both positive points and negative points.

Table 4.22: Summary of positive and negative points on separating auxiliary services

Positives	*Negatives*
+ Working on auxiliary services separately before integration is considered beneficial. + Focusing on one thing improves service quality. + There is no strong relationship or benefit in integrating auxiliary services into MaaS. + Auxiliary services have different use cases, clients, and supply chains, indicating they should be treated as separate systems.	

+ There should be a limit to the amount of information in a single application for efficiency. + Logistics investments, like drones, can enhance efficiency but may not directly relate to MaaS. + Auxiliary services bring value to the gig economy, but their connection to MaaS is limited. + Passenger apps should accommodate items that need to be transported with passengers. + Simpler travel choices and processes are preferred for disadvantaged users. + Underlying data may have some similarities, but the systems for auxiliary services and MaaS remain separate.	

Table 4.23: Summary of positive and negative points on including auxiliary services

Positives	*Negatives*
+ Linking auxiliary services to the travel journey can add value and convenience for users. + Integrating travel routes with package deliveries can reduce vehicle usage and provide a more efficient delivery system.	- Full integration of auxiliary services may not happen in the near future. - The European market may not be ready for such integration at present.

+ Including auxiliary services can enhance the one-stop shop concept of MaaS and benefit users.	- Integrating auxiliary services adds complexity and requires additional regulations to address concerns like hygiene, particularly in the post-COVID era.
+ Auxiliary services help in understanding user preferences and can be a business model for MaaS operators.	
+ Integration with existing apps catering to auxiliary services can make the MaaS platform more commercially viable.	
+ Combining journey destinations, such as hotel bookings and restaurant reservations, adds value and enhances the lifestyle-as-a-service concept.	
+ Contextual trip planning and personalized recommendations based on user patterns and situations are valuable additions.	
+ + Integration of food delivery and logistics services with MaaS platforms has already begun.	

Additional Points Through the analysis of the qualitative data, some points were neutral. This means it could be in favour of a mixture of the concepts being compared or a statement to consider when deciding on including auxiliary services into the same app or platform for MaaS passenger transport.

- There is a debate in the MaaS industry about the difference between Mobility-as-a-Service (MaaS) and Mobility-on-Demand (MoD). Auxiliary services are more of a MoD feature.

4.3 MaaS Dichotomies: Discussion

4.3.1 Market Model

The quantitative results indicate that a larger proportion of respondents support setting up an open market model for MaaS (69%), while 17% remain neutral, and 14% prefer a broker model.

The qualitative points from the interviews shed light on the reasons behind the disagreement on the market model. These points can be organized into the following aspects:

a) **Inclusivity of Operators** - Open markets facilitate the inclusion of operators of any size, while broker models tend to favor larger, more technologically ready operators that generate higher profits.

b) **Appeal to transport operators** - Broker models, by forming exclusive contracts, can offer commercial advantages to transport operators, making it easier to establish trust compared to an open market.

c) **Objectives** - An open market aligns with just and inclusive principles, eliminating monopoly and aiding in achieving sustainable goals and city objectives. On the other hand, a broker model is more adept at achieving the commercial objectives of MaaS.

d) **Funding and Self-sustainability** - Open markets often require continuous subsidies or venture capital investment, making scalability and long-term sustainability challenging. Broker models, being profit-oriented, have a higher potential to reach critical mass.

e) **Complexity** - Broker models involve higher complexity as each operator needs to be custom integrated onto the platform with varying contracts. Open markets, once standards are set, rely on open data and standardization, reducing complexity.

f) **Cost** - Open markets incur higher costs for transport operators as they require migration to interoperable standards. Broker models, on the other hand, incur higher costs for the MaaS provider, who needs to custom integrate each operator.

g) **User Experience** - An open market with numerous options may create noise and make it difficult for users to filter through the available choices. This could impact the user experience.

Based on the results, an open market model appears to be more representative and suitable for MaaS. However, it is crucial to ensure that the open market model encourages the democratization of data and does not have discriminatory conditions for operators. A continuum between the two models is possible, with broker models serving as a starting point to gain the trust of transport operators. However, transitioning from a closed, monopolized model to an open market may present challenges.

Regarding the MaaS provider, if it is the government or an organization operating most public transit services, building MaaS with fewer brokering transactions is feasible since public transport forms the majority of MaaS services. However, if the MaaS provider is also an operator of its own services, a conflict of interest may arise, prioritizing the provider's own services when recommending trips to users.

In conclusion, a decentralized broker model, combining elements of both models, seems most ideal. This model entails opening up data, integrating ticketing and payment systems based on feasible standards for all operators. Multiple aggregators can then develop unique MaaS solutions from the available data and services, targeting different customer groups. This approach promotes healthy competition, innovation, and overcomes the current limitations caused by data monopolization.

4.3.2 Modality

Quantitatively, the majority of participants (72%) support the inclusion of intermodality in MaaS, with 19% maintaining a neutral stance and only 9% favoring unimodality.

The qualitative points derived from the interview results shed further light on the modality debate:

a) **Coordination** - Achieving seamless coordination between different modes in a single trip is challenging, making unimodal journeys more reliable in terms of mode availability compared to intermodal journeys.

b) **Type of Trip** - Some participants perceive MaaS primarily as a solution for daily commutes, where a unimodal platform would suffice due to the prevalence of single-mode (public transport) trips. However, in car-first countries and areas situated away from main transport lines, intermodal planning becomes crucial to address the first mile and last-mile problem.

c) **Commercial feasibility** - Establishing a fee structure and commercial framework, including responsibilities and liabilities, is easier to agree upon in a unimodal platform compared to intermodal scenarios.

d) **Urban development** - Well-developed urban areas may find unimodal solutions sufficient, whereas rural regions may benefit more from intermodality.

e) **Objectives** - Intermodal planners effectively address the first-mile and last-mile problem, which is a significant barrier to reducing reliance on private cars. Therefore, achieving the sustainability goals of MaaS requires intermodality and integration between modes.

f) **User Experience** - A unimodal planner streamlines account integration, eliminating the need for users to switch between apps to find travel options. However, intermodality is necessary for MaaS to provide a door-to-door experience and recommend the most optimal routes to users.

g) **Complexity** - Achieving intermodality poses technical, commercial, and legislative complexities compared to unimodal solutions.

In conclusion, a continuum exists between unimodal and intermodal concepts, as a unimodal planner serves as a prerequisite for an intermodal planner. However, the ultimate goal should be to achieve intermodality and raise the interoperability of MaaS by breaking barriers related to data standards and ticketing systems. Acknowledging and addressing these challenges will pave the way for a more integrated and effective MaaS system.

4.3.3 Features of Intelligent Routing

Quantitative results indicate a relatively equal split among the three features, with 39% supporting real-time factors and context-aware routing, 31% favoring generating insights, and 30% prioritizing balancing demand to all modes.

Balancing Demand to Different Modes - Ensuring the resilience of the network and optimizing asset utilization through balanced demand across modes is crucial. However, implementing such measures raises challenges of equity for customers and operators, as discouraging customers from using certain modes may disproportionately affect specific groups. Striking a balance that promotes efficiency while considering equitable access is essential.

Generating Insights - The ability to generate insights from multimodal data holds substantial value for network management. Data-driven changes can enhance the efficiency and effectiveness of the system. However, careful discussions are needed to determine the appropriate level and depth of insights to be shared. Furthermore, achieving large-scale MaaS implementation is necessary before the insights generated become of significant value.

Real-time Factors and Context-aware Routing - Incorporating real-time factors and context-aware routing can greatly enhance the user experience, particularly in areas with varying weather conditions or frequent disruptions. It also allows for the inclusion of sustainability aspects, such as considering carbon emissions. However, caution must be exercised to prevent potential dangers, such as embedding racism or classism into the system. Transparency and integrity are vital in ensuring that routing recommendations are fair and unbiased.

In conclusion, all three features hold valid importance and have the potential to add significant value to a MaaS platform. However, it may be premature to consider implementing these features universally at this stage. Additionally, different cities will face varying struggles and requirements. For networks with frequent disruptions, real-time factors become crucial, while cities dealing with high congestion may prioritize balancing demand. The priority given to each feature should align with a country's major challenges and specific context.

4.3.4 Ticketing and Payment Integration

Quantitative results demonstrate a relatively equal split among the three types of integration, with 34% supporting a unified payment method, 33% favoring a single invoice, and 32% prioritizing unified access methods.

Unified Payment Method - A unified payment method offers significant advantages to users, eliminating the need for multiple payment tools or cards by allowing a single account to pay for any available services. However, potential disadvantages include excluding operators that only support cash payments and the possibility of missing out on discounts offered through non-MaaS payment methods. Furthermore, there is a risk of excluding customers without bank accounts. To ensure inclusivity, a unified payment gateway that integrates various payment methods while accommodating all customers and operators would be more ideal.

Unifying Access Method - Unifying the access method brings convenience and contributes to a seamless user experience. However, several barriers exist in achieving complete unification. Modes of transportation on a MaaS platform inherently differ, with bikes and trains requiring different access methods.

Additionally, varying security requirements pose challenges, such as the risk of theft with bikes. To address these challenges, enabling a card or mobile device to unlock all services may be more practical. However, it is important to consider the risk of excluding users without smartphones, ensuring accessibility for all.

Single Invoice - A single invoice is necessary to convey the perception of integration between modes and reduce transaction fees for operators during micro-transactions. However, achieving a single invoice becomes more complex if users need to use different payment methods for different modes in their trip. The feasibility of a single invoice depends on the extent of unified payment methods available.

In conclusion, all three types of integration are essential for creating a seamless user experience in MaaS. The results build on the categorisation of integration features by Kamargianni et al. (2016b) where the qualitative insights highlight the benefits and challenges associated with each type of integration. Additionally, ticketing and payment integrations are necessary to enable subscriptions to MaaS platforms. However, implementing these integrations poses challenges, particularly due to the diverse liabilities and security requirements of different modes of transportation. Striking a balance between convenience, security, and inclusivity is crucial to ensure the successful implementation of these integration types.

4.3.5 Booking Features

Quantitatively, a neutral stance was the most common response among participants, with 52% equally supporting both types of booking systems. This was followed by 45% supporting on-demand bookings and 3% supporting scheduling in advance.

The majority of participants believe that MaaS should offer both on-demand and scheduled booking options, recognizing that each type of booking is more suitable in different scenarios. On-demand bookings are particularly beneficial for ad-hoc trips, rural regions where regular commuting is less common, and trips predominantly composed of on-demand modes. Scheduled bookings, on the other hand, provide advantages for regular commutes and fixed-schedule modes of transport.

Scheduling rides in advance brings several benefits to MaaS. It facilitates intermodality by guaranteeing service availability, which is especially important for integrating operators relying on legacy technology. Additionally, advanced scheduling proves valuable for trips such as hospital appointments and paratransit, where timely and reliable transportation is

essential. Furthermore, it allows for discounted rates on long-distance trips, even though they may represent a smaller proportion of overall MaaS trips. While both on-demand and scheduled booking features are important,
A fully on-demand MaaS platform that ensures immediate availability of rides upon booking requires a higher degree of interoperability and system integration. To achieve this, it is crucial to address the challenges associated with interoperability, enabling seamless integration among different service providers and systems.

In conclusion, participants widely support the inclusion of both on-demand and scheduled booking options in MaaS. The ability to cater to diverse user needs and different trip scenarios is key. However, the realization of a fully on-demand platform necessitates increased interoperability and system integration. By addressing these challenges, MaaS can offer a comprehensive and flexible booking experience for its users.

4.3.6 Geographical Coverage

Quantitatively, participants' preferences for geographical coverage varied. The highest vote, at approximately 34%, was for national coverage, followed by 30% supporting city-wide/state-wide coverage, 22% favoring continental coverage, and 15% supporting intercontinental coverage.

It is important to consider the influence of regional differences on participants' perspectives. For example, in European countries, it may be realistic to discuss cross-border travel and aim for continental coverage due to proximity and existing transportation networks. However, in larger countries like the USA, achieving even national coverage presents significant challenges due to the vast territory and diverse range of networks and services.

Transportation is fundamentally a local problem, and addressing it requires tailored local solutions. Each city has its own integration challenges and expanding a MaaS operator's services to a new city entail understanding and resolving the specific transportation issues faced by that city. This highlights the importance of developing city focused MaaS solutions that cater to local contexts.

While focusing on city solutions, it is essential to avoid replicating the existing silos of individual operators as isolated city silos. The objective of MaaS is to remove barriers between operators, and expanding the scope from operator silos to city silos should be approached with caution. Interoperability and connectivity between cities should be prioritized to ensure a seamless MaaS experience for users.

Balancing the localized nature of transportation challenges, it is crucial to capture the value of car ownership and provide users with a sense of freedom that matches the nationwide reach often associated with owning a car. While city-focused solutions address local needs, it is equally important to enable MaaS solutions that seamlessly connect transportation options within and beyond a city's boundaries.

In conclusion, the optimal approach to MaaS lies in developing city-focused solutions that address local transportation challenges while maintaining interoperability across cities, countries, and even continents. Tailored solutions should be built to resolve city-specific issues, ensuring that MaaS systems remain connected and comprehensive. By striking this balance, MaaS can deliver a seamless and integrated transportation experience for users on various geographical scales.

4.3.7 User Priorities

Understanding user priorities is crucial for developing a successful MaaS system. The quantitative results indicate an approximately equal split between three key priorities: 37% of participants consider personalized routing as most important for users, followed by 32% emphasizing data privacy and security, and 31% prioritizing pricing and packages.

Data privacy and security are significant concerns, both legally and morally. However, it is important to acknowledge that the average user may not prioritize data privacy, often due to limited awareness or reading terms and conditions. Nevertheless, robust data privacy measures are essential to safeguard user information and maintain trust in MaaS platforms.

User priorities in MaaS are also influenced by cultural and country-specific factors. Different cultures may place varying emphasis on pricing, efficiency, convenience, privacy and security. Recognizing and accommodating these variations is key to providing diverse offerings that resonate with different user segments.

To cater to varying user priorities, it is necessary to foster an open ecosystem where multiple MaaS platforms can coexist. This approach allows for the presentation of different offers that appeal to different sets of users. Embracing diversity within the user base is crucial to meeting the unique needs and preferences of each individual.

While user priorities may differ, integrating personalized routing, data privacy and security, and fair pricing models is essential for a comprehensive MaaS solution. Striving for a balance between user-centric features, robust data privacy measures, and fair pricing ensures a holistic and user-friendly experience.

In conclusion, understanding and addressing user priorities are pivotal in developing a successful MaaS system. By embracing an open ecosystem, considering cultural variations, and integrating key priorities, MaaS can provide a user-centered experience that respects data privacy and meets the diverse preferences of its users.

4.3.8 Payment Model

Understanding the payment models in MaaS is crucial for developing an effective and sustainable system. Quantitatively, the results indicate a split between the Pay-as-you-Go model (41% support), a neutral stance (34%), and subscriptions and bundles (24%).

Subscriptions and bundles hold significant potential in achieving the desired "as-a-Service" model in MaaS. By providing passengers access to a range of transport services as part of their subscription tier, subscriptions can drive new travel behaviors and reduce reliance on car ownership. This approach aligns with sustainability goals and promotes the use of public transport.

However, the current market presents challenges for implementing subscriptions. Offering a subscription price that is cheaper than users' existing monthly expenses is difficult for MaaS providers. Moreover, bundling e-hailing rides and micromobility modes to make subscriptions attractive raises concerns about encouraging the use of unsustainable modes and potentially driving unnecessary travel and higher carbon emissions. Incorporating shared mobility in subscriptions is particularly challenging due to the highly variable demand for these services.

It is essential to customize the payment model based on the transportation dynamics of the specific location where MaaS services are deployed. While subscriptions that include a season pass and allow users to bundle add-ons may be viable and attractive in public transport-first countries, they may not provide a competitive advantage in car-first countries where car commuting is often cheaper.

Looking ahead, the payment model in MaaS should be continuously evaluated and adapted to align with evolving user preferences, market dynamics, and sustainability goals. Striking a balance between cost-effectiveness, user convenience, and environmental considerations will be crucial in designing payment models that drive the adoption of MaaS while addressing local challenges.

In conclusion, the payment model in MaaS is a multifaceted issue that requires careful consideration. While subscriptions hold promise for achieving the "as-a-Service" model, challenges related to pricing, mode bundling, and market dynamics need to be addressed. Customization based on local dynamics and ongoing evaluation of payment models will be vital for creating a competitive and sustainable MaaS ecosystem.

4.3.9 Auxiliary Services

The inclusion of auxiliary services in the same MaaS platform is a topic that garners differing opinions. The results show that 54% of participants believe that these services should be combined, while 40% advocate for their separate systems. A small portion (5%) remains neutral on the matter.

The decision of whether to integrate or separate auxiliary services within the MaaS platform depends heavily on the nature and benefits of these services. For instance, linking journeys to activities like booking movie tickets or meeting rooms can enhance the overall value proposition. However, integrating food deliveries may introduce complexities due to the specific considerations associated with handling and delivering food.

While auxiliary services can serve as incentives to encourage passengers to choose MaaS, it is essential to strike a balance to ensure a user-friendly experience. Including too many features within a single application may pose challenges in terms of usability and complexity, potentially compromising the overall satisfaction of users.

Integrating auxiliary services into the passenger transport application can bring synergies and contribute to the profitability of MaaS providers. Offering incentives or discounts, such as allowing passengers to pick up packages for their neighbors, can promote usage and enhance the overall value for users.

However, it is crucial to approach the integration with caution and prioritize the user experience. Careful planning and consideration are necessary to ensure that the addition of auxiliary services does not compromise the simplicity and convenience that users expect from the MaaS platform.

In conclusion, the decision to combine or separate auxiliary services in MaaS requires careful evaluation of each service's compatibility with the passenger transport application. While there are potential synergies and profitability benefits, maintaining a user-friendly experience and avoiding unnecessary complexity should be prioritized throughout the integration process.

4.4 MaaS Interoperability: Results

4.4.1 Business Models

Investigating the conceptual maturity of MaaS, the question to the interviewees explored the maturity of the MaaS business model. The lowest level represented no business model has been established yet whereas the highest level represented an adaptive business model capable of accommodating a variety in supply chain and adapting to changes in the industry.

The interviewees were asked to describe the current state of the industry and contrast that with the desired state. The following figures show quantitatively the average levels of where the MaaS business model is at versus where it is required to be.

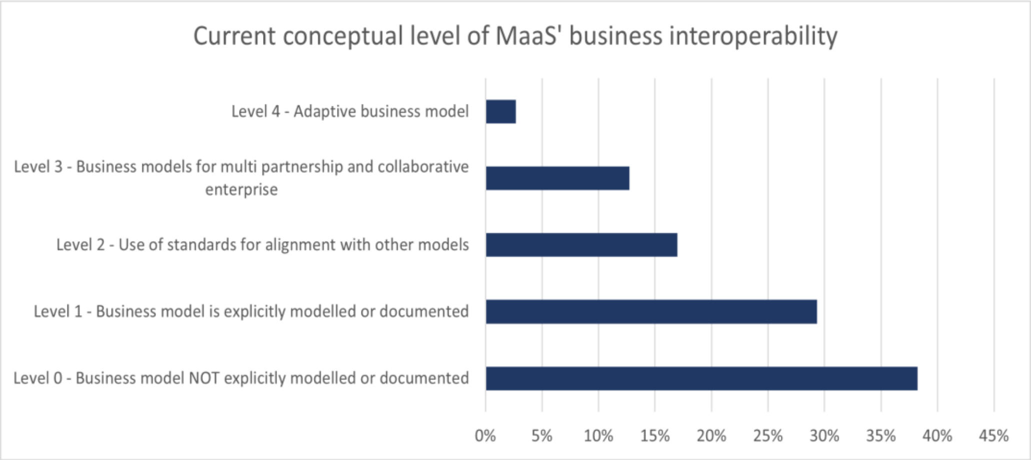

Figure 4.9 Percentage of participants against their perceived current level of business model maturity

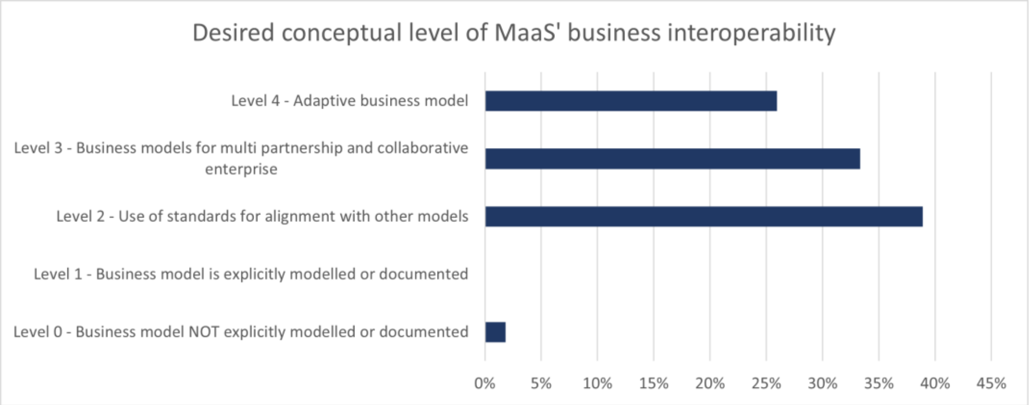

Figure 4.10 Percentage of participants against their desired level of business model maturity

From the interviewees, the participants explained the rationale behind their choices and provided insights which were categorized into three themes as follows:

Maturity of the Business Model:

- The MaaS business model in Scotland is still undefined, with ongoing trials utilizing different business models.
- Switzerland has achieved a level of maturity in public transport integration, but integration with private mobility is less developed.
- The UK has fragmented approaches to developing a viable MaaS business model.
- The Netherlands has a well-developed concept of MaaS with a common understanding of the business model.
- Maturity levels of MaaS vary in Australia, with the Sydney trial being the most mature, while other regions are at a lower level.
- The USA lags behind Europe in terms of MaaS business model maturity, although certain states are advancing, such as Washington D.C.
- Insufficient representation and interest from transport operators hinder the maturity of MaaS models.
- Finland demonstrates a high level of understanding and maturity in the business model, but commercial success has not been achieved due to different stakeholder expectations.
- Public transport-focused models are perceived as more mature.
- Japan has implemented an intelligent model commercially with a Champion Rail Pass for seamless travel.

Standardisation of the Business Model:

- Efforts are focused on standardizing business rules and representing partnerships rather than standardizing the entire business model.
- The need for standard contracts for partnerships between transport operators and MaaS providers is recognized.
- Formalization of the business model is ongoing, but competition often keeps it as a trade secret.
- Non-discriminatory policies and third-party ticket sales need to be

established.

- The Netherlands aims to standardize relationships between parties through organizations like KMV.
- Finland is yet to standardize and set legislation for MaaS business models.

Development of the Business Model:

- Making MaaS profitable is challenging, and subsidies may be necessary.
- Conglomerates can potentially generate profit by integrating MaaS with other services.
- Digitalizing infrastructures while keeping operational costs low is a challenge for profitability.
- The sustainability of B2B models and generating revenue from integration needs further exploration.
- No sustainable MaaS business models have been established yet. Public-private partnerships are seen as an optimal model for building core services.
- Low transaction volume and service costs pose challenges for self-sustainability.
- MaaS operators continuously seek strategic partnerships and buyouts to find an optimal business model.
- Public transport relies on government subsidies, while private transport depends on venture capital.
- Authorities and legislation strongly influence MaaS business model development.
- In the UK, local authorities organizing MaaS through data integration and centralized payments is seen as a favorable model.
- Similar to the Uber model, MaaS is not currently generating profit.
- The public sector’s role in governing the MaaS business model and contracts is becoming clearer in Finland.

4.4.2 IT Infrastructure

Having the necessary IT Infrastructure to enable MaaS was the second aspect of business interoperability that was investigated. Similarly, the interviewees rated the current state of the infrastructure and the desired state where the following figures show an average of their responses.

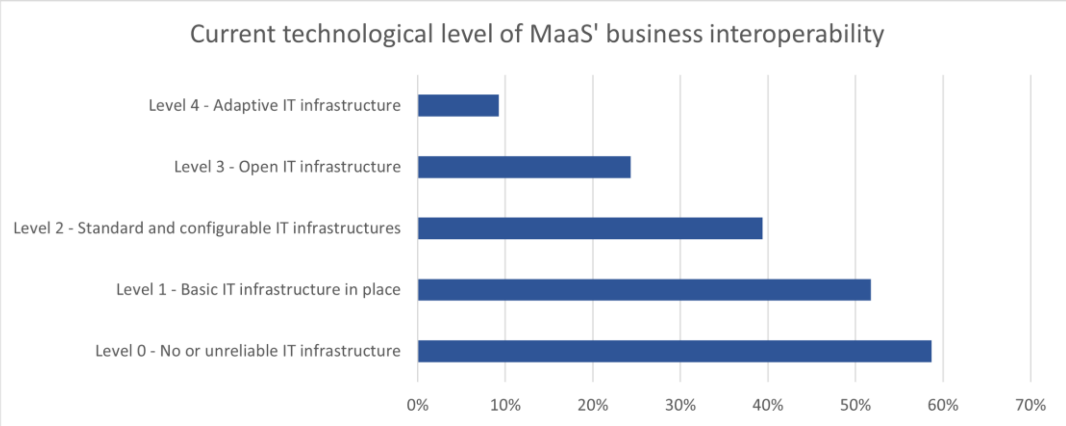

Figure 4.11 Percentage of participants against their perceived current level of IT infrastructure maturity

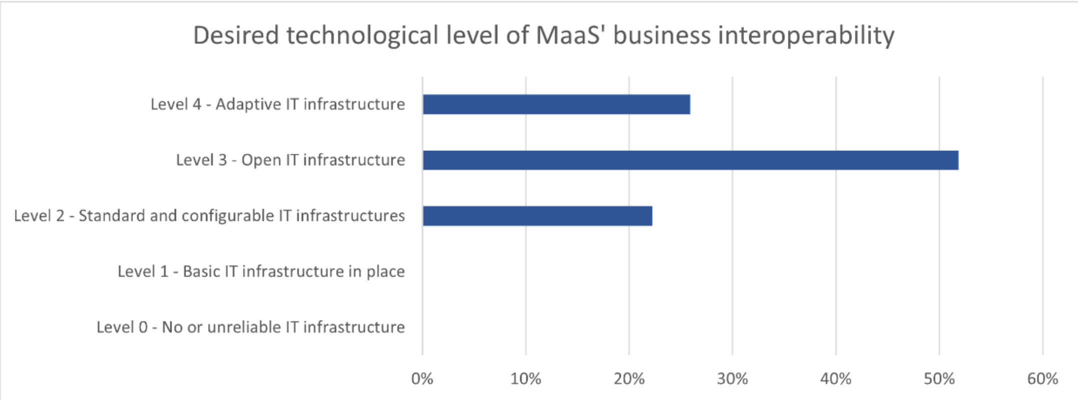

Figure 4.12 Percentage of participants against their desired level of IT Infrastructure maturity

The qualitative insights derived were as follows:

Maturity of the IT Infrastructure:

- IT infrastructure maturity varies among stakeholders, with some applications having integrations but individual operators lacking maturity.
- Scotland has a mix of advanced IT systems in large operators and pen-and-paper systems in small operators.
- Standards like ITxPT and MDS exist, but more work is needed for overall interoperability.
- In the USA, legacy technology and challenges in government procurement hinder IT infrastructure maturity.
- The Netherlands has advanced IT infrastructure, but standardization for ticketing and payment is lacking.

- Switzerland faces complexities in standardizing legalization for deep integration between private and public services.
- Reluctance from stakeholders and lack of appeal pose challenges in achieving open infrastructure.
- Finland has high interoperability maturity due to legal requirements for opening systems and APIs.
- The UK offers debit card usage and CityMapper for planning trips but has room for improvement.
- Interfaces between operators are developed in Finland, but ticketing hardware can be improved.
- The Netherlands uses NFC for payments in public transport but faces challenges in other modes.
- Different IT infrastructure types in the Netherlands are not interoperable.
- Upgrading validation systems is required when migrating to phone and application-based access in Belgium and other countries.
- Network speed and fiber network upgrades are needed for seamless integration, particularly in rural areas.

Standardisation of the IT Infrastructure:

- Open infrastructure may not be necessary if implemented through a broker model.
- Focus should be on standardizing interfaces rather than the infrastructure itself.
- Standardization is more important than flexibility in technology implementation.

4.4.3 Common Goal

To investigate the business organisational interoperability, the question focused on addressing the maturity of a common goal between stakeholders. The following figures show an average of the responses of the current state and the desired state of the common goal for MaaS stakeholders.

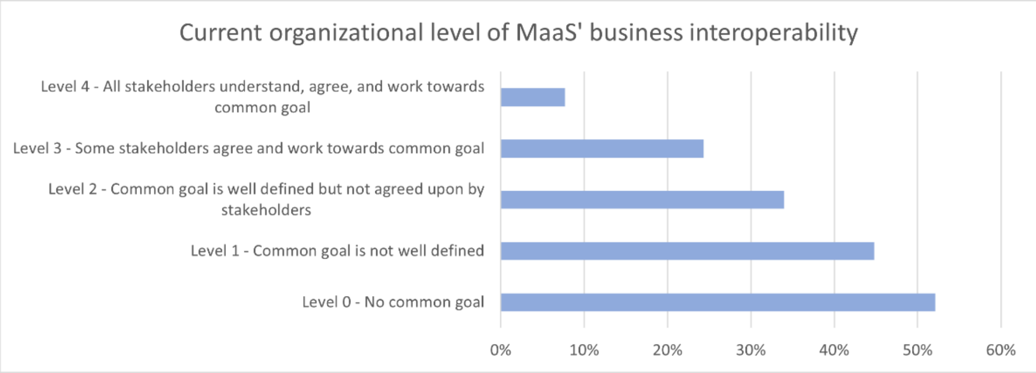

Figure 4.13 Percentage of participants against their perceived current level of common goal maturity

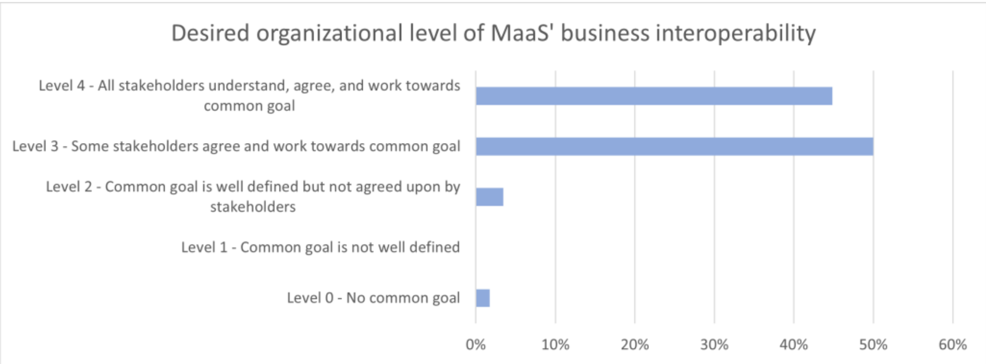

Figure 4.14 Percentage of participants against their desired level of common goal maturity

The qualitative insights derived were as follows:

Barriers to Agreement over a Common Goal:

- Stakeholder management is one of the significant challenges in implementing MaaS, particularly in Scotland where the transport network is primarily delivered by private organizations. The involvement of both public and private sectors brings about complexities in defining roles and responsibilities within the MaaS ecosystem.
- Some stakeholders, including operators and local authorities, lack a clear understanding of MaaS and its implications. There is a need to educate stakeholders about the integrated transport concept and the potential impact on usage and passenger rates. Policy changes may be necessary to facilitate the implementation of MaaS, and governance questions arise regarding who should have control and influence over MaaS regulations and standards.
- The absence of a unified approach to MaaS and a clear shared vision is

acknowledged. Various stakeholders have different perspectives and goals due to their own business models, which sometimes conflict with each other. Achieving complete agreement on a shared vision is challenging and unlikely, as different stakeholders prioritize different modes of transport or have divergent interests.

- Public organizations involved in MaaS tend to have more aligned goals due to their societal objectives. However, alignment may be less pronounced among private MaaS providers and shared micro-mobility service providers, as their primary focus is often on profitability. There is a need to align the public and private perspectives of MaaS for higher levels of integration and efficiency.
- There is a concern about app developers running the agenda and potentially dominating the MaaS ecosystem. These developers often overlook the behavioral aspects, regulatory frameworks, and business models necessary to achieve societal goals. It would be important in that case to introduce subscription plans and bundles to align with larger objectives.
- While public authorities may prioritize reducing stress on transportation networks, MaaS providers and transport operators may have different objectives. Reaching a collective agreement on the same goal may not be realistic.
- Financial targets and concerns about market viability often hinder the establishment of a common goal.
- In Finland, there have been challenges in regulating MaaS due to opposition from certain stakeholders, such as taxi operators. Public transport authorities are also concerned about losing customers and budgetary constraints. The discussion sometimes involves misunderstandings about the concept of interoperability and the benefits it brings to all stakeholders.
- Some countries, like Finland, have implemented national legislation to enforce the opening of electronic interfaces and allow the reselling of services. However, not all stakeholders may fully understand or agree with the legislation, as some may perceive MaaS as a potential threat to their business rather than a new sales channel.
- In some regions, reducing the carbon footprint and achieving a neutral carbon economy are identified as common goals for MaaS. However, translating these broader goals into specific actions and strategies for

mobility remains a challenge.

Development of a Common Goal:

- It is important to consider who is involved in MaaS discussions. Stakeholders can vary from operators and authorities to MaaS and payment providers, third-party providers, mobility providers, and end-users. The engagement of different stakeholders can impact the alignment of goals and the overall success of MaaS implementation.
- Legislation might be necessary to compel transport providers to embrace MaaS. Regulatory measures are required to enable open data sharing and ensure that the best possible outcomes are delivered to users. However, governments are often reluctant to take on regulatory functions in the industry, relying more on private enterprise.
- While the private sector possesses technological expertise and is likely to build the MaaS platform, the public sector should set the rules and steer MaaS toward societal goals such as inclusive access, public health, and environmental sustainability.
- Laws and directives at the national and EU levels exist to provide clarity and define goals for MaaS. While most stakeholders agree on the need for openness, there may be varying levels of adherence and alignment to these goals.
- Not everyone needs to have the same understanding or perspective on MaaS. Different individuals and user segments may have their own preferences and requirements, such as desiring a premium experience or favoring specific mobility service providers.
- It is important to establish arrangements or compromises that work for all stakeholders involved in MaaS. Balancing business models, societal goals, and profitability is a key aspect of achieving collaboration and progress in the MaaS ecosystem.
- Private operators who refuse to cooperate should be shut down to maintain collaboration and progress.
- The short-term goal is focused on making MaaS commercially viable, but in the long-term, a common goal is desired.
- There are ongoing discussions, hackathons, and meetings to define what MaaS should entail and what stakeholders prefer.
- Collaborative regional programs and projects can foster shared goals among stakeholders. These initiatives aim to ensure that any mobility

app or platform offers comprehensive options, including accessible transportation, throughout a specific region. However, challenges can arise when not all stakeholders see the value or have the necessary funding to participate.

Definition of the Common Goal:

- The goals of MaaS may vary depending on the specific city and its needs. The reduction of dependency on privately owned cars and the improvement of livability in cities are common objectives. Each country or region has its own unique context and level of understanding regarding MaaS, with some still exploring its meaning and implications within their transportation networks.
- The common goal shared by many stakeholders is to promote sustainable transport options and reduce reliance on cars, particularly in the UK, where there is a prevailing preference for private car travel.
- There may be multiple goals that require an agreement, however, a common goal that focuses on reducing negative externalities like emissions and car use is essential. Most people involved in MaaS would agree on the need to achieve these societal goals, but there is a disconnect between this common goal and the actions taken by stakeholders.
- Interoperability and standardization should be one of the main goals in MaaS. All modes of transportation need to be integrated under one umbrella, and standards like TOMP (Transport Operator Mobility-as-a-service Provider) need to accommodate different business models while enabling cooperation.
- The common goal should involve providing an easy and accessible way for people to organize and pay for their travel, with a focus on reducing private car usage and promoting sustainable transport modes.
- The common goal in MaaS is to provide access for individuals and consumers to acquire services all in one place, creating a seamless and integrated mobility experience. The goal is to enable users to have a wide range of transportation options available through a single platform or application.
- It is important to set measurable goals. While improving ridership is a measurable goal, achieving it requires addressing multiple factors beyond MaaS alone. There are various considerations, such as

environmental responsibility, financial viability for stakeholders, and the overall attractiveness of MaaS services for users.

– MaaS involves numerous actors, including public and private transport operators, MaaS operators, cities, and users. While there might not be one single goal, a set of common goals covering aspects like profitability, sustainability, and accessibility can provide a framework agreed upon by all stakeholders.

4.4.4 Data Models

The conceptual maturity of the data in MaaS considered the development of a data model. The question discussed the maturity level of data models for different types of operators and the suitability of a central business model. The following figures show the average maturity level of where the data models within the MaaS ecosystem is at and the desired level to achieve.

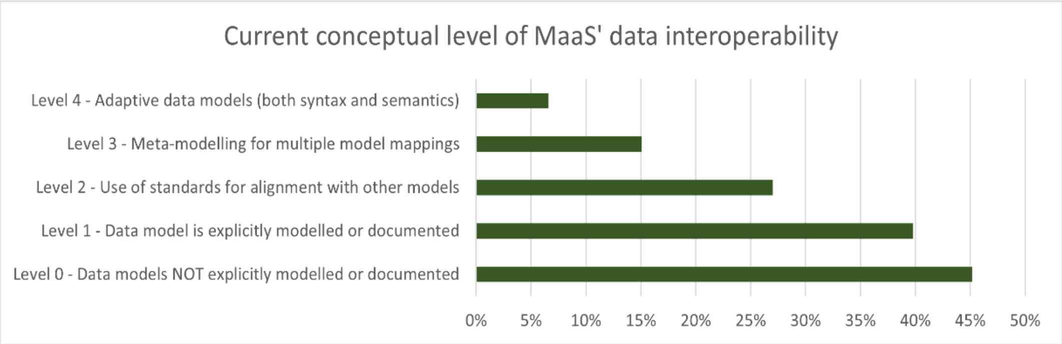

Figure 4.15 Percentage of participants against their perceived current level of data model maturity

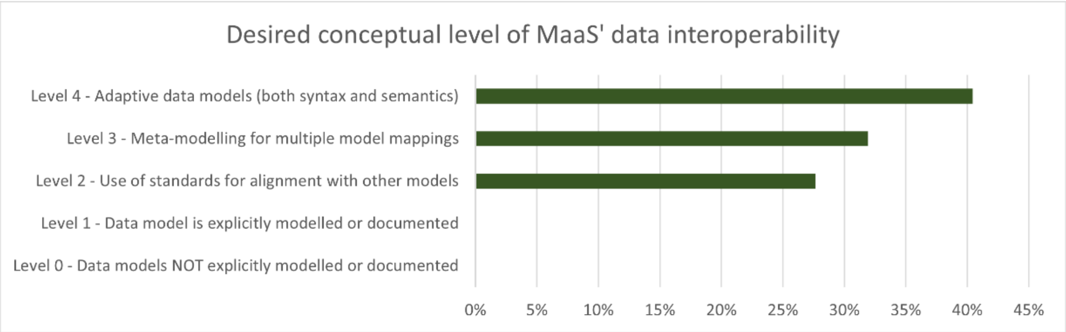

Figure 4.16 Percentage of participants against their desired level of data model maturity

The qualitative insights derived were as follows:

Maturity of the Data Model:

- The maturity of the data model varies for different modes of transport.
- The desired level of data model maturity for MaaS interoperability is expressed as level 4, which corresponds to adaptive data models. Reaching level 4 may take time and effort but its an important direction for the future.
- MaaS encompasses multiple components, such as scheduling and planning, which require various levels of data modeling. Levels three and four are not feasible for widespread adoption due to the complexity of the domain, but level two (use of standards for alignment with other models) is a good starting point.

Development of the Data Model:

- NeTEx, SIRI, GTFS, Mobility Data Specification (MDS), TOMP API, and GBFS are mentioned as data standards and models used in various regions.
- The use of different data models specific to each domain compared to a core MaaS data model is considered more realistic.
- The establishment of ontologies is a step towards achieving higher levels of interoperability. This encompasses meta-modeling and multiple model mappings.
- Efforts are being made to collaborate with different stakeholders, including public transportation and on-demand mobility providers, to establish rules for data consistency. The focus is not only on public transportation but also on integrating on-demand mobility services into the MaaS ecosystem.
- There are some mappings between TOMP and GBFS or GBFS is used in TOMP in some ways. But they are not interoperable together.
- It is crucial to agree on a common set of definitions and standards to achieve interoperability.
- There is progress in certain areas, particularly in service discovery and trip planning. However, there is a need for better support for real-time information, booking, and payment aspects of MaaS services.
- Translations and mappings between different data models is very important. This would facilitate seamless integration between MaaS operators and different transportation systems, eliminating the need for costly and manual adaptations.

Challenges/Barriers:

- There is a concern about the existence of multiple data standards and the challenges they pose for cross-standard interoperability.
- There are mixed opinions about the usefulness and practicality of meta-model mappings and automatic translations between standards. These may not guarantee successful communication between different standards. For example, automatic translations between standards using the OSLO model is not working. In addition, embedding a translator in the data querying process may not be practical when data is required in real-time.
- Google tried to establish the GTFS Standard but not many public transport operators adopted it. You must then integrate various transit feeds to make a route planner and a ticketing format.
- Ideally if you have a standard then there should be no need for mappings, but we would always have a cross-border issue because not everyone is going to adhere to the European standard.
- There is a lack of a single standard for data models in the transportation sector. Different enterprises and organizations have their own standards, leading to the need for adaptation and connection between interfaces when working together.
- In Belgium, while open data is available, the process of integrating it often requires manual migration and lacks a unified approach.
- We need more standards, we are missing some use cases, but thats going to be an everlasting issue, because there is always going to be a new mode or a new service which will require a new model.
- Legislation that requires operators to open up their data does not specify how the operators should do that and what format they should follow.
- While meta-modelling and Linked Data will aid in achieving the best levels of interoperability, technology providers are more interested in the fastest solutions that provide them with pareto-optimal results.
- Requiring operators to express their data in a specific model may not be practical as the standard or model does not fit their business requirements. For example, a standard can require an operator to provide the exact times the vehicles will be at the stations or use a frequency-based schedule instead. Depending on the operators

internal business and operational requirements, one model will always be preferred over the other. In that case, establishing a semantic alignment between the two models that allows you to use them together with no loss of information would be very beneficial.

- There is a limited involvement of taxi companies, Uber, and Lyft in adopting data standards, and standards for on-demand transport is yet to be established.
- The struggles faced by smaller and rural agencies due to financial constraints results in insufficient resources, low wages, high attrition, and a lack of focus on data-related activities.

4.4.5 Data Storage and Access

At the technological layer of data interoperability, the current methods of data storage and how accessible these are were explored. The following figures show an average level of maturity for data storage and access as well as the desired level for a viable MaaS ecosystem.

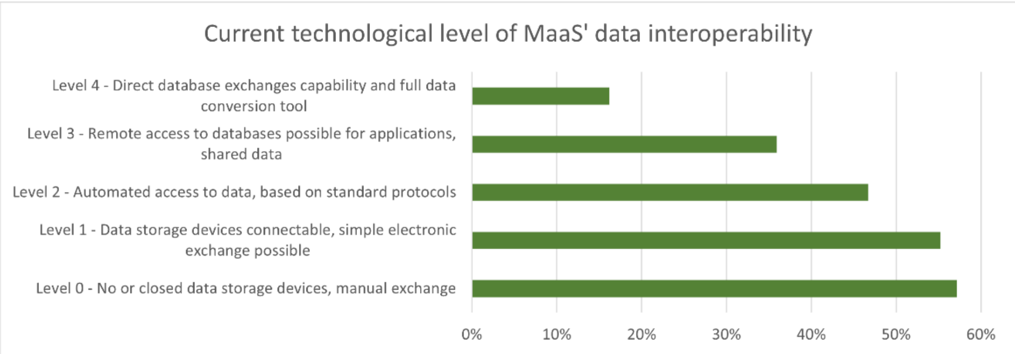

Figure 4.17 Percentage of participants against their perceived current level of data storage and access maturity

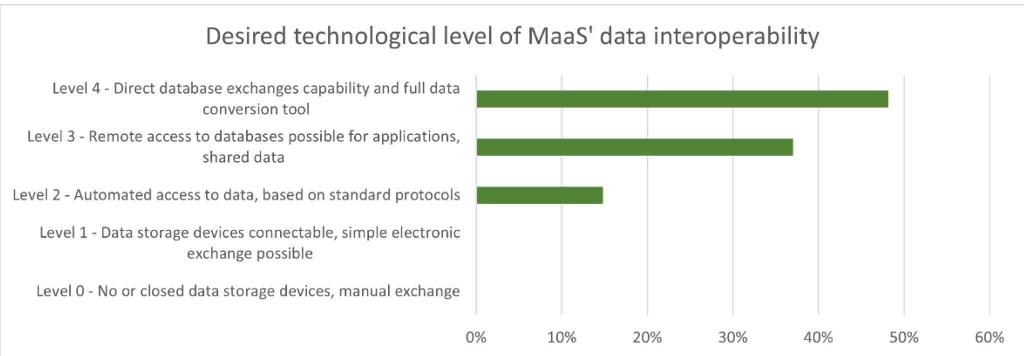

Figure 4.18 Percentage of participants against their desired level of data storage and access maturity

The qualitative insights derived were as follows:

Maturity of the Data Storage and Access:

- In Switzerland, public transportation has one central database, allowing for exchange and access. However, other types of mobility services have a lower level of interoperability. Public transport is considered the major player in terms of data accessibility and sharing.
- There are large transportation operators/cities with advanced data analytics systems and APIs, while some agencies still store data in Excel or similar formats.
- There is a degree of sharing of APIs on basic things like schedules and fares.
- Some operators still use paper-based systems.
- APIs are widely used for various purposes, and everyone is using them for one reason or another.
- Conversion tools are being worked on to facilitate data exchange, especially if the same standard is used.
- The data largely exists in the UK, but some small bus operators still rely on paper-based systems, which is illegal.
- The extent of achievement in levels 2 and 3 varies across different mobility services and countries.
- Technologically, the necessary capabilities exist, but policy enforcement and implementation vary.
- Legal obligations in the European context require relevant data sharing, particularly for public transport information. Ticketing and pricing data sharing is not as common but is expected to increase over time due to regulatory influence.

Development of the Data Storage and Access:

- There may need to be a regulatory push or change to enable data accessibility.
- APIs are appreciated if they are standardized and make life easier.
- Remote access to data is important, especially for IT-focused applications, where expertise is sourced from the cloud.

- Standardization, regulatory changes, and simplification of data translation processes are identified as potential areas for improvement.
- Some stakeholders prefer controlled data access and retain some level of control. Not everyone wants completely open standards; transport operators value control over data.
- Sharing data is considered a political decision, indicating that data sharing is subject to various factors.
- There is a preference for API access to internal databases rather than opening databases to the public.
- Level 4 is seen as too open and not desired even for public data. Controlled Data Access is more the goal which sets the target at level 3.

Barriers / Challenges:

- Most operators have proprietary data APIs.
- Levels 3 and 4 may not be feasible due to data privacy laws.
- Storing personal data is challenging, and it's ideal not to share personal information unnecessarily. It needs to be abstracted and only processed through unique identifiers and following strict contracts.
- Even if the data is open or accessible, there is still a struggle to convert between different types / formats of data. Converting data can be a complex process, requiring multiple steps and manual work. Therefore, it is essential to simplify the process of data translation between different formats.
- Data ownership and control of data is hindering the move towards a higher interoperability level for storage and access.
- Language is not considered a barrier to data accessibility and interoperability.
- In the UK, rail services, run by private companies, possess the data but are not efficient at sharing it, posing a barrier to MaaS.
- Policy-level considerations impact the implementation and enforcement of interoperability standards.

4.4.6 Data Management

For the organisational interoperability of MaaS Data, the way the data is managed was explored and whether there are existing rules for data sharing, access, quality, and maintenance. The following figures highlight the average level of maturity for current data management and the desired level for a sustainable MaaS ecosystem.

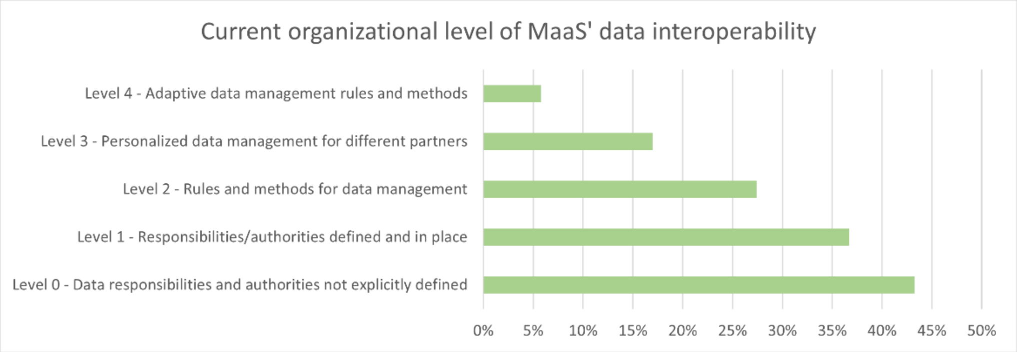

Figure 4.19 Percentage of participants against their perceived current level of data management maturity

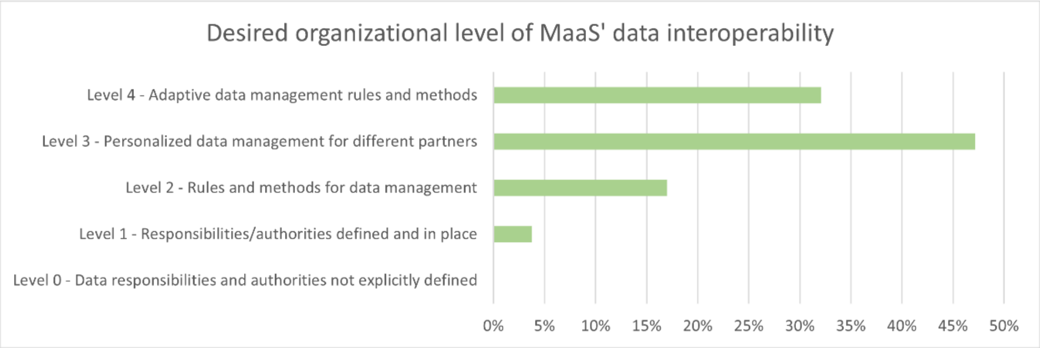

Figure 4.20 Percentage of participants against their desired level of data management maturity

The qualitative results derived were as follows:

Maturity of the Data Management:

- Bus Open Data in the UK is improving how data is shared by establishing the suitable regulations for it.
- The presence of GDPR rules in Europe governs data protection.
- Organizations in the UK are responsible for managing their own data and must comply with GDPR rules.
- In the USA, cities and states are beginning to recognize the importance of data governance. Specific protocols for data management are being

implemented for certain applications, but a comprehensive governance framework is still lacking in the US.

- There is a higher level of maturity when managing vehicle data in comparison to user data.
- The public transport sector is more advanced in terms of data management, while private mobility lacks compliance with data requirements.
- MobilityData is playing a role in adaptive data management and establishing best practices.
- Due to GDPR and related legislation, the mobility sector is highly regulated.
- Medium to large mobility companies follow ISO standards, indicating a high level of maturity in data management.
- In Finland, legislation is already in place, but practical implementation and data sharing by transport companies are ongoing processes.
- Public transport authorities and operators acknowledge their responsibility but highlight challenges in implementation, particularly for smaller operators.
- Road operators are seen as more advanced in terms of data management compared to public transport operators.

Development of Data Management Rules:

- There is a need for an independent governance entity, similar to open banking, to establish rules for privacy, standardization, and interoperability.
- It would be best if the government would act as the trusted broker to instill trust, control data access, and enforce specific security standards.
- Each organization's level of awareness and compliance with data management depends on their specific circumstances.
- It is very important to respect privacy and ensure data benefits everyone, not just those with financial means.
- It is crucial for data to be standardized, accurate, and regularly updated for effective management.
- Achieving Level 3 data management partially depends on the entry

point into the ecosystem and reliance on specific data sources.

- Data management rules will vary based on the adopted business model.
- The data management responsibility should be defined in contracts, emphasizing privacy policies and data handling.
- Policy and legislation set the foundation, but their interpretation and implementation are negotiated through contracts between parties. Agreement on data management rules and methods is crucial for successful partnerships.
- Different operating methods and regulations make it necessary to consider regional contexts when determining data management components.
- The "myData" approach emphasizes user control over their data. This should be implemented as it encourages data sharing while maintaining privacy which is seen as a positive step.

Barriers / Challenges:

- Data sharing beyond what is necessary is seen as potentially impacting data quality and incentivizing lower quality data. Mobility partners often desire extensive data, although it may not be necessary for their operations.
- Privacy laws provide clear guidelines but lack adaptability.
- Privacy legal issues pose a significant challenge in implementing data management.
- Compatibility of formats, data standards, and other technical considerations need to be addressed.
- There is a lack of agreement on data sharing between data owners and users in the mobility context.
- This topic is concerning because data is a valuable asset that could be sold to competitors, leading to the question of who should own and store the data.
- It is difficult to define data management rules and raise its interoperability when the data needed within the MaaS ecosystem is not fully defined yet in order to define the sharing rules to accompany it.
- While GDPR provides a framework, its implementation and

interpretation vary, leading to uncertainties and challenges. Compliance with GDPR is seen as largely achieved, but there are concerns about the practical application and understanding of GDPR rules.

4.5 MaaS Interoperability: Discussion

4.5.1 Business Models

The results regarding the maturity of the MaaS business model provide valuable insights into the current state of the industry and the desired state as perceived by the interviewees. The analysis of these results revealed several key interpretations and arguments:

Regional Variation in Maturity: The responses indicate that different regions exhibit varying levels of maturity in their MaaS business models. Scotland is still in the early stages, with ongoing trials utilizing different business models. Switzerland has achieved a level of maturity in integrating public transport, but the integration with private mobility is less developed. The UK demonstrates fragmented approaches to developing a viable MaaS business model. In contrast, the Netherlands is recognized as having a well-developed concept of MaaS, with a common understanding of the business model. Australia shows variations in maturity levels, with the Sydney trial being the most mature, while other regions lag behind. The USA lags behind Europe in terms of MaaS business model maturity, although certain states like Washington D.C. are making advancements. These regional differences suggest that the level of maturity in the MaaS business model is influenced by local contexts, regulatory frameworks, and stakeholder engagement.

Role of Transport Operators: Insufficient representation and interest from transport operators emerge as a hindrance to the maturity of MaaS models. The involvement and active participation of transport operators are crucial for the development and success of the MaaS business model. Collaborative efforts and partnerships between transport operators and MaaS providers are necessary to establish a mature and integrated system.

Standardization Efforts: The findings indicate ongoing efforts to standardize certain aspects of the MaaS business model. However, the focus is primarily on standardizing business rules and representing partnerships rather than standardizing the entire business model. There is recognition of the need for standard contracts between transport operators and MaaS providers.

Additionally, non-discriminatory policies and the establishment of third-party ticket sales are identified as important areas for standardization. Countries like the Netherlands aim to standardize relationships between parties through organizations like KMV. On the other hand, Finland is still in the process of standardizing and setting legislation for MaaS business models. These findings suggest that while progress is being made, there is still work to be done to achieve comprehensive standardization. It is important to note that the standardization efforts described may vary in their scope and effectiveness across different regions and jurisdictions.

Profitability and Revenue Generation: The development of sustainable and profitable business models for MaaS remains a challenge. The interviews reveal that making MaaS profitable is difficult, and subsidies may be necessary in the initial stages. Conglomerates integrating MaaS with other services have the potential to generate profit. However, digitalizing infrastructures while keeping operational costs low poses a challenge. The sustainability of business-to-business (B2B) models and revenue generation through integration require further exploration. The low transaction volume and service costs present obstacles to achieving self-sustainability. MaaS operators actively seek strategic partnerships and buyouts to find an optimal business model. Public transport often relies on government subsidies, while private transport depends on venture capital. These findings emphasize the importance of innovative revenue models and sustainable financial strategies for the long-term viability of the MaaS business model.

Influence of Authorities and Legislation: The role of authorities and legislation is highlighted as a significant factor in the development of the MaaS business model. The findings suggest that authorities and legislation strongly influence the maturity and direction of MaaS business models. For example, in the UK, local authorities organizing MaaS through data integration and centralized payments are considered favorable. The public sector's role in governing the MaaS business model and contracts is becoming clearer in Finland. These findings underscore the need for collaboration between public and private stakeholders and the importance of supportive regulatory frameworks to foster the growth and maturity of the MaaS business model.

In summary, the analysis of the results demonstrates the regional variation in the maturity of the MaaS business model and highlights the challenges and opportunities associated with its development. The findings emphasize the role of transport operators, the need for standardization, the pursuit of profitability, and the influence of authorities and legislation in shaping the future of MaaS.

4.5.2 IT Infrastructure

The results indicate that the maturity of IT infrastructure for enabling MaaS varies significantly among stakeholders and regions. This finding suggests that there are disparities in technological advancement and implementation across different transportation networks. For example, Scotland exhibits a mix of advanced IT systems in large operators and outdated pen-and-paper systems in smaller operators. This variation in maturity levels could pose challenges in achieving seamless integration and interoperability between different transportation services.

The variation in IT infrastructure maturity can be attributed to factors such as differences in available resources, technological investments, and regulatory frameworks. Larger operators with more resources may have been able to invest in advanced IT systems, while smaller operators may face limitations due to budget constraints. Additionally, regulatory support and government initiatives promoting IT infrastructure upgrades may vary across regions, leading to disparities in maturity levels. While regional variation in IT infrastructure maturity is evident, it is important to consider the context and specific challenges faced by each region. It may not be sufficient to solely attribute the differences to resource availability or regulatory support. Factors such as organizational culture, willingness to adopt new technologies, and stakeholder collaboration could also play significant roles.

The findings highlight challenges related to standardization in the IT infrastructure domain. Despite the existence of standards like ITxPT (Information Technology for Public Transport) and MDS (Mobility Data Specification), there is a need for additional work to achieve overall interoperability. The lack of standardization for ticketing and payment systems in the Netherlands and complexities in standardizing legalization for deep integration between private and public services in Switzerland are notable examples.

The challenges in achieving standardization can be attributed to the complex nature of the MaaS ecosystem, which involves multiple stakeholders, technologies, and data formats. Developing comprehensive standards that address all aspects of IT infrastructure and ensure interoperability is a complex task. Additionally, differences in regulatory frameworks and industry practices across regions can also impede standardization efforts.

While standardization challenges are evident, it is important to recognize that achieving complete standardization across all aspects of IT infrastructure may not be the only approach to enabling MaaS interoperability. The focus on standardizing interfaces rather than the infrastructure itself, as suggested by some interviewees, could provide flexibility and accommodate different technological implementations. By establishing consistent communication protocols and data exchange formats, interoperability can be achieved without imposing rigid infrastructure standardization.

4.5.3 Common Goal

Barriers to Agreement over a Common Goal The results highlight several barriers and challenges in achieving agreement over a common goal among MaaS stakeholders. These barriers include stakeholder management complexities, lack of understanding of MaaS implications, conflicting perspectives and goals, concerns about dominance by app developers, and financial targets inhibiting a shared goal.

The challenges identified underscore the diverse nature of stakeholders involved in MaaS implementation and the inherent complexities of aligning their goals. Stakeholder management becomes crucial in addressing conflicting interests and establishing a collective vision. Educating stakeholders about the benefits of MaaS, clarifying roles and responsibilities, and fostering open communication can help overcome these barriers. While challenges in reaching a common goal are evident, it is essential to recognize that having complete agreement among stakeholders may not always be feasible or necessary. MaaS involves a variety of actors with different perspectives, priorities, and business models. Instead of seeking a uniform vision, it may be more practical to identify a set of overarching goals that accommodate diverse stakeholder interests while promoting sustainability, accessibility, and efficiency.

Development of a Common Goal The findings highlight the importance of stakeholder engagement, legislation, and public-private collaboration in developing a common goal for MaaS. The role of the public sector in setting rules aligned with societal goals is emphasized, while private sector expertise in technology implementation is acknowledged.

The engagement of various stakeholders, including operators, authorities, and end-users, is crucial in aligning goals and ensuring the success of MaaS. Legislation can play a pivotal role in compelling transport providers to embrace MaaS principles and enable open data sharing. Balancing the roles of the public and private sectors, with the public sector guiding MaaS toward societal goals and the private sector driving technological advancements, can lead to a more comprehensive and sustainable MaaS ecosystem. However, it is essential to strike a balance between regulatory measures and market-driven innovation. Over-reliance on regulations and government control may stifle entrepreneurial spirit and limit the potential for innovation and creativity in the private sector. Achieving a common goal should involve collaboration and mutual understanding, allowing both sectors to contribute their expertise and perspectives.

Definition of the Common Goal The results suggest that the definition of the common goal in MaaS varies across regions and stakeholders. Reduction of car dependency, promotion of sustainable transport options, integration of transportation modes, and providing a seamless and accessible travel experience are common objectives mentioned.

The variation in the definition of the common goal reflects the diversity of transportation systems, cultural contexts, and societal priorities across regions. Tailoring the common goal to specific cities or regions allows for customization and adaptation to local needs. A focus on reducing negative externalities, improving accessibility, and integrating diverse transportation options under one platform can provide a framework for achieving alignment among stakeholders. While customization and regional adaptation are important, it is crucial to identify a core set of principles and objectives that form the foundation of the common goal. Emphasizing broader goals such as sustainability, inclusivity, and efficiency can provide a unifying vision that transcends regional differences. A balance between customized approaches and overarching principles is necessary to foster collaboration, interoperability, and progress in the MaaS ecosystem.

4.5.4 Data Model

Maturity of Data Models The results indicate that the maturity of data models varies for different modes of transport within the MaaS ecosystem. The desired level of data model maturity is expressed as level 4, which corresponds to adaptive data models. However, reaching level 4 may require significant time and effort. It is acknowledged that MaaS encompasses multiple components that require various levels of data modeling, and while levels three and four may not be feasible for widespread adoption due to the complexity of the domain, level two (use of standards for alignment with other models) is considered a practical starting point.

Recognizing the varying maturity levels of data models is essential for understanding the current state of MaaS interoperability. Striving for higher levels of maturity, such as adaptive data models, can enhance the flexibility and adaptability of the MaaS ecosystem. Building upon existing data standards and aligning different models through interoperability efforts can contribute to the overall progress of data modeling in MaaS.

Development of Data Models The results indicate the use of various data standards and models, such as NeTEx, SIRI, GTFS, Mobility Data Specification (MDS), TOMP API, and GBFS, in different regions. The establishment of ontologies and collaboration with stakeholders are seen as steps toward achieving higher levels of interoperability. Efforts are being made to establish rules for data consistency and integrate on-demand mobility services into the MaaS ecosystem. However, challenges exist, such as the presence of multiple data standards, mixed opinions on meta-model mappings, lack of a single standard, and the need for translations and mappings between different data models.

The recognition of the importance of ontologies and meta-model mappings reflects a commitment to achieving higher levels of interoperability and data harmonization. While data standards and collaborations are important, it is crucial to address the challenges associated with multiple standards and translations between data models. The lack of a single standard and mixed opinions on meta-model mappings indicate the complexity and diversity of the MaaS ecosystem. Striving for simplicity and practicality in data modeling approaches may be more effective than pursuing numerous mappings and translations. It is important to focus on core principles and ensure that data models align with business requirements and operational needs.

Challenges/Barriers The results highlight various challenges and barriers in data modeling for MaaS interoperability. These include concerns about cross-standard interoperability, practicality of meta-model mappings and automatic translations, limited involvement of certain operators in adopting data standards, financial constraints faced by smaller agencies, and the lack of a unified approach to integrating open data. Encouraging wider adoption of data standards among operators and addressing financial constraints can promote more comprehensive and standardized data modeling practices. Establishing a unified approach to integrating open data can enhance interoperability and collaboration among stakeholders. While challenges exist, it is important not to overlook the progress and achievements made in data modeling for MaaS interoperability. Efforts to overcome challenges, such as the involvement of certain operators and financial constraints, can be addressed through awareness, education, and support mechanisms.

4.5.5 Data Storage and Access

Maturity of Data Storage and Access The results indicate that the maturity of data storage and access varies across different types of mobility services and countries. Public transportation, particularly in Switzerland, demonstrates a higher level of interoperability with a central database for exchange and access. However, other mobility services have a lower level of interoperability, and some agencies still rely on paper-based systems. APIs are widely used for various purposes, but there is a range of maturity levels in terms of data analytics systems and APIs among different transportation operators and cities.

The recognition of the varying levels of maturity in data storage and access highlights the existing landscape of interoperability. The presence of a central database in public transportation demonstrates the feasibility and benefits of data exchange. The use of APIs and data analytics systems by larger transportation operators reflects the technological capabilities available for data storage and access. Efforts to develop conversion tools and standardize APIs can contribute to improving data interoperability and promoting seamless integration within the MaaS ecosystem.

While some sectors demonstrate a higher level of maturity in data storage and access, it is important to address the disparities and challenges faced by other mobility services. Reliance on paper-based systems and the absence of advanced data analytics systems indicate the need for improvement. The wide range of maturity levels among transportation operators suggests that more efforts are required to ensure consistency and equal accessibility to data. Promoting digitalization and providing support for smaller agencies can enhance data storage and access across the board.

Development of Data Storage and Access The results indicate potential areas for improvement in the development of data storage and access for MaaS interoperability. Suggestions include regulatory changes to enable data accessibility, standardization of APIs, remote access to data, and simplification of data translation processes. While some stakeholders prefer controlled data access, there is an appreciation for standardized APIs that facilitate ease of use. Level 4, representing complete openness, is not widely desired, with controlled data access at level 3 being seen as a more realistic and preferable target.

Identifying regulatory changes and standardization as areas for improvement highlights the need for a supportive environment for data storage and access in the MaaS ecosystem. Regulatory changes can enable easier access to data while ensuring privacy and security considerations. Standardized APIs can streamline data exchange and integration, making it easier for different stakeholders to collaborate. Remote access to data and simplified data translation processes can enhance the efficiency and effectiveness of MaaS services.

While regulatory changes and standardization are important, it is essential to strike a balance between openness and control in data storage and access. Recognizing the preferences of stakeholders who value control over their data is crucial for fostering collaboration and trust. Level 4 openness may raise concerns about data privacy and security, and therefore, a more controlled approach at level 3 might be more desirable. It is important to consider the diverse needs and preferences of stakeholders when defining the level of openness and control in data storage and access.

Barriers/Challenges The results highlight various barriers and challenges in data storage and access for MaaS interoperability. These include the presence of proprietary data APIs, data privacy laws, complexity in converting and translating data, data ownership and control, and policy-level considerations. Storing personal data while ensuring privacy and security is identified as a challenge. The struggle to convert data between different formats and the impact of policy-level considerations on interoperability standards are also noted.

Recognizing the barriers and challenges provides an opportunity to find solutions and address the obstacles to data storage and access. Encouraging the use of standardized APIs can reduce reliance on proprietary data APIs, promoting interoperability. Developing privacy-preserving techniques and ensuring compliance with data privacy laws can address concerns related to personal data. Simplifying the process of data conversion and translation can alleviate the complexity and manual effort involved. Policy-level considerations can be addressed through stakeholder engagement and collaboration to ensure alignment and effective implementation of interoperability standards. By recognizing these challenges and actively seeking solutions, the MaaS ecosystem can progress towards improved data storage and access.

4.5.6 Data Management

Maturity of Data Management The results suggest varying levels of maturity in data management within the MaaS ecosystem. Public transport sectors tend to demonstrate higher maturity, with advancements in managing vehicle data. Compliance with regulations such as GDPR in Europe and the establishment of suitable regulations for data sharing, particularly in the UK, indicate progress in data management. However, challenges persist, particularly in private mobility where compliance with data requirements lags. Road operators are perceived as more advanced in data management compared to public transport operators.

The recognition of higher maturity in data management within the public transport sector highlights the potential for best practices and lessons learned to be applied to other sectors. Compliance with GDPR and related legislation demonstrates the commitment to data protection and privacy in the MaaS ecosystem. The involvement of organizations like MobilityData in adaptive data management fosters the development of industry standards and guidelines. By building on existing frameworks and regulations, the MaaS ecosystem can continue to improve data management practices.

Development of Data Management Rules The results highlight the need for the development of data management rules to support MaaS interoperability. Suggestions include the establishment of an independent governance entity, similar to open banking, to define rules for privacy, standardization, and interoperability. The government's role as a trusted broker is proposed to instill trust, control data access, and enforce security standards. Privacy, standardization, and accuracy are emphasized as important considerations, and contracts are seen as a means to define data management responsibilities.

An independent governance entity can provide impartial oversight and ensure compliance with privacy regulations while facilitating data sharing and standardization. Emphasizing user control over their data, as seen in the "myData" approach, aligns with privacy concerns and can foster trust among stakeholders. Contracts play a vital role in defining data management responsibilities and establishing agreements between parties.

While the development of data management rules is important, it is essential to consider the diversity of operating models and regional contexts within the MaaS ecosystem. One-size-fits-all approaches may not adequately address the specific needs and challenges faced by different stakeholders. The complexity of data sharing and privacy issues requires a nuanced approach that balances standardization with flexibility. Instead of relying solely on an independent governance entity, collaboration among stakeholders, including governments, industry players, and user representatives, can ensure that the rules reflect a comprehensive understanding of data management challenges and opportunities.

Barriers/Challenges Recognizing the barriers and challenges provides an opportunity to address them and improve data management practices. Ensuring data quality while avoiding unnecessary data sharing aligns with the goal of maintaining accurate and reliable information. Advocating for adaptable privacy laws can support data management efforts in the rapidly evolving MaaS landscape. Addressing technical considerations, such as compatibility and data format standards, can enhance data interoperability. Clearly defining data ownership and storage guidelines can help resolve disputes and foster trust among stakeholders. Data management is a complex process that evolves alongside technological advancements and regulatory frameworks. Efforts to address these challenges, such as defining data management rules and establishing industry standards, can pave the way for more effective data sharing and interoperability.

4.6 Conclusions

In pursuit of developing a data solution for MaaS ecosystems, an investigation into the interoperability requirements was necessary to define the characteristics of the data solution that would improve the interoperability. The qualitative study carried out above resulted in novel insights into the state of interoperability and the core features needed in a MaaS implementation.

After collecting demographic data on the stakeholders, the questionnaire was divided into two parts:

Part II: MaaS Dichotomies - Explored why stakeholders would refuse to participate in MaaS by investigating areas of disagreement over what constitutes a MaaS ecosystem and how it should be implemented. The 9 areas of disagreement derived from the literature (see subsection 2.1.2) are:

1. Market Model
2. Modality
3. Features of Intelligent Routing
4. Ticketing and Payment Integration
5. Booking Features
6. Geographical Coverage
7. User Priorities
8. Payment Model
9. Auxiliary Services

The results of this part of the questionnaire explained the rationale behind each of the dichotomies above, the two schools of thought on the implementation of MaaS derived from differences in the dynamics of local transport networks and the issues they're facing, and the core / universal characteristics of MaaS implementation. The summary of the findings and conclusions of that part is presented in subsection 4.6.1.

Part III: MaaS Interoperability - Explore why stakeholders would have difficulty participating in MaaS by investigating the maturity levels of the ecosystems business and data interoperability. The 6 barriers investigated are as follows:

Business Barriers

1. **Conceptual:** Business Model
2. **Technological:** IT Infrastructure
3. **Organisational:** Common Goal

Data Barriers

1. **Conceptual:** Data Model
2. **Technological:** Data Storage and Access
3. **Organisational:** Data Management

The results of this part of the questionnaire explained the current and desired levels of MaaS business and data interoperability and revealed key insights into the current levels of maturity, the efforts of development, and the challenges / barriers in both business and data interoperability. he summary of the findings and conclusions of that part is presented in subsection 4.6.2.

Through the combination of the findings from both of these parts, a set of interoperability requirements is derived an presented in subsection 4.6.3 along with a roadmap that aligns the required levels of interoperability maturity to the level of MaaS integration by Sochor et al. (2018).

4.6.1 MaaS Dichotomies

The second part of this mixed-method study explored the areas of disagreement among stakeholders regarding MaaS and aimed to identify the underlying basis for these disagreements. The identified areas of disagreement revealed different interoperability requirements based on the specific cases discussed. Understanding the basis of these disagreements is crucial for defining the interoperability requirements of MaaS.

A total of 65 participants from diverse geographical backgrounds, primarily from European countries, the USA, Australia, and Malaysia, contributed to this study. The participants' geographical regions encompassed countries where MaaS implementation has been initiated, providing insights into different transportation dynamics and cultural contexts. The fundamental source of disagreement among stakeholders appeared to be their geographical background and the variations in transportation networks and travel behaviors in their respective countries. Interestingly, participants' career backgrounds, such as transport operators, government authorities, or MaaS companies, did not appear to bias their responses in favor of any particular direction.

Based on these differing transport dynamics, participants can be categorized into two mindsets: a) **Private car *first*** - participants approaching MaaS from a perspective of reducing private car reliance and b) **Public transport *first*** - participants focused on ensuring that personalized shared modes complement spatially efficient modes rather than replace them. This builds on the existing research by Hensher et al. (2020) which categorised these two extremes of MaaS in terms of geographic contexts. Each group seemed unaware of the other's perspective, as it was not relevant to the specific problems they were addressing. This disparity acts as a barrier to establishing a universal definition for MaaS and agreeing on its implementation.

This conclusion emphasizes that transportation network issues are inherently local in nature. As the implementation of MaaS aims to address these local problems, a universally standardized approach means developing a solution agnostic to specific problems. Consequently, the implementation and interoperability requirements of MaaS will vary based on the dynamics of each city. However, certain characteristics were identified as core to the implementation of MaaS, regardless of local issues. These characteristics stem from the long-term goals of MaaS implementation. The following list summarizes the explored characteristics, their significance to MaaS implementation, and their impact on interoperability requirements:

Market Model: A middle ground between an open market and a broker model, leaning towards an open market, was found to be most suitable. MaaS should be built on open data and open standards while striving for self-sustainability. This calls for raised interoperability to develop open data and standards for data sharing, fostering innovation and healthy competition.

Modality: MaaS should offer multiple mode options within an application, catering to its target audience. The need to raise interoperability to accommodate intermodal trips depends on the transport dynamics of each city. For countries with a private car emphasis, intermodality can help address first and last-mile challenges. Ideally, transport operators should adopt interoperable data structures to facilitate intermodality where required.

Features of Intelligent Routing: Balancing demand across different modes, generating insights, and incorporating real-time factors and context-aware routing are valuable features for MaaS. However, these features do not form core requirements and should be implemented based on the objectives of the MaaS provider.

Ticketing and Payment Integration: Integrating ticketing and payment is a core requirement of MaaS. Unifying payment methods, access methods, and generating single invoices for multi-mode trips all contribute to a seamless user experience. To achieve this, interoperability needs to be raised to accommodate a unified payment gateway supporting various payment methods while ensuring inclusivity for passengers without bank accounts or modern digital devices.

Booking Features: Both on-demand and scheduled bookings have their optimal use cases, and their implementation depends on the target audience and objectives of the MaaS provider. While not core requirements, a fully on-demand service necessitates a higher level of interoperability between modes. Therefore, interoperability should be raised to accommodate such a service if desired.

Geographical Coverage: Implementing city-wide solutions tailored to customer needs was considered practical and beneficial. However, interoperability between these solutions is crucial to avoid perpetuating siloed environments. Open standards, data, and integration are necessary for enabling targeted MaaS solutions to address different problems and use cases. Interoperability should be raised to ensure global compatibility with the standards set for open data and integration.

User Priorities: User priorities vary based on culture and the city where MaaS is implemented, as well as the prevailing transportation dynamics. Priorities such as pricing, packages, and other factors must be explored on a location-by-location basis.

Payment Model: The payment model remains a major dichotomy in MaaS, with questions surrounding the necessity and viability of implementing subscriptions. Pay-as-you-Go should be offered as a model to initiate MaaS adoption. Subscriptions are essential to the implementation of MaaS, as servitization of transport is less appealing without them. However, the current pricing of public transport and shared modes presents challenges for creating an attractive subscription offer. Business interoperability needs to be raised to align stakeholders toward a common goal, allowing for reasonable compromises and the development of viable subscription models.

Auxiliary Services: Integrating auxiliary services into MaaS passenger transport applications can bring various benefits to providers, operators, and users. However, these services do not constitute core requirements and need not be implemented immediately. Interoperability should be raised to ensure that transport data can be integrated with other forms of data in the future, facilitating the incorporation of auxiliary services.

The quantitative results aligned with the qualitative findings above; however, the sample size limited the statistical significance of the results. Nevertheless, the generalizability of the findings across a global implementation of MaaS is valid, as the sampling strategy ensured the selection of experts who led the MaaS implementation in most regions where it has been initiated.

It can be argued that raising the interoperability of MaaS to enable cross-border integration, intermodality, and a higher end of the spectrum is ambitious at this stage. However, failing to consider the desired interoperability requirements will lead to new silos within the MaaS-based environment. This will perpetuate the siloed environment currently present between transport operators but instead occur between MaaS operators, necessitating reinvention in the future.

In conclusion, the core concepts essential to MaaS implementation include open data and open standards, inclusivity of transport operators and mobility providers, offering multiple modes to users, integrating ticketing and payment, and implementing subscriptions. However, when structuring an implementation plan for MaaS, it is crucial to raise both business and technical interoperability to enable intermodal trips, fully on-demand services, worldwide standards interoperability, and integration of transport data with other data sources.

4.6.2 MaaS Interoperability

In this part of the research, the questionnaire concentrated on investigating the maturity level of interoperability of MaaS. In alignment with the Maturity Model for Enterprise Interoperability (MMEI) Guédria et al. (2011), the questions were phrased to ask the participants about the current state of interoperability and the desired state as per the model. Out of the 4 *areas of concern*, the study focused on Business interoperability and Data interoperability as Service and Process interoperability were too premature to be investigated at that stage.

Under the Business aspect, the conceptual interoperability looked at the maturity of the business model, the technical interoperability looked at the maturity of the IT Infrastructure, and the organisational interoperability looked at the interoperability of stakeholders through a common goal.

The findings highlight regional variations in maturity levels, emphasizing the influence of local contexts, regulatory frameworks, and stakeholder engagement. While some regions, such as the Netherlands, have well-developed MaaS concepts with common understanding, others, like Scotland and parts of the United States, are still in the early stages of implementation. This variation underscores the need for tailored approaches that consider specific regional challenges and priorities.

Transport operators play a crucial role in the maturity of MaaS models, and insufficient representation and interest from these operators pose hindrances. Collaborative efforts and partnerships between transport operators and MaaS providers are essential for achieving a mature and integrated system. Moreover, standardization efforts are underway, with a focus on business rules, partnerships, contracts, and non-discriminatory policies. However, comprehensive standardization remains a work in progress, with variations in scope and effectiveness across different regions and jurisdictions.

The development of sustainable and profitable business models for MaaS is challenging, with the need for subsidies in the initial stages and innovative revenue models for long-term viability. The influence of authorities and legislation is significant in shaping the maturity and direction of MaaS business models. Supportive regulatory frameworks and collaboration between public and private stakeholders are vital for fostering growth and maturity.

The maturity of IT infrastructure for enabling MaaS varies significantly among stakeholders and regions. Differences in technological advancement, available resources, and regulatory frameworks contribute to this variation. Standardization in the IT infrastructure domain poses challenges, with complexities in ticketing systems, deep integration, and regulatory differences. Striking a balance between standardizing interfaces and maintaining flexibility can facilitate interoperability.

Achieving agreement over a common goal among MaaS stakeholders presents barriers and challenges. Stakeholder management complexities, conflicting perspectives and goals, and concerns about dominance by app developers hinder the establishment of a shared vision. While complete agreement may not always be feasible, stakeholder engagement, legislation, and public-private collaboration are crucial in developing a common goal. Balancing the roles of the public and private sectors allows for societal goals to be addressed while fostering technological advancements.

The definition of the common goal in MaaS varies across regions and stakeholders, reflecting the diversity of transportation systems, cultural contexts, and societal priorities. Customization to local needs is important, but overarching principles like sustainability, inclusivity, and efficiency can provide a unifying vision. Striking a balance between customized approaches and common objectives is necessary to foster collaboration, interoperability, and progress in the MaaS ecosystem.

Under the Data aspect, the conceptual interoperability looked at the maturity of the data models, the technical interoperability looked at the maturity of the data storage and accessibility, and the organisational interoperability looked at the maturity of data management and responsibilities.

The results indicate variations in the maturity levels of data models, with adaptive data models at level 4 being the desired goal. However, reaching level 4 may require significant time and effort, and starting with level 2, which involves the use of standards for alignment, is considered a practical starting point. Standardization efforts and collaboration with stakeholders are seen as crucial steps toward achieving higher levels of data model interoperability.

The development of data models for MaaS interoperability involves the use of various standards and models, such as NeTEx, SIRI, GTFS, MDS, TOMP API, and GBFS, in different regions. Efforts to establish ontologies, ensure data consistency, and integrate on-demand mobility services into the MaaS ecosystem are underway. Challenges include the presence of multiple data standards, mixed opinions on meta-model mappings, and the need for translations and mappings between different data models. Striving for simplicity and practicality in data modeling approaches, while ensuring alignment with business requirements, can enhance interoperability and progress in data modeling for MaaS.

The maturity of data storage and access varies across different types of mobility services and countries. Public transportation demonstrates higher levels of interoperability, with central databases for data exchange and access. However, other mobility services exhibit lower levels of interoperability, and some agencies still rely on paper-based systems. APIs are widely used, but there is a range of maturity levels in data analytics systems and APIs among different transportation operators and cities. Efforts to develop conversion tools, standardize APIs, and promote digitalization can contribute to improving data storage and access interoperability in the MaaS ecosystem.

Data management within the MaaS ecosystem also shows varying levels of maturity. Public transport sectors tend to demonstrate higher maturity, with advancements in managing vehicle data and compliance with regulations such as GDPR. Challenges persist in private mobility, where compliance with data requirements lags behind. The development of data management rules, including the establishment of an independent governance entity and the government's role as a trusted broker, is suggested to promote privacy, standardization, and interoperability. Collaborative efforts among stakeholders are essential to address the diversity of operating models and regional contexts, ensuring that the rules reflect a comprehensive understanding of data management challenges and opportunities.

Despite progress in data modeling, data storage and access, and data management for MaaS interoperability, challenges and barriers remain. These include concerns about cross-standard interoperability, data privacy laws, complexity in converting and translating data, data ownership and control, and policy-level considerations. Addressing these challenges requires standardized approaches, privacy-preserving techniques, simplified data conversion processes, and stakeholder collaboration. By overcoming these obstacles, the MaaS ecosystem can achieve improved data interoperability, enhance collaboration among stakeholders, and provide better services to users.

In conclusion, the study identified a number of challenges in the industry that are hindering the progress towards an interoperable MaaS ecosystem which include the lack of agreement over a common goal, cross-standard interoperability, and a viable and equitable business model. Furthermore, the study highlighted insights into the approaches of different regions to overcome such challenges and uncovered the need to have a local focus when developing a MaaS ecosystem. Through the results of this study, a clearer vision of the interoperability requirements of MaaS is developed enabling the next step of this research where the features of an interoperable data ecosystem for MaaS are investigated.

4.6.3 Interoperability Roadmap

Through the results of the of both Part II and Part III, the interoperability requirements of MaaS are derived as follows, outlining the desirable levels of interoperability required to achieve the objectives of MaaS. Based on these defined requirements, this chapter explores the data interoperability requirements and proposes a solution to raise the interoperability of the data ecosystem in MaaS while taking into account the relationship between the data and its stakeholders.

Business interoperability requirements:

1. Adaptive Business model - flexible for accommodating new stakeholders
2. Open IT Infrastructure
3. Standardised contracts (Ownership, Responsibilities, Liabilities) - defined at a geographical level of regions with similar transportation regulations.
4. Define common goal - standardized for regions facing the same transportation challenges (Private-car first / Public-transport first)

Data interoperability requirements:

1. Data adhering to open standards
2. Standardised APIs
3. Cross-mode interoperability (Data models interoperate across modes)
4. Interoperable payment and booking data (across services on a MaaS app)
5. Real-time data to allow for on-demand bookings
6. Cross-border interoperability for data models / standards and cross-border accessibility for APIs
7. Cross-domain interoperability (Mobility data needs to be interoperable with other domains)
8. Data contracts need to accompany the above requirements defining rules for management, access, and privacy.

The required maturity levels to be associated with the requirements above are:

1. Data needs to have standards for each mode that allows interoperability with other modes. Standards can vary across modes and borders but need to be aligned with each other.
2. These models / standards need to be setup to enable adaptivity in the future which allows accommodating changes and advancements in the

mobility realm, including being stakeholder agnostic to enable accommodating new types of stakeholders.

3. Data sharing / exchange method needs to accommodate stakeholders with low technological readiness / advancement.

4. Data sharing and exchange rules need to be established supporting open access and sharing but with the necessary privacy, security, and control. Data access rules need to be flexibly encoded to allow operators to set the rules that align with their contracts.

The required level of maturity is fleshed out against the level of MaaS integration in Figure 4.21. The levels of MaaS integration (Sochor et al., 2018) were described in subsection 2.1.2. This roadmap serves as a guideline for stakeholders to upgrade the level of their business and data elements according to the level of MaaS integration they intend to implement.

4.6.4 Summary

In conclusion, this chapter has addressed the first and second objective of this research, exploring the state of interoperability of MaaS ecosystems. The findings offered key insights into the reasons why stakeholders disagree over the implementation of MaaS, highlighting the two mindsets, **Private car *first*** and **Public transport *first***, which govern the stakeholders' approach and understanding of the MaaS concept. In addition, the findings highlighted the core characteristics of any MaaS implementation including open data and open standards, inclusivity of transport operators and mobility providers, offering multiple modes to users, integrating ticketing and payment, and implementing subscriptions.

The second part of the qualitative study was crucial in understanding the current and desired levels of business and data interoperability. This led to significant observations related to the current efforts of developing business and data elements and the challenges hindering such development. Finally, the results of both parts of the qualitative study were combined to produce a list of interoperability requirements which was put into perspective through an interoperability roadmap that aligns the required level of interoperability with the levels of integration of MaaS.

	Level 0 No Integration	**Level 1** Integration of Information	**Level 2** Integration of booking & payment	**Level 3** Integration of the service offer	**Level 4** Integration of societal goals
Business					
Conceptual	**Level 0: Unprepared** Business model NOT explicitly modeled or documented	**Level 1: Defined** Business model is explicitly modeled or documented	**Level 2: Aligned** Use of standards for alignment with other models	**Level 3: Organized** Business models for multi-partnership and collaborative enterprise	**Level 4: Adaptive** Adaptive business model
Technological	**Level 0: Unprepared** No or unreliable IT infrastructure	**Level 1: Defined** Basic IT infrastructure in place	**Level 2: Aligned** Standard and configurable IT infrastructures	**Level 3: Organized** Open IT infrastructure	**Level 4: Adaptive** Adaptive IT infrastructure
Organisational	**Level 0: Unprepared** No common goal	**Level 1: Defined** Common goal is not well defined	**Level 2: Aligned** Common goal is well defined but not agreed upon by stakeholders	**Level 3: Organized** Some stakeholders agree and work towards a common goal	**Level 4: Adaptive** All stakeholders understand, agree, and work towards a common goal
Data					
Conceptual	**Level 1: Defined** Data model is explicitly modeled or documented	**Level 2: Aligned** Use of standards for alignment with other models	**Level 3: Organized** Meta-modeling for multiple model mappings	**Level 4: Adaptive** Adaptive data models (both syntax and semantics)	**Level 4: Adaptive** Adaptive data models (both syntax and semantics)
Technological	**Level 1: Defined** Data storage devices connectable, simple electronic exchange possible	**Level 2: Aligned** Automated access to data based on standard protocol	**Level 3: Organized** Remote access to databases possible for applications, shared data	**Level 4: Adaptive** Direct database exchanges capability and full data conversion control	**Level 4: Adaptive** Direct database exchanges capability and full data conversion control
Organisational	**Level 0: Unprepared** Data responsibilities and authorities are NOT explicitly defined	**Level 1: Defined** Data responsibilities and authorities are defined and in-place	**Level 2: Aligned** Rules and methods for data management	**Level 3: Organized** Personalized data management for different partners	**Level 4: Adaptive** Adaptive data management rules and methods

Figure 4.21 Interoperability Roadmap for Mobility as a Service Stakeholders

Chapter 5

5. Development of the Data Solution

5.1 Introduction

Through the results of chapter 4, the data interoperability requirements of MaaS were derived. Based on these defined requirements, this chapter proposes a solution to raise the interoperability of the data ecosystem in MaaS while taking into account the relationship between the data and its stakeholders.

To address the defined requirements and maturity levels, the following features were sought as the foundation of the design of the proposed data ecosystem for MaaS:

Standardisation: How can the entry points to the ecosystem be standardised for each mode of transport to enable interoperability?

- Firstly, we need to identify what are the modes of transport available and how can operators be classified according to their data.
- To achieve that, a literature review of data entities within the MaaS realm is conducted to identify key data elements and the relationships between them.
- Through the results of the review, a taxonomy is developed to classify different types of operators and modes of transport based on their data elements.
- The proposed taxonomy sets a base for standardized mobility profiles.
- These profiles can be used as the entry point to the data ecosystem which allows operators to identify their required data structures. In addition, it can enable standardising contracts for each mobility profile, establishing data governance and privacy requirements.

Modularity : How can these entry points be modular in their syntax and semantics to accommodate a spectrum of operators, from new and uncertain profiles to low technological readiness?

- Firstly, we need to identify what are the most common syntax and data models used in the industry and ensure that the ecosystem can work with these models.
- To achieve that, a review of the common syntax and semantics is required. These are to be integrated into the ecosystem with the accommodation of new syntax and semantics being a part of the maintenance and continuous improvement of the ecosystem.
- This modularity will allow the ecosystem to speak in different languages and avoid enforcing expensive translation and upgrade processes on small operators.

Alignment : How can we align the different profiles to allow modularity of syntax and semantics?

- In the process of developing the profiles, existing standards are accommodated for their relevant profiles. A review of existing alignments between these profiles is required.
- Existing alignments between profiles are integrated into the ecosystem and development of alignments between new syntax and semantics is required as part of the maintenance and continuous improvement of the ecosystem.
- This will enable profiles and standards to interoperate which is required for cross-mode and cross-border interoperability.

The three features above need to allow for **Customisation** and leverage **Semantic Web Technologies (SWTs)** which inherently promote:

- data to be in a machine-readable format enhancing interoperability,
- cross-domain interoperability, and
- open data standards.

The literature that supports the gap addressed by this chapter has been discussed in section 2.5. The methodology taken to derive the taxonomy, validate it and present a practical workflow for its application has been discussed in section 3.3. The following sections first present an analysis of prominent data standards and specifications is then carried out to identify the different possible cases of operation. This is used to build a taxonomy that classifies the data an operator shares for moving a passenger through their service from point A to point B. The taxonomy is then validated using a list of services in the city of Moscow and compared to other taxonomies in the literature. Subsequently, a data workflow is presented that demonstrates the potential use of the taxonomy in conjunction with Semantic Web Technologies to automate the process of on-boarding transport operators into a Data Space. Finally, the chapter is concluded by providing a holistic vision of a MaaS data ecosystem utilising the proposed solution.

5.2 Standardisation: The Mobility Profiles Taxonomy

5.2.1 Review of Data Standards

Building on the review conducted in subsection 2.2.3, a select set of data standards were analysed which focused on the most commonly used standards within the MaaS ecosystem. The sections below present a brief discussion on the results of the review for each. Some of these standards have already been discussed in subsection 2.2.3, where the results of this section will carry forward.

General Transit Feed Specification (GTFS) ***static***

GTFS *static* is designed for transit agencies with generally fixed routes and timetables. The standard provides a description for a set of CSV files which define how such agencies would model their data. The standard covers the data elements described in Table 5.1.

GTFS realtime

GTFS realtime [1] supports the publishing of realtime data by transit agencies. The standard includes models for three types of feeds: **(a) Trip Updates** - represent fluctuations in the timetable e.g. *"Bus X is delayed by 5 minutes"*, **(b) Service**

[1] developers.google.com/transit/gtfs-realtime

Table 5.1: Review of data elements in GTFS

Data Element	Description	Journey Phase
agency.txt, feed_info.txt, attributions.txt, translations.txt	Metadata / Identification	None / All
stops.txt, routes.txt, trips.txt, shapes.txt	Fixed routes	Planning
calendar.txt, calendar_dates.txt, frequencies.txt	Fixed schedules	Planning
fare_attributes.txt, fare_rules.txt	Fare information	Payment
transfers.txt, pathways.txt, levels.txt	Factors affecting the journey and user preferences	Planning

Alerts - represent a problem with a particular entity in the form of a textual description e.g. *"Station Y is closed due to construction"*, and **(c) Vehicle Positions** - represent basic information about a specific vehicle within the network.

General Bikeshare Feed Specification (GBFS)

GBFS 2 is a data standard designed for shared mobility. The standard provides a description for a set of JSON files which define how shared mobility operators can share the status of their system in a given moment. The feed is expected to be republished by the operator at a reasonable frequency (in seconds) to provide realtime visibility of the service for planning. The JSON files are described in Table 5.2.

Table 5.2: Review of data elements in GBFS

Data Element	Description	Journey Phase
gbfs.json, gbfs_versions.json, system_information.json	Metadata / Identification	None / All
station_information.json,	Station-base services	Planning

station_status.json		
free_bike_status.json	Dockless services	Planning
system_hours.json, system_calendar.json	On-demand services	Payment
system_pricing_plans.json	Fare information	Planning
vehicle_types.json, system_regions.json, system_alerts.json, geofencing_zones.json	Factors affecting the journey and user preferences	Planning

Transmodel

Short for the European Standard Public Transport Reference Data Model, Transmodel was also developed to provide a common language for public transport. The standard is a conceptual model divided into 8 parts as described in figure 2.9. In comparison to other data standards, Transmodel is considered very rich with over 1500 concepts covering different modes of transportation and various functional domains.

In addition to the parts presented in figure 2.9, an additional part was added in 2021 to cover alternative modes of transport. With this update, Transmodel caters for operations of fixed routes and schedules but also for demand-based operations by managing vehicle meeting points in cases such as vehicle sharing or carpooling. The parts of transmodel allow for standardisation of data beyond what needs to be shared with a public user, such as driver rosters. Based on Transmodel, a data exchange standard, Network Timetable Exchange (NeTEx) [3], was developed which inherits the concepts of Transmodel.

The TOMP-API

Although the TOMP API[4] is an API specification, it plays a major role in shaping the data exchange in the MaaS ecosystem. In the term TOMP, TO stands for Transport Operators, and MP stands for MaaS Providers. The API specification standardises how data is exchanged betweeen operators and MaaS providers according to the different phases of a journey as shown in Figure 2.8.

5.2.2 Results of the Review

Through the review of the data standards presented above, the phases of a journey and the corresponding variation in operator data profiles were derived.

Although there are a number of other standards within the realm of Mobility such as Mobility Data Specification (MDS) [5] or Open Standard for

[3]http://netex-cen.eu/
[4]https://github.com/TOMP-WG/TOMP-API

Linked Organisations (OSLO) [6], they did not add to the cases of operations already derived from the standards above. Other standards covering mobility domains that affect a journey, such as DATEX II [7], were not considered as the scope of the taxonomy did not include such factors.

A breakdown of the phases of the journey derived through the data standards review is shown in Table 5.3. The table shows the data request by a user in each phase and the corresponding variations on the operator's side. This breakdown will form the core layers of the taxonomy.

Table 5.3: Breakdown of the Phases in a Journey Illustrating the Data Interaction Required Between a User and an Operator

PLANNING	
User	**Operator**
I need to know where to start and end	I need to specify available start and end locations: - *Fixed locations* - *Flexible / demand-based locations*
I need to know what time to start and end	I need to specify available timings of my service: - *Fixed schedule / frequency* - *On-demand timings*
BOOKING	
User	**Operator**
I need to know if I can get a place on the service	I need to specify how the user can guarantee a place on my service: - *No Booking* - *Booking in advance* - *Booking on demand*
TICKETING / ACCESS	
User	**Operator**
I need to access the service	I need to specify how the user can access my service: - *Non-electronic* - *Contactless Ticketing* - *Biometric Ticketing*
PAYMENT	
User	**Operator**

[5]https://github.com/openmobilityfoundation/mobility-data-specification
[6]https:// data.vlaanderen.be/ns/
[7]https://www.datex2.eu/datex2/

I need to know how I can pay for my journey	I need to specify the payment instrument options that can pay for my service: - *Methods that require users' personal data.* - *Methods that do not require users' personal data*
I need to know the pricing and fare rules	I need to specify the prices and fare rules for my service: - *Pay-as-you-go* - *Subscription*

Building on the review conducted in subsection 2.2.3, a select set of data standards were analysed which focused on the most commonly used standards within the MaaS ecosystem. The sections below present a brief discussion on the results of the review for each. Some of these standards have already been discussed in subsection2.2.3, where the results of this section will carry forward.

In addition to Planning, Booking, Ticketing / Access, and Payment, a journey of a passenger on a service would include the following phases, however, these were not considered in the taxonomy for the reasons listed below:

- USER REGISTRATION - The profile of a user and the data required to be shared with an operator would vary significantly between different types of services. This is due to different reasons such as safety, liability, accessibility, preferences, among others. It is therefore recommended to develop a similar taxonomy to breakdown, at a high-level, the building components of a user profile. This would then allow the standardisation of user data and can be used for automating and regulating the exchange of user data and account registration across different services.

- TRAVELING - This phase represents data updates during the journey. It was excluded based on the assumption that this would include realtime data on the service that would not vary significantly amongst the different types of operations. This is likely to include the location of the vehicle, changes to the Estimated Time of Arrival (ETA), disruption updates, etc. It is assumed that the data model for such information wouldn't vary between fixed and flexible services and commonly fall under the same data model describing the data for the Planning phase.
- SUPPORT and AFTER SALES - These phases are considered to not vary between operators as it revolves around customer support information and operations like refunds which can be linked to the payment layer defined in

the operator's Mobility Profile.

In addition to the journey phases, two other ares of variation were important to consider as they can affect the operation model. These two layers are listed in Table 5.4.

Table 5.4: Breakdown of Additional Layers of Operator data

DRIVERS
I need to specify drivers for my service: *Autonomous / No Driver* *Employed Driver / Fixed Shifts and Pay* *Ride Coordination / Flexible Shifts and Pay*
SERVICE OWNERSHIP
I need to specify the type of ownership to the service: *Public Service* *Private Service* *Public Private Partnership* *Individual Service*

The DRIVERS layer was included as it may specify data that needs to be shared in the case of products resale, especially in the case of ride coordination (services like Uber) where the drivers' data is required for the PLANNING phase.

The SERVICE OWNERSHIP aspect needs to be included as it affects the liabilities associated with the operation. The Mobility Profiles taxonomy is foreseen to be useful for automating contracts and data access regulation which may be heavily dependent on the type of ownership of the service. However, this was deemed unnecessary to have as an independent layer but instead as part of the metadata associated with the profile.

The 4 Journey phases and the DRIVERS layer serve as the core layers of a Mobility Profile. The next section will describe how these layers fit together to develop a profile, in addition to any hierarchical or exclusive relationships between / within these layers.

5.2.3 Description of the Taxonomy

The taxonomy of the Mobility Profiles consists of 5 layers. The function of a layer is to:

- **Define the case** for the operator within the context of that layer.

- **Identify the standard data models or API specifications** that can be used based on the chosen case.
- **Link between the case and its access rules** defined by a data ecosystem.

This section will discuss the 5 layers and the cases that fall under each.

PLANNING Layer

The first layer is the **PLANNING** Layer. This layer sits at the root of the profile and has exclusivity over its cases. This means that a Mobility Profile can only include one of the case options to identify how its service can be planned. The layer is split by temporal and spatial variations as shown in figure 5.1.

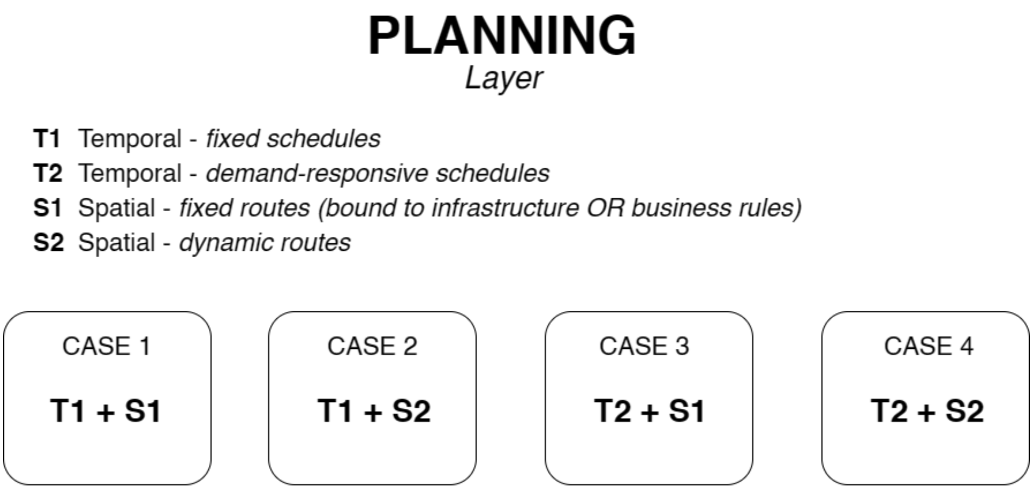

Figure 5.1 Illustration of the profile cases within the PLANNING layer

The layer includes four cases based on the operations varying temporally and spatially. Temporally, the schedules of the mode can either be fixed or on-demand. Similarly, the routes of the mode can either be fixed or dynamic.

The 4 cases are defined below:

1. **Case 1** - Fixed Schedules (**T1**) and Fixed Routes (**S1**) - This case describes modes that have fixed schedules and fixed routes. Fixed schedules means the vehicle has fixed timings or frequencies by which it leaves certain locations. Fixed routes means the route between the origin and destination does not change for a specific service.

2. **Case 2** - Fixed Schedule (**T1**) and Dynamic Routes (**S2**) - This case describes services which leave certain locations at fixed timings but have variable destinations likely based on demand.

3. **Case 3** - Demand-Responsive Schedule (**T2**) and Fixed Routes (**S1**) - This case describes services such as Demand-Responsive Transit which move between fixed locations but only runs on-demand.

4. **Case 4** - Demand-Responsive Schedule (**T2**) and Dynamic Routes (**S2**) - This case describes services which move on-demand and do not follow a fixed route such as e-hailing, car-sharing, and most micromobility services seen to date.

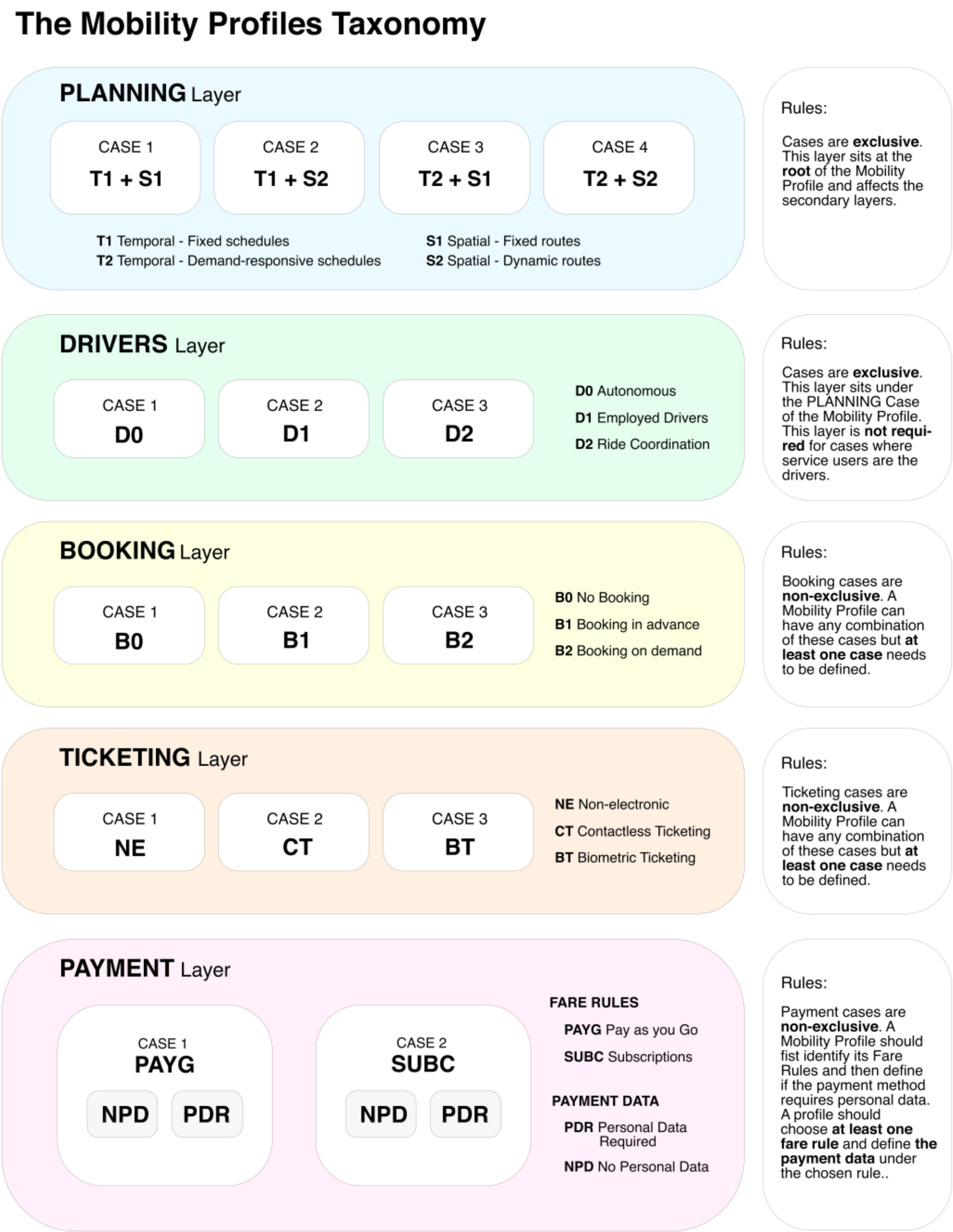

Figure 5.2 Illustration of the Mobility Profiles Taxonomy

DRIVERS Layer

Closely linked to the PLANNING layer, the DRIVERS layer serves as the second layer in the hierarchy of a profile which also has an exclusive relationship between its cases. A Mobility Profile can either be *Autonomous* (**D0**), have *Employed Drivers*(**D1**), or run on *Ride Coordination* (**D2**). The profile **does not need to include this layer** to accommodate cases where the users of a service are its drivers.

BOOKING, TICKETING, and PAYMENT Layers

The BOOKING, TICKETING, and PAYMENT layers do not have exclusivity over their cases and a profile can operate more than one variation under these layers. There is no hierarchy among these layers.

The BOOKING layer defines whether the service can be booked. Booking here means that the user can guarantee themselves a spot on the mode of transport. If the service is bookable, the operator defines whether users can book in advance and / or on demand.

The TICKETING layer defines how a user can access the vehicle. The cases were defined based on the type of data required by an operator. Non Electronic (NE) ticketing refers to methods of access that do not have an electronic transaction such as cash, keys, tokens, etc. Contacless Ticketing (CT) refers to access methods such as card-based access, QR code scanners, Bluetooth, or other types of readers. Biometric Ticketing (BT) was classified separately as it requires the collection and verification of biometric data.

Under the PAYMENT layer, the fare rules sit at the top of the layer, which are split into Pay as You Go (PAYG) and Subscriptions (SUBC). Under each type of rule, the payment method either requires personal data or does not require.

Illustration of the Taxonomy

The taxonomy is presented in Figure 5.2. A Mobility Profile should define the standards and regulations for services that fall under that profile. In that sense, a profile will enable the standardisation of entry to a data ecosystem, such as Mobility Data Spaces, by specifying the data models, API specifications, and exchange formats that are supported for each profile. An operator would then identify which profile fits its service best and provide its data according to the rules of the Mobility Profile. An example of how a Mobility Profile can be set up and used as an entry specification to a data ecosystem is shown in Figure 5.3.

This allows the data space to be more flexible, although, it would require the development of verified alignments and interoperability solutions to allow the integration of various standards supported by a profile as well as interoperability across profiles.

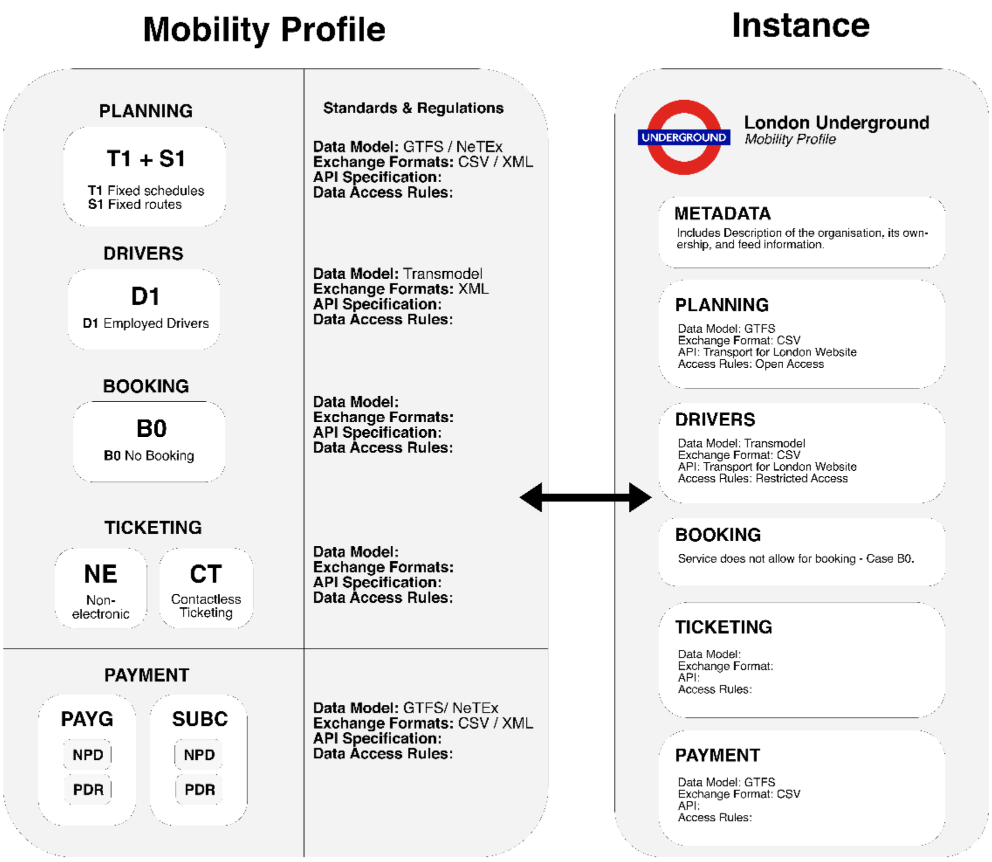

Figure 5.3 Example of how a Mobility Profile and an instance of the profile would be set up - The details in this figure are just an example and are not the actual standards used by the London Underground

Taxonomy Validation

To check whether the layers in the taxonomy comprehensively cover the different types and elements that build up an operator's dataset required for moving passengers, a list of services in Moscow are reviewed against the taxonomy layers as shown in table 5.5. For each service, the taxonomy is validated by checking whether a case from each layer is applicable to the service.

Table 5.5: Validation of Mobility Profiles against Mobility Services in Moscow

Service	Description	PLANNING	DRIVERS	BOOKING	TICKETING	PAYMENT - PAYG	PAYMENT - SUBC
Metro	Railway service	T1+S1	D1	B0	CT, BT	PAYG - PDR, NPD	SUBC - PDR, NPD
Moscow Central Circle (MCC)	Railway service	T1+S1	D1	B0	CT, BT	PAYG - PDR, NPD	SUBC - PDR, NPD
Aeroexpress	Railway service	T1+S1	D1	B0	CT	PAYG - PDR, NPD	SUBC - PDR, NPD
Moscow Central Diameters	Railway service	T1+S1	D1	B0	CT	PAYG - PDR, NPD	SUBC - PDR, NPD
Bus	Fuel-based bus service, running on fixed routes by the operator	T1+S1	D1	B0	CT	PAYG - PDR, NPD	SUBC - PDR, NPD
Trolleybus	Electric bus service, Have allocated lanes as they are connected to overhead lines	T1+S1	D1	B0	CT	PAYG - PDR, NPD	SUBC - PDR, NPD
Tram	Rail vehicles traveling on tracks on public urban streets	T1+S1	D1	B0	CT	PAYG - PDR, NPD	SUBC - PDR, NPD
Marshrutka (Shared Minivans)	Minibuses	T1+S1	D1	B0	CT	PAYG - PDR, NPD	SUBC - PDR, NPD
Velobike	Bikesharing, retrieved and returned to nearest available dock	T2+S2	-	B2	CT	-	SUBC - PDR
Delimobil	Carsharing	T2+S2	-	B2	CT	PAYG - PDR	-
Anytime	Carsharing	T2+S2	-	B2	CT	PAYG - PDR	-
Car5	Carsharing	T2+S2	-	B2	CT	PAYG - PDR	-
Udrive	Carsharing	T2+S2	-	B2	CT	PAYG - PDR	-
BelkaCar	Carsharing	T2+S2	-	B2	CT	PAYG - PDR	-
Yandex Taxi	Taxi Service	T2+S2	D1	B2	CT	PAYG - PDR	-
Uber	Ride-hailing	T2+S2	D2	B2	CT	PAYG - PDR	-
Whoosh	E-scooter Sharing, dockless	T2+S2	-	B2	CT	PAYG - PDR	-
Yurent	E-scooter Sharing, dockless	T2+S2	-	B2	CT	PAYG - PDR	-
Yandex Go	E-scooter Sharing, dockless	T2+S2	-	B2	CT	PAYG - PDR	-

Comparison with other Taxonomies

With the proliferation of shared mobility services and the development of various types of operations, establishing policies and regulations around these services have become a focal point. In the endeavor of regulating these service, a few taxonomies have emerged. Cledou et al. (2018) presented a taxonomy for planning and designing smart mobility services. The taxonomy is made of 8 dimensions: type of services, maturity level, users, applied technologies, delivery channels, benefits, beneficiaries, and common functionality. Under each dimension, the authors define common concepts providing a vocabulary to guide discussions and information sharing around smart mobility services. The taxonomy gives definitions for different types of services such as journey planners, parking, transport monitoring, and payment, to name a few. In contrast, the Mobility Profiles taxonomy is geared towards categorizing the data essential for efficiently moving a passenger from origin to destination across diverse transportation services. This taxonomy transcends the confines of smart mobility, focusing solely on dimensions pertinent to data exchange for passenger movement. Unlike Cledou et al. (2018)'s taxonomy, which caters to a broader planning and developmental context, the Mobility Profiles hone in on the specific requirements for passenger mobility. Therefore, while Cledou et al. (2018)'s taxonomy serves a distinct purpose, primed for policy-makers and mobility solution developers to align their understanding, it does not encompass the intricate operational distinctions that the Mobility Profiles taxonomy seeks to define.

Another taxonomy contributing to the field of Mobility as a Service is the Levels of MaaS Integration (LMI) taxonomy' by Lyons et al. (2020). The taxonomy covers levels of integration within and between mobility services beyond the private car emulating 05 SAE taxonomy for automation of road vehicles. Similar to Sochor et al. (2018), this taxonomy defines 5 levels of integration for MaaS services. This taxonomy can complement the Mobility Profiles where different policies are applied through the Mobility Profiles depending on the level of integration of the operator. In parallel, the SAE taxonomy introduced by SAE International (2018) offers a classification system for diverse automation levels, aligning with concepts closely related to the DRIVERS layer established within the Mobility Profiles. It's important, however, to appreciate the nuanced distinctions between these taxonomies. The DRIVERS layer primarily serves to identify the driving model associated with a given operational type, guiding the requisite data provisioning for operators.

In contrast, the SAE taxonomy delves deeper, concentrating on a hierarchical classification of automation levels, albeit with a narrower focus limited to road vehicles exclusively.

More taxonomies relevant to the mobility field have been found in previous studies. For instance, Solmaz and Turgut (2019) introduced a taxonomy classifying different human mobility models which defines four classes that differentiate between how people move including Class1: Pedestrian walk models and Class 3: Vehicular models. Hyland and Mahmassani (2017) put forward a taxonomy that classifies vehicle fleet management problems to inform future research on autonomous vehicle fleets. The layers of the taxonomy dive into various factors that affect the operation of a fleet such as pickup and delivery, size of vehicle fleet, pricing structures, network congestion, among others. The purpose of this taxonomy is to highlight areas where there are challenges faced by fleet managers. While these taxonomies are related to the field, their scopes are distinct from the Mobility Profiles taxonomy.

Through this comparative study with other taxonomies found in the literature, a number of classifications were uncovered which shed light on various aspects of shared mobility. Each taxonomy presented a unique perspective enriching the understanding of various dimensions within the field. However, it is noteworthy that none of the taxonomies directly align with the distinct approach of the Mobility Profiles taxonomy. It stands apart from other taxonomies through its scope which focuses on the data of an operator required to move a passenger from A to B. This focus underscores the novelty of the taxonomy filling a gap within the data exchange practices of Mobility as a Service.

Implications and Limitations of the Taxonomy

The purpose of the taxonomy is to standardise the entry of mobility operators into a data ecosystem. The taxonomy was developed by conducting a review of existing data standards and specifications utilized in the realm of Mobility as a Service for data exchange and service integration. The review led to the derivation of five core layers within the taxonomy: Planning, Drivers, Booking, Ticketing, and Payment. Each layer encompasses distinct operational cases, providing a structured framework for the high level identification of how an operator runs their service in order to enable its integration and interoperability with other mobility services.

The taxonomy was validated by examining a list of mobility services offered in Moscow, being one of the top 10 cities for urban transportation according to

McKinsey & Company McKinsey & Company (2021). The city offers a variety of services under Moscow Transport and Yandex Moscow Transport (2017). These services were compared against the taxonomy and found to fall under the different cases defined. This, however, is a limited validation that only verifies the coverage extent of the taxonomy. Further validation is required through methods such as an experts review or data experiments to ensure the applicability of this taxonomy.

The Mobility Profiles derived from the taxonomy are to be used as a method to standardise entry to data ecosystems such as Mobility Data Spaces. This would be valuable in avoiding the independent development of standards within data ecosystems leading to further silos and interoperability issues. To make this taxonomy more practical, it is proposed to develop a machine-readable version (e.g., an ontology) which would enable the use of the taxonomy within data architectures to automate data validation and access.

Other limitations of the taxonomy include that it does not account for user data which includes personal information, preferences, accessibility, etc. It is recommended that an extension to the taxonomy is defined for standardising Mobility Profiles of users. As discussed, the scope of the taxonomy does not include factors affecting the journey, such as transfers between stations, parking availability, etc. An investigation into the elimination of these factors is recommended to ensure the practicality of the taxonomy.

In conclusion, the taxonomy represents a novel contribution to building mobility specifications which can be used to raise interoperability between specifications and prevent the development of silos among data ecosystems. The Mobility Profiles is predicted to be beneficial for advancing the integration of mobility data and regulations for Multimodal Digital Mobility Services (MDMS), especially within the context of MaaS. If proven to be efficient, this approach can be replicated for standardising entry to data spaces of other domains.

5.3 Modularity, Alignment, and Customisation

In every attempt towards standardisation, elements of flexibility are lost. Yet, in a dynamic domain such as mobility, flexibility is required to accommodate the diverse set of stakeholders and continuously evolving mobility services. Therefore, the Mobility Profiles taxonomy was developed with an emphasis on modularity, divided into 5 layers that can be interchangeable to accommodate different methods of operation.

Building on the Mobility Profiles taxonomy, this section will discuss elements to be considered when setting up a data space to become more adaptable in terms of accommodating a diverse set of stakeholders.

Modularity: Syntax and Semantics

In the process of data exchange, the syntax and semantics of datasets that need to be merged require an alignment. When discussing syntax, this is referring to the format that a data is stored in. This may vary from a simple .txt file to a more complex SQL database. The challenge here lies in accommodating as many formats as possible to reduce the cost required by the operators to join a data space.

The syntax used by operators is usually closely related to the semantic model they choose to follow, for example, the GTFS standard specifies the use of CSV data, while the GBFS standard uses JSON. Therefore, the modularity of syntax and semantics needs to be examined together.

An approach towards improving the modularity and customisation of the data exchange process is proposed in this section through the following process, which will include screenshots and code snippets from a prototype or experimental platform developed to investigate the viability of these steps:

1. Based on the Mobility Profile of the operator, the standard for each layer is to be defined. For this example, it is assumed that a public transport operator is entering a data space where allowed standards include GTFS and NeTEx.

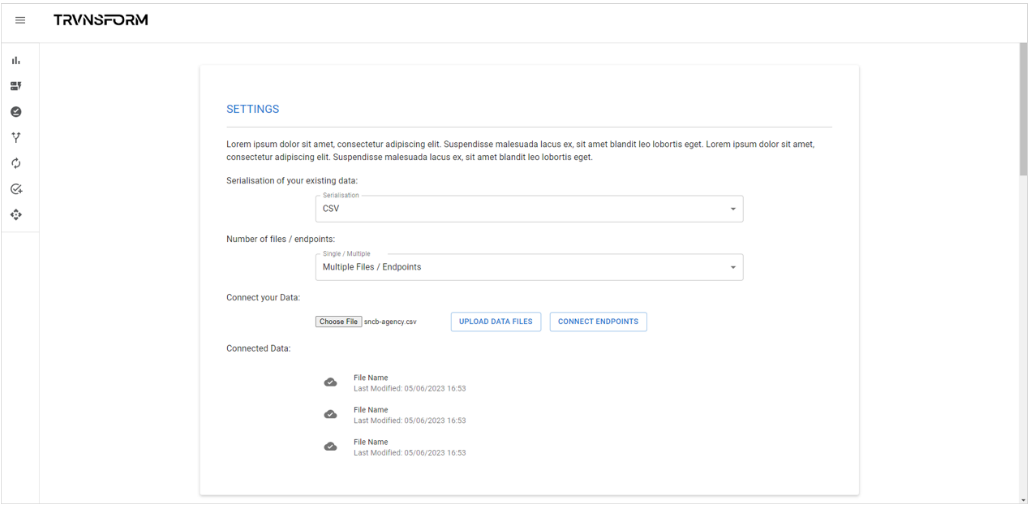

Figure 5.4 Example of data processor settings to upload / connect an operator’s data to a data space

2. Ideally, mobility operators should connect their data over an endpoint to enable realtime updates. However, to accommodate operators with lower technological maturity, a data dump can also be enabled. The settings chosen by the operator sets out how the their data will be processed. The

settings shown in Figure 5.4 are an example of the fields an operator can define that would alter how their data can be processed when uploaded or connected to a data space.

3. Instead of converting between data formats for an entire dataset, this approach recommends only the alignment of headers in a dataset. This would avoid imposing a specific syntax on an operator in order to connect to a dataset but also prevent the conversion of entire databases to a different syntax which presents a risk of data loss. An expansion of the Serialisation dropdown is shown in Figure 5.5 as an example. This, however, will require the continuous development of additional functionality to accommodate more data formats. Though this is not perceived to be a major blocker as there already exists a number of libraries that support conversions and extractions of headers including the OpenRefine [8] platform which is a powerful tool for cleaning and transforming different types of data.

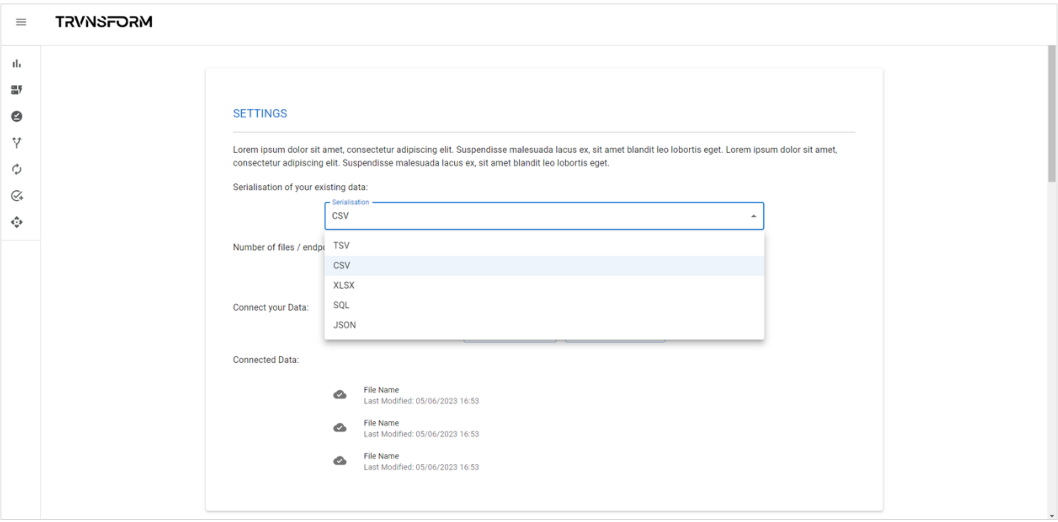

Figure 5.5 Example of user interface for choosing different data serialisations

4. Once the headers are retrieved from the data set, they are listed down for the operator to align them with fields in the required standard, in this case GTFS. Based on this process, the operator does not need to follow GTFS in their internal database which allows them to retain additional richness and granularity in their data that may not be offered by GTFS whilst aligning their data to GTFS. In figure 5.6, the user interface allows the operator to choose which header retrieved from the preceding step aligns with which field in GTFS.

---

[8]https://openrefine.org/

```
const getHeaders = (csvFile, jsonFile) => {
    console.log(csvFile, jsonFile);

    d3.csv(csvFile).then((csvResponse) => {
      console.log(csvResponse);
      const csvHeaders = csvResponse.columns;
      const keys = extractKeys(jsonFile);
      console.log(keys);

      const uniqueValues = new Set();

      for (let i = 0; i < keys.length; i++) {
        const value = keys[i].replace(/"/g, ""); // Remove the quotes
        if (isNaN(value)) {
          // Check if the value is not a number
          uniqueValues.add(value); // Add the value to the Set object
        }
      }

      const jsonHeaders = [...uniqueValues];
      const allHeaders = [...csvHeaders, ...jsonHeaders];
      setHeaders(allHeaders);
      console.log(allHeaders);
    });

    function extractKeys(obj) {
      let keys = [];
      for (let key in obj) {
        keys.push(key);
        if (typeof obj[key] === "object") {
          keys = keys.concat(extractKeys(obj[key]));
        }
      }
      return keys;
    }
  };
```

listing 5.1: Example of retrieving headers from a CSV file

5. When the operator completes the alignment of their data to GTFS, a number of different processes can be triggered through the submission button. First, the development of an RDF Mapping is recommended which will allow the conversion of the data from its current format to RDF. The RML [9] Specification is a suitable mapping language as it already supports a variety of formats including XML, CSV, TSV, JSON, including data from SQL databases. The code listing below shows an example of how an RML mapping can take inputs from the headers where this mapping can be stored for the conversion of the data into RDF. Aside from developing a mapping, the aligned headers can be used as inputs for any import codes into databases that would automate the translation of the correct entities into the database according to the standard aligned to. In addition, the alignment can be used to produce a GTFS feed for the operator to be published on their

[8]https://openrefine.org/

respective servers. This approach to aligning the headers allows the alignment of headers from different files across the database of the operator onto the different sections of the standard. Through these possible outcomes, modularity, alignment, and customisation all become inherent features of the entry process to a mobility data ecosystem. It would be upto the stakeholders setting up a Mobility Data Space to define the optimal requirements according to the business case.

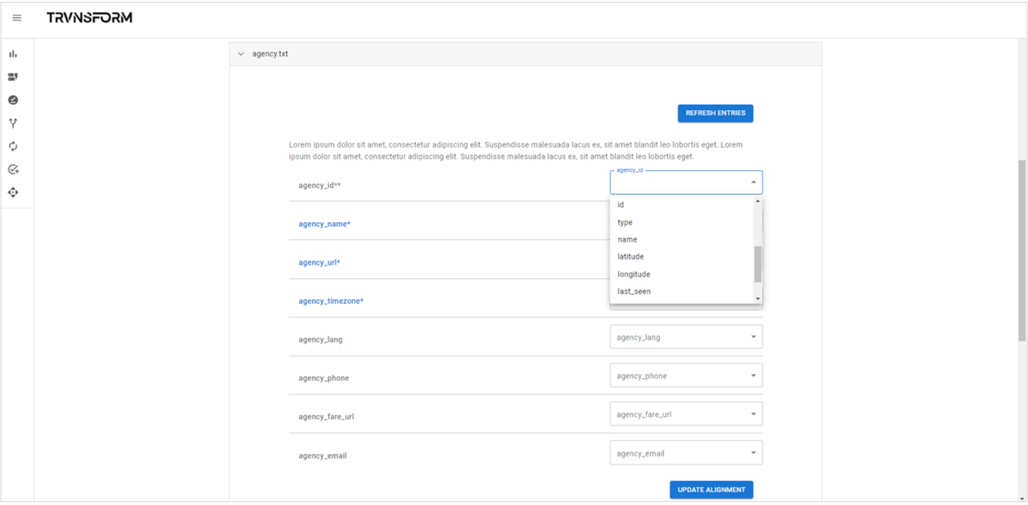

Figure 5.6 Example of user interface for aligning operator's data with GTFS

```
const updatedMapping = `
        @prefix rr: <http://www.w3.org/ns/r2rml#> .
        @prefix foaf: <http://xmlns.com/foaf/0.1/> .
        @prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
        @prefix rml: <http://semweb.mmlab.be/ns/rml#> .
        @prefix ql: <http://semweb.mmlab.be/ns/ql#> .
        @prefix gtfs: <http://vocab.gtfs.org/terms#> .
        @prefix dct: <http://purl.org/dc/terms/> .
        @prefix geo: <http://www.w3.org/2003/01/geo/wgs84_pos#> .
        @prefix csvw: <http://www.w3.org/ns/csvw#> .
        @prefix rmlt: <http://semweb.mmlab.be/ns/rml-target#> .
        @prefix formats: <http://www.w3.org/ns/formats/> .

        @base <http://example.com/base/> .

        <#TargetAgency> a rmlt:LogicalTarget;
          rmlt:target [ a void:Dataset;
            void:dataDump <"${props.outputURL}">;
          ];
          rmlt:serialization formats:Turtle;
        .
```

```
<#AgencyGTFSSource> a csvw:Table;
  csvw:url "${props.inputURL}";
  csvw:dialect [ a csvw:Dialect;
    csvw:trim "true"^^xsd:boolean;
  ];
.

<#TriplesMapGTFSAgency> a rr:TriplesMap;
  rml:logicalSource [
    rml:source <#AgencyGTFSSource>;
    rml:referenceFormulation ql:CSV;
  ];

  rr:subjectMap [
    rr:template "${props.uniqueIdentifier}";
    rr:termType rr:IRI;
    rr:class gtfs:Agency;
    rml:logicalTarget <#TargetAgency>;
  ];

  rr:predicateObjectMap [
    rr:predicate gtfs:timeZone;
    rr:objectMap [
      rml:reference "${props.agencyTimezone}";
    ]
  ];

  rr:predicateObjectMap [
    rr:predicate foaf:name;
    rr:objectMap [
      rml:reference "${props.agencyName}";
    ]
  ];

  rr:predicateObjectMap [
    rr:predicate foaf:mbox;
    rr:objectMap [
      rml:reference "${props.agencyEmail}";
    ]
  ];

  rr:predicateObjectMap [
    rr:predicate dct:language;
    rr:objectMap [
      rml:reference "${props.agencyLang}";
```

[9] https://rml.io/

```
        ]
      ];

      rr:predicateObjectMap [
        rr:predicate foaf:page;
        rr:objectMap [
          rml:reference "${props.agencyURL}";
          rr:termType rr:IRI;
        ]
      ];

      rr:predicateObjectMap [
        rr:predicate gtfs:fareUrl;
        rr:objectMap [
          rml:reference "${props.agencyFareURL}";
          rr:termType rr:IRI;
        ]
      ];
    .`;
```

listing 5.2: Example of an RML Mapping for GTFS Agency file

6. An authentication layer is required to top the data of the operator allowing them to configure who can access what kind of data. The Mobility Profile can define the access rules required for each layer where, for example, only stakeholders involved in a payment transaction can have access to the payment data. These rules can be defined using the Web Access Control (WAC)[10] Specification which uses terms from the Access Control Lists (ACLs) ontology to define the permissions associated with various agents. Different access modes include `acl:Read` , `acl:Write` , `acl:Append` , and `acl:Control` . These modes are attached to resources and attribute to different agents such as groups, users, applications, etc.

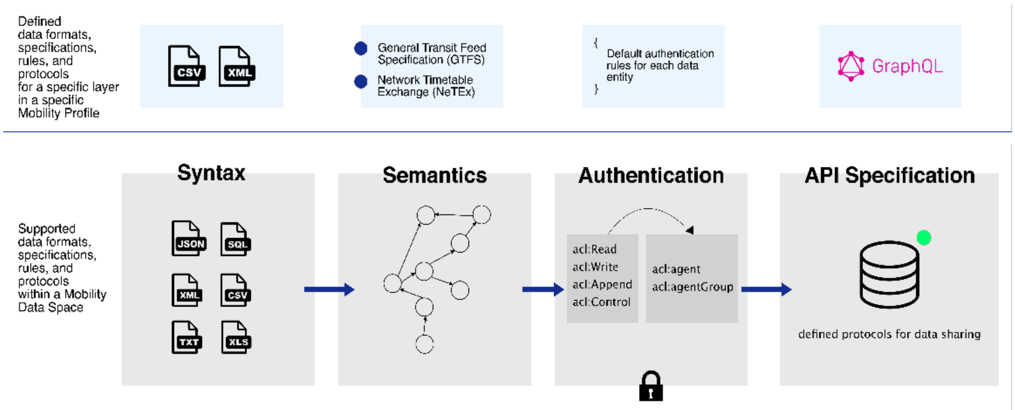

Figure 5.7 An example of defining the fundamental specification elements for each layer in a Mobility Profile

[10]https://solid.github.io/web-access-control-spec/

Through the steps above, the modularity, customisation, and alignment were highlighted discussing potential benefits of adopting each step and how it aligns with the interoperability requirements. The illustration in Figure 5.7 summarises the elements discussed through these steps which become the fundamental items that the stakeholders must define for each layer in a Mobility Profile.

5.1 Conclusions

In this Chapter, the interoperability requirements outlined in the roadmap developed in chapter 4 were revisited, leading to a set of characteristics to improve the data exchange for MaaS:

a) Standardisation

b) Modularity

c) Alignment

d) Customisation

The characteristics were described with the recommendation to utilise Semantic Web Technologies in the construction of data ecosystems for mobility given their inherent features of enabling machine-readability, open standardisation, and hence, enhanced interoperability.

Following this, an exploration into the present status of endeavors related to standardisation and regulation of data exchange for MaaS data is conducted. The review concluded that there is a gap in standardising the entry of mobility operators into a Mobility Data Space (MDS) as these are currently developed independently where a set of stakeholders define the appropriate data models to be used in their data space. Therefore, this will lead to the development of silo-ed data spaces within the mobility domain, expanding the size of the current walled gardens instead of eliminating the barriers to interoperation.

To address this challenge, a review of the existing data standards was conducted to develop a taxonomy that can standardise how the data of a mobility operator can be categorised to define their requirements for entry into a data space. The review led to the derivation of 5 layers: Planning, Drivers, Booking, Ticketing, and Payment. Under each layer, the different types of operation cases were defined. The taxonomy was validated against a complete list of mobility services available in the city of Moscow. A comparison between the Mobility Profiles and other taxonomies in the literature was carried out, highlighting potential synergies and the novelty of the Mobility Profiles Taxonomy. At the end of subsubsection 5.2.3, the implications and limitations of the taxonomy were dicsussed, emphasising on the need to develop a machine-readable version of the taxonomy to enable its use in data structures and architectures for the automation of processes.

Due to time constraints, the development of a machine-readable version was not feasible within the duration of this research, however, the modularity, customisation, and alignment features were examined with the potential benefits of a machine-readable version taken into account. This outlined a process which begins by defining standards for each layer based on the operator's Mobility Profile, followed by enabling connectivity options such as real-time endpoints or data dumps to cater to varying technological capabilities. Rather than converting entire datasets, the approach focuses on aligning headers, allowing operators to retain data richness while adhering to standards like GTFS. This alignment process is facilitated through user-friendly interfaces, empowering operators to map their data to standard fields efficiently. Subsequently, various processes can be triggered, including RDF mapping for data conversion and import codes generation for database integration. Additionally, the workflow incorporates an authentication layer to regulate data access based on defined rules, ensuring security and privacy.

Stakeholders can adopt this process to meet the interoperability requirements defined in chapter 4 and adapt to meet their business requirements. The process explored the incorporation of different Semantic Web Technologies to enhance the modularity and customisation of connecting an operator's dataset into a data ecosystem. The process defined 4 core elements that should be specified for each Mobility Profile:

1. Syntax
2. Semantics
3. Authentication Rules
4. API Specification

It is envisaged that the Mobility Profiles will be set at a Global level for syntax and semantics. This is because the definition of these elements are not exclusive where an operator can pick whichever syntax or semantics to align with from the possible options. For the authentication rules and API specification, these can be set at a country level where different data regulations may apply.

A holistic view of how the Mobility Profiles and the publishing process fit together as an entry to a data ecosystem is illustrated in Figure 5.8. The figure shows that the operator first chooses the profile that fits with their operational design. The profile will then define for the operator the set of syntax, semantics, rules, and specifications associated with their entry to a data space. The operator can then set up their data using a publishing process where it is recommended to follow similar steps and tools as demonstrated by the prototype described in section 5.3. A similar querying process that is a reverse of Figure 5.7 would enable different parties to query each other's data according to the authentication rules set by the operator.

In conclusion, this chapter proposed a novel solution that has the potential to improve the interoperability between transport operators in a MaaS ecosystem. The solution focuses on alleviating interoperability barriers between operators, opening up the silo-ed data environments and preventing the development of closed data spaces. Further research is required to complete the elements shown in Figure 5.8 where there remains a gap in how users may enter a mobility data ecosystem while retaining control over their data yet retrieving the necessary information to plan and optimise their journey to their personal preferences.

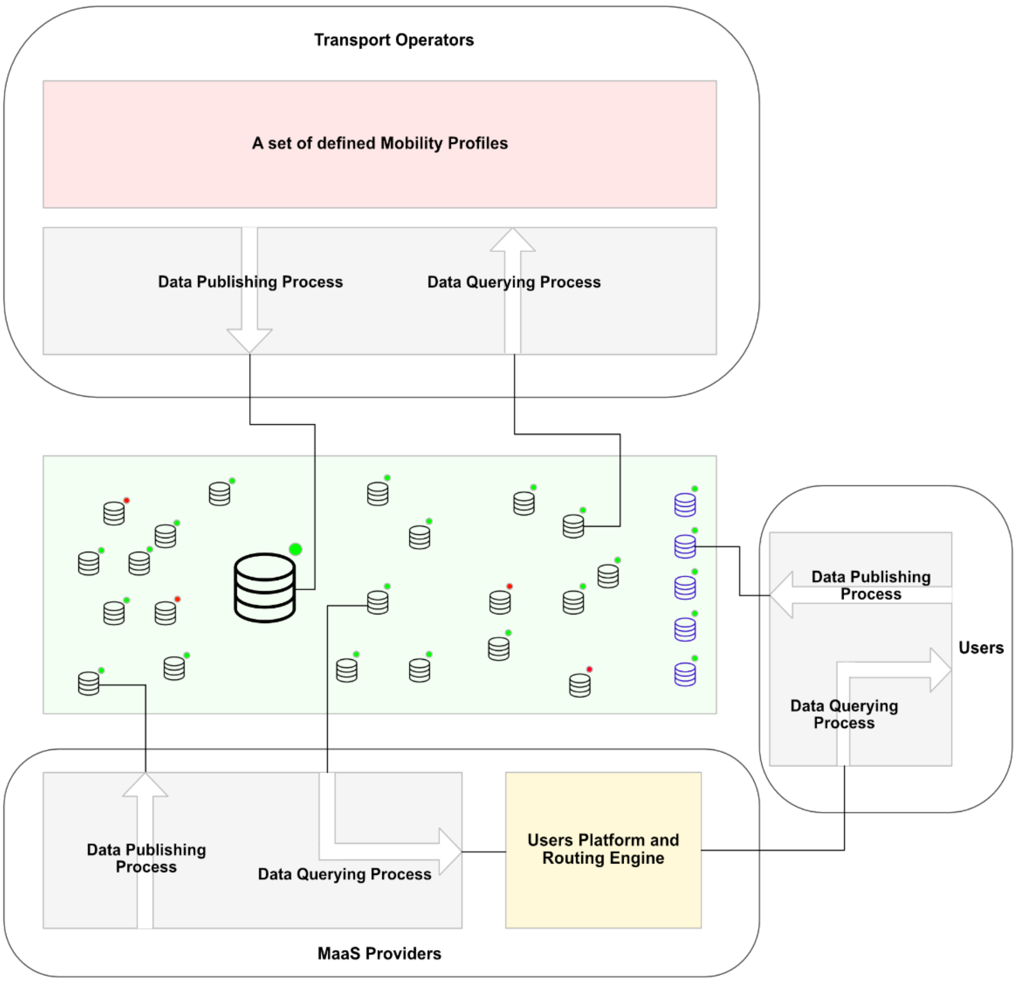

Figure 5.8 Illustration of the Decentralized Data Ecosystem

Chapter 6

6 Conclusions

6.1 Overview

In the final chapter of this study, the key insights and outcomes that have emerged from this research are recapped. The chapter begins by summarizing the key findings that have unfolded in pursuit of achieving the research's aim and objectives. The research contributions are fleshed out, explaining the solution the study puts forward for the research problem, how the outcomes relate to existing theory, and its practical implications. The limitations of the research are acknowledged and a vision is charted for future research endeavors to improve an take the outcomes forward. This chapter provides a definitive cumulation of our academic journey, synthesizing the knowledge we have acquired and identifying the avenues that lie ahead.

6.2 Summary of Research Findings

The aim of this research was to develop a solution that standardises the entry of transport operators into a MaaS data ecosystem. However, the state of literature lacked investigation into the interoperability required for MaaS, and therefore, it was unclear what characteristics the solution needs to possess to address the gap in standardisation. Therefore, a qualitative study was performed that explores the aspect of interoperability in MaaS ecosystems.

Firstly, the research aimed to investigate why stakeholders disagree over the implementation of MaaS. Through the literature review, 9 areas of disagreement were identified as below:

1. **Market Model** - The disagreement arises over whether the market should adhere to an open model, where multiple providers operate independently,

or a broker model, where a single entity coordinates transactions between providers and users.

2. **Modality** – There is disagreement regarding whether MaaS services should prioritize supporting various modes of transportation (intermodal) or if focusing on a single mode (unimodal) is sufficient to meet user needs and preferences.

3. **Features of Intelligent Routing** - Disagreement exists regarding the importance of specific features within intelligent routing for MaaS services, including demand balancing, generating insights on the transport network, and context-aware routing.

4. **Ticketing and Payment Integration** - There is disagreement over the priority between establishing a unified payment method, a unified access method, or a single invoice within MaaS platforms to streamline ticketing and payment processes across different transportation modes.

5. **Booking Features** - Disagreement arises concerning whether MaaS platforms should offer both on-demand booking and booking in advance, with differing opinions on the necessity and practicality of each option.

6. **Geographical Coverage** - The disagreement lies in determining the optimal geographical coverage of a MaaS solution, including the extent of area or region covered and the allocation of resources for expansion.

7. **User Priorities** - - Disagreement surrounds the features, functionalities, and aspects of MaaS solutions that users prioritize, with stakeholders holding differing views on what users find most important or valuable.

8. **Payment Model** - There is disagreement over the preferred payment model for MaaS solutions, with some advocating for subscription-based models while others argue that pay-as-you-go models are more suitable for meeting user needs and market demands.

9. **Auxiliary Services -** Disagreement exists regarding the inclusion of auxiliary services within MaaS platforms, with differing opinions on whether integrating additional services beyond transportation enhances or detracts from the overall user experience.

The findings addressed each area of disagreement providing a rationale behind why these areas exist. This answers the first research question, "**RQ-1:** *What are the disagreements over the implementation of MaaS and what is* *causing them?*". The results show that stakeholders are divided into two mindsets caused buy the different transportation dynamics they are dealing with. The first mindset is **Private car *first*** where participants were approaching MaaS from a perspective of reducing private car reliance. The second mindset is **Public transport *first*** where participants focused on ensuring that personalized shared modes complement spatially efficient modes rather than replace them. These two mindsets governed the rationale behind each area of disagreement. The results of this part of the qualitative study also led to the identification of core characteristics for the implementation of MaaS, namely, open data and open standards, inclusivity of transport operators and mobility providers, offering multiple modes to users, integrating ticketing and payment, and implementing subscriptions. These characteristics are considered to be universal for any service attempting to implement the concept of MaaS.

The research aimed to examine the maturity of MaaS business and data interoperability. Whilst the research is focused on alleviating the gap in data standardisation, business elements were essential to explore due to the role business requirements play in shaping data solutions. The study looked at the following barriers to business and data interoperability, structuring the levels of maturity according to Guédria et al. (2015)'s Maturity Model for Enterprise Interoperability (MMEI).

Business Barriers

1. **Conceptual:** Business Model

2. **Technological:** IT Infrastructure

3. **Organisational:** Common Goal

Data Barriers

1. **Conceptual:** Data Model

2. **Technological:** Data Storage and Access

3. **Organisational:** Data Management

Answering the second research, "**RQ-2:** *What are the current and desired levels of business and data interoperability?*", the results showed the current and desired levels of each of the 6 elements for a sustainable MaaS ecosystem. The analysis of the qualitative data also provided important insights into the current efforts of development for each of the elements above and the issues hindering such development. Influenced by the core characteristics of MaaS implementation and the required levels of maturity of business and data, the analysis of the qualitative study addressed the third research question, "**RQ-3:** *What are the business and data interoperability requirements of a MaaS ecosystem?*", resulting in a set of interoperability requirements for MaaS ecosystems. In addition, to link the required maturity levels with the level of MaaS integration a stakeholder is participating in, an interoperability roadmap was produced to show an alignment that serves as a guidance to stakeholders.

The defined interoperability requirements for data ecosystems provided the research with a clear checklist that data solutions are required to meet to enable an interoperable and sustainable MaaS ecosystem. Based on these requirements, a set of characteristics were defined for the proposed data solution. These characteristics address the fourth research question, "**RQ-4:** *What characteristics must the data exchange process possess in order to meet the requirements?*":

1. **Standardisation -** The requirement for data exchange processes in MaaS to adhere to standardized formats and protocols across different modes of transport, facilitating interoperability by establishing uniform entry points to the ecosystem for data integration.

2. **Modularity** : The requirement for entry points in the MaaS ecosystem to be modular in both syntax and semantics, allowing flexibility to accommodate diverse operators with varying profiles, technological readiness levels, and data formats.

3. **Alignment** : The requirement to align different profiles within the MaaS ecosystem to ensure consistency and interoperability, enabling modularization of syntax and semantics across various data exchange processes and platforms.

4. **Customisation** : The requirement to enable customization within data exchange processes to achieve a balance between flexibility and standardization, allowing operators to tailor their data integration approaches according to their specific needs while adhering to interoperability standards.

Addressing the study's objective to propose a solution for standardising the entry of transport operators into a MaaS data ecosystem, an analysis of prominent data standards and specifications was conducted to derive a list of possible operation cases. Based on these cases, a taxonomy was proposed that consists of 5 layers: Planning, Drivers, Booking, Ticketing, and Payment. Under each layer, the different types of operation cases were defined. The purpose of the taxonomy is to act as a tool for specifying the accepted Syntax, Semantics, Authentication Rules, and API specifications for transport operators. The taxonomy was validated against a complete list of mobility services available in the city of Moscow and a comparison with other taxonomies in the literature was conducted which delineated the novelty of the taxonomy.

As a result of time limitations, creating a machine-readable version proved unattainable during the course of this research. Nevertheless, we thoroughly assessed the modularity, customization, and alignment functionalities, all while considering the potential advantages that a machine-readable version could offer. This delineated a step-by-step procedure that stakeholders can adopt to fulfill the interoperability requirements defined by the qualitative study and to flexibly adapt this process to their unique business needs. The demonstration of this process in section 5.3 achieves the research objective to show the practicality of applying the proposed taxonomy in a data exchange process. The taxonomy and the data flow demonstration address the fifth question, "**RQ-5:** *What data solution would meet the defined characteristics?*", and the final question, "**RQ-6:** *How does the proposed data solution fit within the current data ecosystems?*".

6.3 Research Contributions

6.3.1 Research Outcomes

Over the course of this research, a number of research outcomes were produced. These are categorised into primary and secondary outcomes. The primary outcomes are the result of the objectives of the research and were produced to a degree ready for application. The secondary outcomes are additional contributions offered by the research. The outcomes are listed below:

Primary Outcomes

1. A list of Interoperability requirements for buiness and data interoperability in a MaaS ecosystem.
2. An Interoperability Roadmap that aligns the required levels of interoperability maturity to the required levels of MaaS integration.
3. The Mobility Profiles Taxonomy - a taxonomy which standardises entry to

Mobility Data Spaces by providing a method to define the syntax, semantics, authentication rules, and API specifications based on the operators Mobility Profile.

Secondary Outcomes

1. The rational behind each area of disagreement over the MaaS implementation.
2. The two mindsets on the implementation of MaaS (Private-car first / Public transport first).
3. Core / universal characteristics of any MaaS implementation
4. Key insights into the current levels of maturity, the efforts of development, and the challenges / barriers in both business and data interoperability.
5. A step-by-step process that demonstrates the applicability of the data solution and how to enable modularity, alignment, and customisation in the data flow process of on-boarding operators into a MaaS data ecosystem. The process also shows the potential benefits of incorporating Semantic Web Technologies into the data flow.

6.3.2 Addressing the Research Gap

At the onset of this study, through a comprehensive review of the literature, a gap was identified in the standardisation of how data ecosystems are set up. The review showed that Mobility Data Spaces were setup independently according to the design principles specified by the IDSA which did not include any domain specific guidance. Therefore, it gives the freedom to each Data Space to specify its own syntax, semantics, and data sharing specifications. To prevent the development of silo-ed spaces, this research proposed the Mobility Profiles taxonomy. This taxonomy provides a high level classification that allows attributing transport operators to their relevant Mobility Profile which will specify the recognised syntax and semantics for entering a Data Space. The taxonomy is designed according to the interoperability requirements derived through the qualitative study. These requirements specified that the data solution needs to strike a balance between flexibility and standardisation in order to be adaptive for entry of new types of mobility services. Therefore, the Mobility Profiles were designed to be modular, enabling transport operators to mix and match between the cases of each layer to build the profile that suits them. In addition to the taxonomy, the interoperability requirements and roadmap address a gap in defining these requirements for business and data interoperability of MaaS ecosystems. This gap was essential to address in order to set the groundwork for the development of policies, regulations, contracts, data management rules, and technological solutions.

6.3.3 Research Implications

The results of the qualitative study revealed novel findings that contributes to the existing knowledge base on the implementation of MaaS. The insights into the areas of disagreement over the implementation of MaaS can serve as a foundation for designing effective policies, guidelines, and standards that promote interoperability and foster collaboration among stakeholders. In addition, the research on policy and regulatory frameworks that promote MaaS interoperability is relatively limited. This study provided an interoperability roadmap that contributes to the policies, regulations, and governance structures in fostering interoperable MaaS ecosystems. The roadmap can serve as a guidance or a standard requirement of interoperability maturity for stakeholders in a MaaS ecosystem to follow depending on the level of integration they are participating in. Together with the interoperability requirements, these outcomes lay the foundation for an interoperable MaaS ecosystem.

The benefits of achieving a mature interoperable MaaS ecosystem are extensive. Improved interoperability can lead to enhanced user experiences, reduced congestion, optimized resource allocation, and increased sustainability in urban transportation systems. It can also unlock new business opportunities, encourage innovation, and foster collaboration among public authorities, transport operators, technology providers, and other stakeholders. By providing valuable insights into the current state of MaaS interoperability and its potential for growth, the outcomes of the qualitative investigation catalyze efforts towards creating a truly integrated and efficient mobility ecosystem.

In addition, the Mobility Profiles taxonomy serves as a powerful solution against the development of silo-ed Data Spaces. Defining data models, exchange formats, and API specifications for each profile would enable a) A workaround to imposing a specific standard for all mobility providers,
b) Defining all the standards that fall under the same profile which will show gaps in vertical interoperability, e.g., Both NeTEx and GTFS can be used for T1 + S1 but there is no verified alignment between these two standards, c) Identifying gaps in horizontal interoperability where certain Mobility Profiles are commonly combined together but their data models do not have an alignment, and d) Identifying and prioritising areas and types of operations that do not have

existing standards or specifications. In addition, prominent Mobility Profiles can be used as a basis for standardising contracts which includes data sharing rules, liability and insurance, and other clauses defined according to the layers of the taxonomy.

The data exchange process and overall vision of the MaaS Data Ecosystem presented in chapter 5 supplement the proposed taxonomy by demonstrating the practical application of the taxonomy. The data flow was designed to be modular and enable customisation. This promises an adaptive environment, capable of accommodating new types of stakeholders with the least disruption to the ecosystem. The application of this process with the incorporation of Semantic Web Technologies have the potential to transition MaaS data ecosystems to not only an interoperable but an automated realm of data exchange.

The outcomes of this thesis hold significant potential for both countries already operating Mobility as a Service (MaaS) systems and those that have yet to adopt such systems. For countries already implementing MaaS, the research provides a comprehensive understanding of the interoperability challenges and disagreements among stakeholders, offering insights into the key areas of contention such as market models, modality support, and payment models. By addressing these areas of disagreement and deriving core characteristics essential for MaaS implementation, countries can refine their existing systems, enhance interoperability, and foster collaboration among stakeholders. Additionally, the proposed Interoperability Roadmap offers a practical framework for aligning interoperability maturity levels with MaaS integration levels, enabling countries to set clear guidelines and standards for MaaS ecosystems.

For countries without established MaaS systems, the research serves as a guiding tool for initiating and designing interoperable MaaS ecosystems from the outset. By highlighting the core characteristics necessary for successful MaaS implementation, such as standardization, modularity, alignment, and customization, countries can develop robust frameworks and policies to support the integration of diverse transportation modes and services. Moreover, the Mobility Profiles Taxonomy offers a standardized approach to classifying transport operators data and defining syntax, semantics, and API specifications, providing a blueprint for structuring MaaS data ecosystems.

Overall, the outcomes of this thesis offer valuable insights and practical solutions that can benefit countries at various stages of MaaS development, from initial planning to advanced implementation. By leveraging the research findings and utilising the proposed tools and frameworks, countries can overcome interoperability challenges, enhance user experiences, and promote sustainable mobility solutions tailored to their unique contexts and needs.

6.4 Limitations and Future Recommendations

The qualitative study carried out involved 65 participants sampled through a purposive sampling method which selected experts in the field from a diverse set of professional and geographical backgrounds. The sample size of 65 participants was determined once the qualitative data converged. While the number of participants offered a significant amount of qualitative data, it was not a statistically significant sample for quantitative analysis despite the collection of quantitative data. It would be beneficial to collect further quantitative data to uncover insights from categorical and relationship analysis that would ground differences in views based on professional backgrounds or geographical expertise. In addition, interviewing experts yielded a rich and comprehensive view over the disagreements in implementation and interoperability requirements, however, the insights miss out on the effect of the perception of non-experts that may demonstrate further rationale behind the barriers facing MaaS. Another limitation of the sampling method was the diversification of the sample. Whilst this brought on a universal perspective on each research question, it may have missed on the local intricacies of each location. It is recommended that future research takes a deeper dive into each country's interoperability requirements and the applicability of the derived core characteristics of MaaS implementation.

In the interpretation of the qualitative results, it is important to acknowledge the presence of potential research bias as a limitation. Despite exercising all efforts to minimise its impact, it may have influenced some aspects of the findings. For example, a different researcher may have provided a different discussion of the rationale behind the disagreement over the Market Model. Despite this limitation, the consistent patterns and trends observed throughout the study suggest that the results remain robust and credible. Nevertheless, the complete set of results were included in chapter 4 to enable complete transparency over the original qualitative data.

Aside from the research method, the scope of the qualitative study was limited to two areas of interoperability: Business and Data. The barriers investigated were also limited to Conceptual, Technical, and Organisational. It is recommended that further research is conducted to explore Service and Process interoperability whilst investigating the legal barriers across all 4 areas of interoperability.

Due to the time constraints of the research, the taxonomy was not developed into a machine-readable version. Such version would enable the practical use of the taxonomy in automating data workflows according to standards set in a Mobility Profile. Therefore, further work is required to develop a machine-readable version of the Mobility Profiles taxonomy. The taxonomy was validated by verifying its coverage over a complete list of mobility services from the city of Moscow. This, however, is a limited validation that only verifies the coverage extent of the taxonomy. Further validation is required through methods such as an experts review or data experiments to ensure the applicability of this taxonomy.

In terms of the scope of the taxonomy, it was limited to only covering the cases of transport operators. This scope is sufficient to address the research gap, however, it is highly recommended that an extension of the taxonomy is developed for the definition of user (travelers) profiles. This is to account for the standardisation in syntax, semantics, and data authentication and exchange rules of users' personal information, preferences, accessibility, etc. In addition, the scope does not include factors affecting the journey, such as transfers between stations, parking availability, etc. An investigation into the elimination of these factors is recommended to ensure the practicality of the taxonomy.

Finally, whilst the research puts forward a solution designed according to the requirements of the ecosystem, no quantifiable measurement was taken to demonstrate the benefits to data interoperability. It is recommended that further research experiments a full data workflow using the machine-readable version of the taxonomy to identify whether the modularity, customisation, and alignment characteristics provide significant benefits to existing workflows. In addition, Further research should conduct case studies that apply both the derived interoperability requirements and the Mobility Profiles taxonomy to comprehensively evaluate their effectiveness in enhancing data exchange and interoperability within the Mobility as a Service (MaaS) ecosystem.

6.5 Closing Summary

In closing, this study has navigated a complex landscape of interoperability within Mobility as a Service (MaaS) ecosystems, addressing the challenges and disparities that stakeholders encounter in their pursuit of seamless data exchange. The research journey began with a qualitative exploration of the disagreements and requirements surrounding MaaS implementation, leading to the identification of core characteristics for successful implementation. These characteristics were then translated into the innovative Mobility Profiles Taxonomy, offering a comprehensive solution to standardize the entry of transport operators into

MaaS data ecosystems. The taxonomy, coupled with an interoperability roadmap, has the potential to pave the way for a more inclusive and harmonious MaaS environment.

Furthermore, the study uncovered the current state and desired levels of business and data interoperability, providing valuable insights into the challenges and efforts of development. It also contributed to the foundational understanding of policy and regulatory frameworks necessary for fostering interoperable MaaS ecosystems. The proposed data exchange process, enriched by the integration of Semantic Web Technologies, exemplifies the practicality of applying the Mobility Profiles Taxonomy, promising a future of adaptable and automated data exchange.

Nevertheless, the research journey is not without its limitations. The sample size of the qualitative study, although rich in insights, was not statistically significant, and the potential presence of research bias must be acknowledged. Additionally, the taxonomy remains in need of further development into a machine-readable version to truly realize its potential benefits.

Looking ahead, this study offers a roadmap for future research endeavors, encouraging deeper dives into regional intricacies, user profiles, and additional areas of interoperability such as service and process interoperability. Quantitative measurements are also recommended to assess the practical impact of the proposed taxonomy on data workflows.

In summation, this research has made significant strides in advancing the understanding and practical implementation of interoperability in MaaS ecosystems. By offering innovative solutions and insights, it has laid the groundwork for more seamless and inclusive mobility systems in the future. The thesis contributes to the guidance for any set of stakeholders looking to initiate a MaaS solution in their region.

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APPENDIX A

Mixed Method Study - Questionnaire

The questionnaire used in the mixed method study is attached in this appendix.

MaaS Interoperability

Start of Block: Default Question Block

Q1 Defining Interoperability in Mobility-as-a-Service (MaaS)

Our research team is honored to have you as part of this study. Through your expertise, the research aims to develop a complete understanding of the interoperability problem faced throughout the implementation of Mobility-as-a-Service (MaaS) solutions. We are exploring the understanding from the point of view of different MaaS stakeholders.

All information provided and identity will be kept confidential and strictly used for academic purposes only.

This research is organized and funded by the University of Nottingham, Malaysia. If you have any questions, please contact Shams Ghazy keey6ske@nottingham.edu.my

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Q2
Please leave your **email** in the field below. (Work email is preferred)

____

Q43 Would you like to remain anonymous?

▼ Yes (1) ... No (3)

Q55 Please select what type of MaaS stakeholder best describes you?

- ☐ Transport (MaaS provider, Mobility-service provider, Transport operator, etc.) (1)
- ☐ Regulation & Planning (Public Authority, Policy Director, Enabler Group, City Planners, etc.) (2)
- ☐ Research (Academic & Research institutes, universities, etc.) (3)
- ☐ Financial (Insurance, Investor, etc.) (5)
- ☐ Technology & Data (IT infrastructure, Third-party routing, Payment solutions, Data provider, etc.) (4)
- ☐ Other (7) ____

Display This Question:

If Please select what type of MaaS stakeholder best describes you? = Transport (MaaS provider, Mobility-service provider, Transport operator, etc.)

Q3 How would you describe your firm?

- ☐ MaaS provider (1)
- ☐ Ride Coordinator (2)
- ☐ Fleet Manager (4)
- ☐ Fixed Route Operator (5)
- ☐ Manufacturer (6)
- ☐ Other (3) ____

Display This Question:

If How would you describe your firm? = MaaS provider

Q57 What modes of transport are offered on your service?

- ☐ Car Rental/Car-Sharing (1)
- ☐ Train/Metro/Rail (4)
- ☐ Bus (5)
- ☐ Bike Rental (2)
- ☐ Taxi/Car-hailing (3)
- ☐ Ferry (6)
- ☐ E-scooter (7)
- ☐ Other (8) ____

Q42 If applicable, please describe your background.

- ○ Management (1)
- ○ Technical (2)
- ○ Other (3) ____

Q48 Which country are you based in?

____

Q51 Region type:

- ○ predominantly urban region (1)
- ○ intermediate region (2)
- ○ predominantly rural region (3)

Q4 How many years of experience do you have in your field?

- ○ 0 to 10 (4)
- ○ 11 to 20 (5)
- ○ 21 to 30 (6)
- ○ >30 (7)

Q49 Gender:

- ○ Male (1)
- ○ Female (2)
- ○ Other (3)

Q50 Age:

- ○ <20 (1)
- ○ 20 to 30 (2)
- ○ 31 to 40 (3)
- ○ 41 to 50 (4)
- ○ 51 to 60 (6)
- ○ >61 (5)

Q52 What is your understanding of MaaS? What do you think of the interoperability problem?

____

Page Break

Q5 **Section 1 of 3:** Prioritizing MaaS System Characteristics

Please read the following explanations of the characteristics before proceeding to the questions.

(a) "Single Platform with aggregated transport modes"

1) Single Platform with a broker model (variety of modes - vertical integration)
2) Single Platform with an open market (majority of mobility opportunities in a region - horizontal integration)

(b) "Journey Planner intermodality"
3) Journey Planner - multimodal
4) Journey Planner - intermodal

(c) "Data Analytics and Intelligent Routing"
5) Intelligent routing - balancing demand (on different modes)
7) Intelligent routing - generating insights (demands, needs, and travel behaviors)
8) Intelligent routing - real time factors and context-awareness (factors in real-time information that affects a route)

(d) *"Route scheduling"*
9) On-demand mobility
10) Scheduled mobility

(e) *"Ticketing & Payment Integration"*
11) One payment method for all modes (online banking/credit card/etc.)
12) One access method for all modes (ticketing method like a smartcard/watch/etc.)
13) One invoice per trip

(f) "Mobility Packages"
14) Payment - Pay-as-you-go or post-paid for all modes on the platform
15) Payment - Personalized Bundles/Subscriptions or pre-paid

(g) "*Multi-Services*"
16) Multi-Services MaaS apps (Delivery of goods and necessities, logistics transportation)
17) Multi-Services as an add-on to MaaS apps

(h) *"Geographical coverage"*
18) City-wide
19) National
20) Continental
21) Inter-continental

In this section, the above characteristics are compared to each other according to their level of importance as a MaaS characteristic. In order to compare the options, you can think of the question "Which one is more representative of the definition of MaaS and why?"

Q59 Which of a broker model vs an open market is more representative of a MaaS Single Platform?
A broker model is ___________ *of MaaS than an open market.*

- ○ Strongly less representative (1)
- ○ Less representative (4)
- ○ Slightly less representative (5)
- ○ Equally representative (6)
- ○ Slightly more representative (7)
- ○ More representative (8)
- ○ Strongly more representative (9)

Q65 Which level of modality is more representative of MaaS?
A unimodal journey planner is ___________ of MaaS than an intermodal journey planner.

- ◯ Strongly less representative (1)
- ◯ Less representative (4)
- ◯ Slightly less representative (5)
- ◯ Equally representative (6)
- ◯ Slightly more representative (7)
- ◯ More representative (8)
- ◯ Strongly more representative (9)

Q48 Which **capability of intelligent routing** is more representative of MaaS?

	3 (3)	2 (4)	1 (5)
Balancing demand to all modes (4)	◯	◯	◯
Generating insights (6)	◯	◯	◯
Real time factors and context-aware routing (7)	◯	◯	◯

Q41 Which **ticketing and payment integration** is more representative of MaaS?

	3 (1)	2 (2)	1 (3)
unified payment method (1)	◯	◯	◯
unified access method (4)	◯	◯	◯
single invoice (5)	◯	◯	◯

Q64 Which **type of scheduling** is more representative of MaaS?
The ability to book transport on demand is ___________ of MaaS than scheduling transport in advance.

- Strongly less representative (1)
- Less representative (4)
- Slightly less representative (5)
- Equally representative (6)
- Slightly more representative (7)
- More representative (8)
- Strongly more representative (9)

Q47 Which **geographical coverage** is more representative of MaaS?

	4 (1)	3 (2)	2 (9)	1 (3)
City-wide / State-wide (1)	○	○	○	○
National (4)	○	○	○	○
Continental (5)	○	○	○	○
Inter-continental (8)	○	○	○	○

Q49 Which of the following is more important to **users of MaaS**?

	3 (2)	2 (9)	1 (3)
Data Privacy & Security (1)	○	○	○
Pricing and Packages (4)	○	○	○
Personalized routing (5)	○	○	○

Q63 Which type of package is more representative of MaaS?
The ability to pay-as-you-go (post-paid) for all modes is __________ of MaaS than personalized bundles/subscriptions (pre-paid).

- ○ Strongly less representative (1)
- ○ Less representative (4)
- ○ Slightly less representative (5)
- ○ Equally representative (6)
- ○ Slightly more representative (7)
- ○ More representative (8)
- ○ Strongly more representative (9)

Q45 Which understanding of transportation of goods is more representative of MaaS?
Building MaaS apps for delivery of goods and logistics is ___________ of MaaS than goods delivery being an add-on to passenger MaaS apps.

- Strongly less representative (1)
- Less representative (4)
- Slightly less representative (5)
- Equally representative (6)
- Slightly more representative (7)
- More representative (8)
- Strongly more representative (9)

Q6 Compare the importance of the following MaaS characteristics:

	6 (2)	5 (12)	4 (3)	3 (5)	2 (11)	1 (6)
Single Platform with aggregated transport modes (6)	○	○	○	○	○	○
Journey Planner/Routing (5)	○	○	○	○	○	○
Ticketing & Payment Integration (7)	○	○	○	○	○	○
Mobility Packages (8)	○	○	○	○	○	○
Multi-services (4)	○	○	○	○	○	○
User Preferences (10)	○	○	○	○	○	○

Page Break

Q16 **Levels of Interoperability**

The following diagram explains the 5 levels of interoperability, according to the Maturity Model for Enterprise Interoperability (MMEI) (2015), which will be referred to for the rest of the questionnaire. Please read through the descriptions before moving forward. **The questions are asked regarding the ecosystem of MaaS in general and not your specific organization.**

Q17

Page Break

Q18
Section 2 of 3: Evaluating Business Interoperability of MaaS

In this section, you will evaluate the current and desired level of Business interoperability in MaaS.
Business interoperability refers to the ability to work in a harmonized way and to share and develop business between companies despite the difference of methods, decision-making, culture of enterprises, etc.

definitions:
A **business model** describes the rationale of how an organization creates, delivers, and captures value.
IT infrastructure include hardware, software, networking components, an operating system (OS), and data storage, all of which are used to deliver IT services and solutions.

Q19 In your opinion, what is the **current** conceptual level of MaaS' business interoperability?
(Not Achieved = We are at a lower stage than this,
Fully Achieved = We have passed this stage)

	Not Achieved (1)	Partially Achieved (2)	Largely Achieved (3)	Fully Achieved (4)
Level 0 - Business model NOT explicitly modelled or documented (1)	○	○	○	○
Level 1 - Business model is explicitly modelled or documented (2)	○	○	○	○
Level 2 - Use of standards for alignment with other models (3)	○	○	○	○
Level 3 - Business models for multi partnership and collaborative enterprise (4)	○	○	○	○
Level 4 - Adaptive business model (5)	○	○	○	○

Q20 In your opinion, what is the **desired conceptual** level of MaaS' business interoperability?

○ Level 0 - Business model NOT explicitly modelled or documented (1)

○ Level 1 - Business model is explicitly modelled or documented (2)

○ Level 2 - Use of standards for alignment with other models (3)

○ Level 3 - Business models for multi partnership and collaborative enterprise (4)

○ Level 4 - Adaptive business model (5)

Q21 In your opinion, what is the **current** technological level of MaaS' business interoperability? (Not Achieved = We are at a lower stage than this,
Fully Achieved = We have passed this stage)

	Not Achieved (1)	Partially Achieved (2)	Largely Achieved (3)	Fully Achieved (4)
Level 0 - No or unreliable IT infrastructure (1)	○	○	○	○
Level 1 - Basic IT infrastructure in place (2)	○	○	○	○
Level 2 - Standard and configurable IT infrastructures (3)	○	○	○	○
Level 3 - Open IT infrastructure (4)	○	○	○	○
Level 4 - Adaptive IT infrastructure (5)	○	○	○	○

Q22 In your opinion, what is the **desired** technological level of MaaS' business interoperability?

- ○ Level 0 - No or unreliable IT infrastructure (1)
- ○ Level 1 - Basic IT infrastructure in place (2)
- ○ Level 2 - Standard and configurable IT infrastructures (3)
- ○ Level 3 - Open IT infrastructure (4)
- ○ Level 4 - Adaptive IT infrastructure (5)

Q23 In your opinion, what is the **current** organizational level of MaaS' business interoperability? (Not Achieved = We are at a lower stage than this,
Fully Achieved = We have passed this stage)

	Not Achieved (1)	Partially Achieved (2)	Largely Achieved (3)	Fully Achieved (4)
Level 0 - No common goal (1)	○	○	○	○
Level 1 - Common goal is not well defined (2)	○	○	○	○
Level 2 - Common goal is well defined but not agreed upon by stakeholders (3)	○	○	○	○
Level 3 - Some stakeholders agree and work towards common goal (4)	○	○	○	○
Level 4 - All stakeholders understand, agree, and work towards common goal (5)	○	○	○	○

Q24 In your opinion, what is the **desired organizational** level of MaaS' business interoperability?

○ Level 0 - No common goal (1)

○ Level 1 - Common goal is not well defined (2)

○ Level 2 - Common goal is well defined but not agreed upon by stakeholders (3)

○ Level 3 - Some stakeholders agree and work towards common goal (4)

○ Level 4 - All stakeholders understand, agree, and work towards common goal (5)

Page Break

Q39

Section 3 of 3: Evaluating Data Interoperability of MaaS

In this section, you will evaluate the current and desired level of Data interoperability in MaaS.
Data interoperability refers to enabling different data models with different query languages, sharing information coming from heterogeneous systems, to work together efficiently.

definitions:
A **data model** is an abstract model that organizes elements of data and standardizes how they relate to one another and to the properties of real-world entities. For instance, a data model may specify that the data element representing a car be composed of a number of other elements which, in turn, represent the color and size of the car and define its owner.
Data management is an administrative process that includes acquiring, validating, storing, protecting, and processing required data to ensure the accessibility, reliability, and timeliness of the data for its users.

Q40 In your opinion, what is the **current** conceptual level of MaaS' data interoperability? (Not Achieved = We are at a lower stage than this,
Fully Achieved = We have passed this stage)

	Not Achieved (1)	Partially Achieved (2)	Largely Achieved (3)	Fully Achieved (4)
Level 0 - Data models NOT explicitly modelled or documented (1)	○	○	○	○
Level 1 - Data model is explicitly modelled or documented (2)	○	○	○	○
Level 2 - Use of standards for alignment with other models (3)	○	○	○	○
Level 3 - Meta-modelling for multiple model mappings (4)	○	○	○	○
Level 4 - Adaptive data models (both syntax and semantics) (5)	○	○	○	○

Q41 In your opinion, what is the **desired conceptual** level of MaaS' data interoperability?

- ○ Level 0 - Data models NOT explicitly modelled or documented (1)
- ○ Level 1 - Data model is explicitly modelled or documented (2)
- ○ Level 2 - Use of standards for alignment with other models (3)
- ○ Level 3 - Meta-modelling for multiple model mappings (4)
- ○ Level 4 - Adaptive data models (both syntax and semantics) (5)

Q42 In your opinion, what is the **current** technological level of MaaS' data interoperability?
(Not Achieved = We are at a lower stage than this,
Fully Achieved = We have passed this stage)

	Not Achieved (1)	Partially Achieved (2)	Largely Achieved (3)	Fully Achieved (4)
Level 0 - No or closed data storage devices, manual exchange (1)	○	○	○	○
Level 1 - Data storage devices connectable, simple electronic exchange possible (2)	○	○	○	○
Level 2 - Automated access to data, based on standard protocols (3)	○	○	○	○
Level 3 - Remote access to databases possible for applications, shared data (4)	○	○	○	○
Level 4 - Direct database exchanges capability and full data conversion tool (5)	○	○	○	○

Q43 In your opinion, what is the **desired** technological level of MaaS' data interoperability?

- Level 0 - No or closed data storage devices, manual exchange (1)
- Level 1 - Data storage devices connectable, simple electronic exchange possible (2)
- Level 2 - Automated access to data, based on standard protocols (3)
- Level 3 - Remote access to databases possible for applications, shared data (4)
- Level 4 - Direct database exchanges capability and full data conversion tool (5)

Q44 In your opinion, what is the **current** organizational level of MaaS' data interoperability?
(Not Achieved = We are at a lower stage than this,
Fully Achieved = We have passed this stage)

	Not Achieved (1)	Partially Achieved (2)	Largely Achieved (3)	Fully Achieved (4)
Level 0 - Data responsibilities and authorities not explicitly defined (1)	○	○	○	○
Level 1 - Responsibilities/authorities defined and in place (2)	○	○	○	○
Level 2 - Rules and methods for data management (3)	○	○	○	○
Level 3 - Personalized data management for different partners (4)	○	○	○	○
Level 4 - Adaptive data management rules and methods (5)	○	○	○	○

Q45 In your opinion, what is the **desired organizational** level of MaaS' data interoperability?

- ○ Level 0 - Data responsibilities and authorities not explicitly defined (1)
- ○ Level 1 - Responsibilities/authorities defined and in place (2)
- ○ Level 2 - Rules and methods for data management (3)
- ○ Level 3 - Personalized data management for different partners (4)
- ○ Level 4 - Adaptive data management rules and methods (5)

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