New Mobility Options and Urban Mobility

Challenges and Opportunities for Transport Planning and Modelling

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815069.

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Summary sheet

Deliverable No.	2.1
Project Acronym	MOMENTUM
Full Title	Modelling Emerging Solutions for Urban Mobility
Grant Agreement No.	815069
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Quality Assurance Committee Review	General Assembly
Date	21/11/2019
Status	Draft
Dissemination level	Public

Abstract	This document reviews recent disruptive changes in transport caused by new transport technologies and identifies the challenges and opportunities for sustainable urban mobility planning brought about by these innovations. The document delivers a series of future scenarios to reflect upon the evolution of these emerging mobility solutions and analyses to what extent transport planning tools and techniques, i.e. data sources, transport models and decision support tools, are prepared to cope with the upcoming trends in urban mobility.
Version	Issue 1 Draft 4
Work Package No.	2
Work Package Title	Conceptual framework and problem definition
Programme	Horizon 2020
Coordinator	EMT Madrid
Website	www.h2020-momentum.eu
Starting date	01/05/2019
Number of months	36

Project partners

Organisation	Country	Abbreviation
EMPRESA MUNICIPAL DE TRANSPORTE DE MADRID SA	Spain	EMT
NOMMON SOLUTIONS AND TECHNOLOGIES SL	Spain	NOMMON
DIMOS THESSALONIKIS	Greece	THESS
ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	Greece	CERTH
STAD LEUVEN	Belgium	LEUVEN
TRANSPORT & MOBILITY LEUVEN NV	Belgium	TML
STADT REGENSBURG	Germany	REGENSBURG
TECHNISCHE UNIVERTITAET MUENCHEN	Germany	TUM
AIMSUN SL	Spain	AIMSUN SL
POLIS – PROMOTION OF OPERATIONAL LINKS WITH INTEGRATED SERVICES, ASOCIATION INTERNATIONALE	Belgium	POLIS
UNION INTERNATIONALE DES TRANSPORTS PUBLICS	Belgium	UITP
UNIVERSIDAD DE LA IGLESIA CATÓLICA DE DEUSTO ENTIDAD RELIGIOSA	Spain	UDEUSTO

Document history

Version	Date	Organisation	Main area of changes	Comments
Issue 1 Draft 1	21/11/2019	NOMMON	Initial draft	
Issue 1 Draft 2	02/12/2019	NOMMON	3.1.3, 3.2.2 and 5.4	
Issue 1 Draft 3	04/12/2019	NOMMON	Final draft	
Issue 1 Draft 4	15/01/2019	NOMMON	Inclusion of all contributing authors	

List of acronyms

ABM	Activity Based Modelling	IoT	Internet of Things
ANPR	Automatic Number Plate Recognition	IPCC	International Panel on Climate Change
ATIS	Advanced Traveller Information Systems	ITS	Intelligent Transport Systems
ATM	Air Traffic Management	KPI	Key Performance Indicator
BEV	Battery Electric Vehicles	LEZ	Low Emission Zone
BRT	Bus Rapid Transit	MaaS	Mobility-as-a-Service
CAV	Connected Autonomous Vehicles	MCA	Multicriteria Analysis
CAT	Connected and Automated Transport	NFC	Near-Field Communication
CBA	Cost Benefit Analysis	ODD	Operational Design Domain
D	Deliverable	OEDR	Object and Event Detection Responses
DEP	Distributed Electric Propulsion	PHEV	Plug-in Hybrid Electric Vehicles
DCM	Discrete Choice Modelling	PTA	Public Transport Authority
DDT	Dynamic Driving Tasks	P&R	Park & Ride
DRT	Demand Responsive Transport	SSP	Socio-Shared Socioeconomic Pathways
EC	European Commission	SUMP	Sustainable Urban Mobility Plan
EEAB	External Experts Advisory Board	TOD	Transit Oriented Development
FCD	Floating Car Data	UAM	Urban Air Mobility
FCEV	Fuel-Cell Electric Vehicles	UAV	Unmanned Aerial Vehicles
FSM	Four Step Model	UVAR	Urban Vehicle Access Regulations
GIS	Geographic Information System	VTOL	Vertical Take-off and Landing
GTFS	General Transit Feed Specification	TNC	Transportation Network Company
ICT	Information and Communication Technologies	WP	Work package

Executive summary

Information and communication technologies (ICTs) are bringing **radical changes in urban mobility**. On the demand side, phenomena like teleworking and e-shopping, for instance, are reducing commuting and shopping trips while increasing leisure and freight trips, thus modifying temporal demand patterns and modal split. On the supply side, ICTs are facilitating new options such as vehicle sharing and demand responsive transport, the emergence of Mobility as a Service (MaaS), and the rapid development of Connected and Autonomous Vehicles (CAVs).

The acceleration of technology evolution is changing urban mobility at a much faster pace than we have seen in previous decades, leading to an **increasingly uncertain future**. New mobility solutions hold great promise for moving towards a more sustainable and resilient mobility system, but they also raise concerns such as the induction of new trips, the switch from public transport to less sustainable modes, and the exclusion of vulnerable groups.

Planners and decision makers need to understand these disruptive changes and evaluate the impact of different policies under a range of possible alternative futures, or they risk being unprepared as they were for the likes of Uber. However, to date most Sustainable Urban Mobility Plans (SUMPs) and other policy instruments still lack a **clear and integrated vision of how to harness the potential of new emerging technologies**, while most existing research tends to highlight isolated positive findings, often overlooking the complex links between behavioural changes and new transport options.

This document provides an **overview of the concepts** that have to be taken into account to interpret and implement the enhancements that policy-makers require from transport modelling and simulation techniques to actually consider emerging mobility solutions in urban mobility planning processes. This framework is built upon a combination of a **literature review** and a stakeholder consultation process articulated through **a series of workshops and a Delphi poll**. The review of the existing literature provides a deep description of recent disruptive changes experienced by urban transport and the related policy measures, as well as an updated state-of-the-art of the transport planning tools and techniques which covers transport data sources, models and planning support tools. This, together with the consultation with transport practitioners, paves the way for an identification of the main **challenges and opportunities for sustainable urban mobility planning** that accompany emerging mobility options. Additionally, a set of **alternative futures** in relation to the evolution of these innovations are explored through a series of scenarios. The impacts of new mobility solutions on cities, and more precisely, on transport planning tools and techniques, are assessed in order to identify the envelope of **all possible future requirements that transport models and decision support tools will be expected to satisfy**. Finally, by analysing the role of these tools in current urban mobility planning cycles, we identify additional gaps that any enhancement effort has to take into account for making a meaningful contribution to sustainable mobility.

1. Introduction

1.1 Scope and objectives

The overall goal of the MOMENTUM project is to develop a set of mobility data analysis and exploitation methods, transport models and planning and decision support tools able to capture the impact of new transport options and ICT-driven behavioural changes on urban mobility, in order to support local authorities in the task of designing the right policy mix to exploit the full potential of emerging mobility solutions.

The objective of this document is to set up a **conceptual framework** for the research activities that are conducted in the MOMENTUM project. The report is the result of the work conducted in part of the WP2 of the project, particularly in the tasks T2.1 “Review of emerging mobility options” and T2.2 “Data, models and decision support tools: challenges and opportunities”. As a consequence, this document:

- reviews the **recent disruptive changes** in urban transport caused by new transport technologies and policy strategies;
- identifies the **challenges and opportunities for sustainable urban mobility** planning brought about by mobility innovations and policy measures;
- delivers **future scenarios** relevant for mobility planning in Europe and the evolution of emerging mobility solutions;
- evaluates the **current capabilities and the applicability of transport planning tools and techniques** for managing new transport options;
- **explores the role of transport planning tools and techniques in the urban policy cycle** in relation to the requirements that emerging mobility options imply for such tools and techniques.

1.2 Methodology

The document integrates the results of all the research activities included in T2.1 and T2.2:

- An extensive **literature review** on the emergence of new mobility options, and the state-of-the-art of transport data sources, transport models and their role in the urban policy cycle. This review has included recent literature from institutions and research groups and other sources such as technical reports, white papers and market analyses conducted by key players in the field of emerging mobility solutions.
- An **Open Session in the framework of the 2019 CIVITAS Forum**, a well-known yearly meeting point for urban mobility stakeholders, where the attendees reflected upon the impacts of emerging mobility solutions in European cities. The event took place in Graz, Austria, on 3rd October 2019.
- A **workshop with policy-makers**, where the members of the MOMENTUM City Pool held a detailed discussion on the challenges and opportunities that new mobility options have brought about for cities and the policy strategies that cities can follow to manage this change. The event took place in Graz, Austria, on 4th October 2019.
- A **workshop with transport modelers**, where the members of the MOMENTUM External Experts Advisory Board (EEAB) shared their views about the improvements that transport models require for coping with new mobility options, in terms of modelling techniques and indicators. The event took place in Brussels, Belgium, on 31st October.

- A **Delphi poll handed out to a transport experts' panel**, in order to reflect upon the implications of several alternative futures for European cities in terms of urban mobility, with a particular focus on the expected evolution of emerging mobility options and their impacts. The Delphi poll was structured in two rounds. In the 1st Round, carried out during October 2019, 16 experts participated. In the 2nd Round, carried out during November 2019, 10 of the 16 initial experts participated.

1.3 Structure of the document

The document is organised as follows:

- **Section 2 "Urban mobility trends"** describes the main emerging mobility options and the associated technological innovations, together with relevant policy strategies that cities can apply to manage urban mobility. The contents of this part of the document are mainly based on the literature review and the working sessions with policy-makers.
- **Section 3 "Urban mobility futures"** presents a group of exploratory scenarios for the evolution of the context where urban mobility will operate in European cities, and a set of alternative futures for emerging mobility options. The Section also presents the results of the Delphi poll in relation to these scenarios.
- **Section 4 "Present and future of transport data sources"** reviews the current state-of-the-art of data sources that provide travel demand information to transport practitioners, and formulates research questions in this field taking into account the identified challenges brought about by mobility innovations.
- **Section 5 "Present and future of transport modelling and decision support tools"** reviews the current state-of-the-art of transport simulation and decision support tools, describing the approaches that are expected to contribute to the analysis of new mobility options within cities and the correlative research gaps to be explored.
- **Section 6 "Integration of transport planning tools in the Policy Cycle"** explores the role of transport models and decision support tools in sustainable urban mobility planning, with a particular focus on the governance and organisational conditions for the adoption of these tools among policy-makers.

1.4 Reference and applicable documents

Applicable documents:

[I] Grant Agreement No 815069 MOMENTUM – Annex 1 Description of the Action.

[II] MOMENTUM Consortium Agreement, Issue 1, April 2019.

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2. Urban mobility trends

Cities are an extraordinarily dynamic context. The concentration of people in fairly limited spaces entails specific opportunities and challenges for urban societies, given the wide range of derived demands that the vibrant urban activity generates. Among these demands, transport is arguably one of the most relevant and visible.

Hence, urban mobility draws the attention of numerous stakeholders. It constitutes both a market, where different supply options are offered to citizens, and a tool for urban transformation, since its footprint in public space has an impact on many dimensions that affect the value of places within cities. As a consequence, it is far from being a static field. Rather it suffers continuous changes promoted -and sometimes, stopped- by those agents that have a matter in relation to it. The illustrative example included in this page, of a centric square in a European city, show the evolving nature of urban mobility and its reflection in urban areas.

This helps to give context to an era where urban mobility is repeatedly said to be immersed in disruptive changes. Even though it is not much worth stopping at debating whether past transformations were more disruptive or not than the ongoing changes that motivate the MOMENTUM project, it is interesting to bear in mind that evolution is inherent to urban mobility history.

As it is mentioned in the Introduction, the rapid technological developments (e.g. automation) and societal transformations (e.g. shared economy) seem to accelerate the pace of urban mobility changes, and therefore the need for response from authorities in charge of its management. The goal of this section is to **explore the role of the drivers for change in urban mobility**. The discussion is guided through two main areas:

- **Supply innovations trends**: Information and Communication Technologies (ICTs) have multiplied the possibilities in terms of transport services operation. The list of concepts that are in deep transformation thanks to the outcomes of these technological advances is large: road vehicles can now run on electricity and automatically, the access to transportation services can be managed through smartphone applications, etc. Section 2.1 reviews all these trends and identifies common and specific enablers, opportunities and risks of the emerging concepts for cities.
- **Policy measures trends**: public authorities hold the responsibility of managing and regulating urban transport systems. This involves a continuous effort to cope with the numerous externalities that transport entails. Many of the actions that local governments and metropolitan entities carry out are devoted to mitigating the impacts of private car usage on cities and promoting modal shift towards more sustainable options. In any case, these policies cannot be static, since supply innovations push the limits towards unexpected situations that may need new solutions, or change those that already seemed consolidated. Section 2.2 explores the main types of policy measures that cities take into account when planning and managing urban mobility.

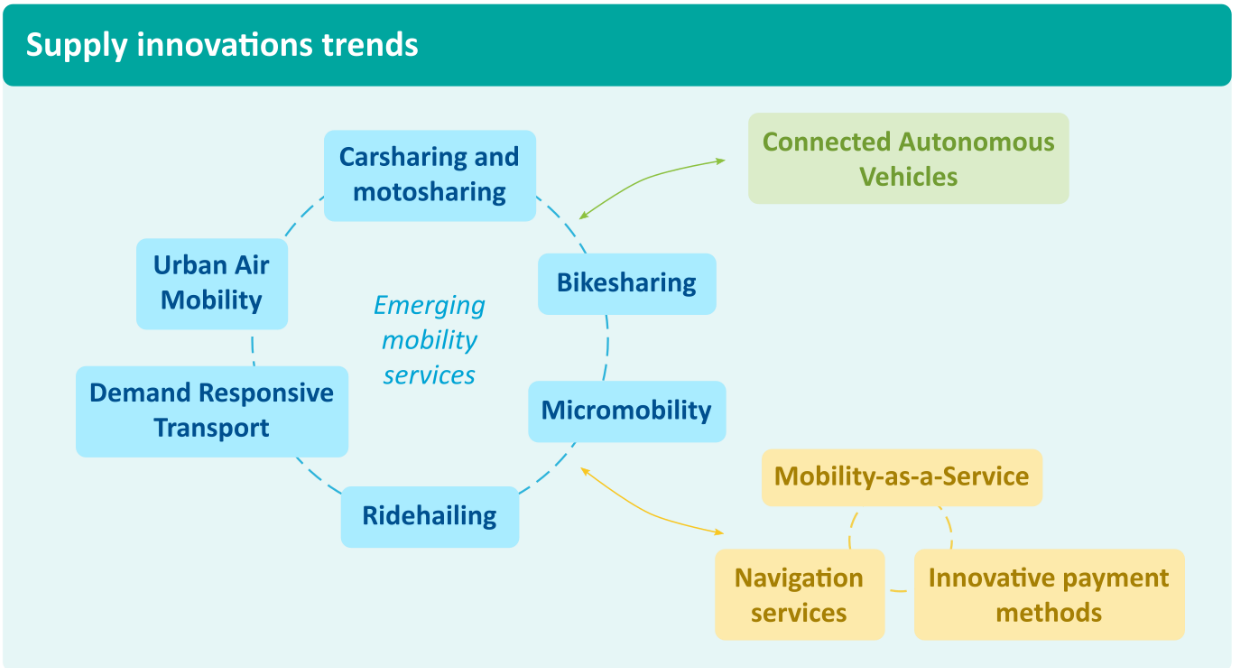
Evolution of Madrid's Puerta del Sol. Source: adapted from www.secretosdemadrid.es

2.1 Supply innovations trends

In recent times, urban transport supply is experimenting several transformations with an uncertain impact for the future of sustainable mobility. ICTs are facilitating a wide range of new mobility options that were not attainable just a few decades ago. These novel solutions are often grouped under the banner of **smart mobility**. Expectations about smart mobility are high: emerging mobility services and the future irruption of CAVs are expected to contribute to a cleaner, cheaper, safer, more inclusive and more efficient transport, by facilitating multimodality, increasing the use and efficiency of public transport, reducing car ownership, improving accessibility in areas of low demand, and reducing fatalities.

This section reviews the basic concepts behind each of these supply innovation trends. It explores the **enabling technologies** and **societal changes** that explain their evolution, unveils **which stakeholders are promoting** their implementation and provides insights on the **opportunities and risks** that they entail for cities. The section picks relevant examples from worldwide cities and regions to identify **key factors behind a successful contribution** of these new concepts to sustainable mobility, and also to detect what aspects can block such contribution.

The trends have been selected from the dynamic and alluring ongoing conversation around supply innovations in urban mobility. First, the section takes a look at several **emerging mobility services**, which can be understood as different reflections of shared economy in urban mobility. This includes solutions that were already in place some decades ago but have been transformed by GPS positioning and smartphone applications (e.g. carsharing and bikesharing), recent newcomers (e.g. micromobility) and services that are not yet deployed at large scale, such as Urban Air Mobility. Next, **vehicle automation** is analysed, taking into account its transformative potential in relation to emerging mobility services. Finally, a series of innovations in **transport services management** are explained, of which Mobility-as-a-Service stands out as a powerful tool to integrate the present and the future of urban mobility from a user-centric perspective.



2.1.1 Carsharing and motosharing

2.1.1.1 What is it?

Carsharing and motosharing schemes consist of a fleet of cars or motorbikes that are made available to the public to meet their mobility needs. The fleet operator provides the energy supply of the vehicles and the maintenance, while users pay a fee for using the vehicles [1]. Three main types of schemes can be found in the market: (i) **round-trip**, which requires from users to return the vehicle to the initial location; (ii) **station-based one-way**, which allow users to go from one depot to another; and (iii) **free-floating one-way**, where the operator does not appoint specific parking locations. Instead, vehicles are parked across the coverage area of the service making use of the existing parking lots for private cars and motorbikes.

2.1.1.2 How does it work? What are the enabling technologies?

Although these vehicle sharing systems have considerably grown in the last years, they come from a long path of pioneer experiences and trials [2]. First round-trip schemes appeared in US and extended to Europe in the second half of 20th century. Early one-way trip schemes appeared later, and most failed to succeed due to high costs and low demand. The disruptive surge of carsharing and motosharing experienced in the last decade is enabled by several technological improvements and the spread of shared economy models across the world [3]. On the one hand, the maturity of ICT solutions has facilitated fleet management and access to the service [4]. Users and vehicles interact through **smartphone applications** and operators maintain a real-time control over the fleet thanks to **GPS positioning**. In parallel, the perceived relevance of ownership is dropping among certain population groups (e.g. urban millennials), who are attracted by **shared economy**. Drivers such as the increasing environmental consciousness or the lack of economic resources to purchase a car feed this trend and boost the potential demand of carsharing and motosharing services.

2.1.1.3 Who provides carsharing and motosharing services?

The favourable conditions for the implementation of carsharing and motosharing have caught the attention of both public and private agents. **Most of the systems are privately-owned** and seek a financial profit from the operations [5]. However, given the potential positive and negative impacts of carsharing and motosharing on urban mobility, many private operators and cities have established collaboration frameworks in order to ensure that the interests of both parts are preserved.

2.1.1.4 What is the role of the service in urban mobility? What are its opportunities and risks?

The agents that have implemented carsharing and motosharing systems highlight the following opportunities:

- Carsharing and motosharing can **complement public transport services**, by providing a convenient way to perform first and last mile legs of trips in less dense areas where the provision of frequent bus services is not viable [6]. Moreover, they can supplement public transport services during off-peak hours or even relieve them from saturation during peak hours [7].
- Services based on electric vehicles have allowed the first contact of many users with **electric propulsion**, increasing the popularity of a technology that can improve air quality in urban areas [6].

- It is still unclear if all carsharing and motosharing services have had an impact on **car ownership**. If these systems achieve a reduction in car ownership, the reduced need for parking will alleviate the pressure on public space in cities [6, 7].

However, these systems are not exempt from risks:

- In general, there is a concentration of supply in inner areas, where public transportation networks are dense enough and services are frequent. This would imply that, instead of taking a complementary role in suburban areas, certain carsharing and motosharing services would **compete with public transport**. In the particular case of motosharing, it is also feared that it may be **taking trips from active modes** such as walking and cycling [7].
- There are no standard mechanisms to tax the **use of public space** by privately owned free-floating systems. Hence, the fees they offer, which are usually not affordable for everyone [8], do not include this aspect [7].
- Some operators are **reluctant to share their data with cities**, which limits the capacity of authorities for understanding the impact of these systems and managing the transport system [8].

2.1.1.5 What are the conditions for the success or failure of carsharing and motosharing?

Carsharing and motosharing systems are increasingly common among European cities. It is clear that urban cores guarantee a high level of potential demand for operators. Indeed, **population density** has been identified as a key factor for the success of these services [7, 9]. This fact contravenes the deployment of services in those areas where complementarity with public transport could be more obvious. Another success factor is the **collaboration between private operators and local governments** or transport authorities, organized through specific teams devoted to maintain these partnerships and launch pilot projects where indicators targeting both public and private interests are properly evaluated [10]. There is a relative ease for developing **pilot projects** compared to other transport modes or services, given the limited needs for infrastructure. Hence, reversible pilot projects have to be taken into account as a strategy for identifying success strategies [7]. In addition, for those carsharing and motosharing systems based on electric vehicles, it seems that the existence of **electric vehicle infrastructure** in the city can also boost the success of these systems [9].

Many experiences provide valuable lessons in this field. **Autolib'** was a carsharing system covering the metropolitan area of Paris. It started in 2010 as a joint initiative of several metropolitan municipalities, by launching a tender aimed at deploying a one-way station-based electric carsharing system in the city. The tender was won by Bolloré group, who started operations in October 2011 [11]. The number of cars, stations and registered users grew fast, but the service did not reach the expected profitability. Indicators such as trips per registered user declined almost from the very beginning of the system [3]. The competition of free-floating systems [12] and of ridehailing apps [12] impacted the attractiveness of the service. After recurrent economic losses, the operator claims for a financial compensation of up to 300M€ due to the unsuccessful development of the system. The consortium that promoted the system rejected these claims and decided to shut down the system. Other cities have also experienced bitter evolutions of carsharing services. For instance, car2go abandoned **London** in 2014 after the difficulties to operate in a fragmented governance scenario. Specifically, parking permits needed to be requested separately to all London boroughs.

On the contrary, other large cities host more than one service, with apparent enough demand to support operations, such as **Madrid** or **Milano**. In any case, it is interesting to look at success stories in middle-size cities. For instance, the city of **Flensburg**, Germany has integrated a modest fleet of shared cars in its transport system, operated by the company cambio. The collaboration of several institutions who started to perform their business trips using this fleet promoted the service across citizens. The system reached economic viability the second year of operations [7].

2.1.2 Bikesharing

2.1.2.1 What is it?

Bikesharing (or *bicycle sharing*, or *public bicycle scheme*) is a mobility service that relies on the short-term access of rented bicycles on an as-needed basis [1]. Similar to carsharing concepts, bikesharing systems can be conceived as **station-based** schemes, where bicycles can be used for performing trips between the system depots; or as **free-floating** schemes, where bicycles can be picked and dropped at any point within a certain service area.

2.1.2.2 How does it work? What are the enabling technologies?

The concept of bikesharing originated in Europe in 1965, when the world's first bicycle sharing scheme was introduced in Amsterdam, and has since then developed and expanded to the rest of the world. The Amsterdam scheme relied on a limited number of free-floating "white bicycles" that could be used by anyone for free and then left to other users anywhere in the city [13]. Over time, bikesharing has developed into a highly technologised mode of transport [14]. As it is the case for carsharing and motosharing systems, modern bikesharing schemes rely on technologies such as **GPS positioning** as well as on electronic booking and automated payment systems through **smartphone applications**. GPS tracking systems benefit both the users and the bikesharing operators. Firstly, users can quickly identify the closest available stations and/or bikes; secondly, operators are able to track users' trips and collect relevant data about the use of the system and the demand for mobility in the city. The introduction of technologically advanced **locking systems** was key to ensure the safety of bikes and to prevent thefts.

2.1.2.3 Who provides bikesharing services?

Since bikesharing's inception, various models of provision have existed. Bikesharing providers include governments, transport agencies, universities, non-profits, advertising companies, and for-profits private companies.

Table 1 – Bikesharing provision models. Source: adapted from [14].

Government model	Local authorities operate the bikesharing service as it would any other transit service, having therefore greater control over the service. *Sevici, run by Seville Municipality*
Transport operator model	Traditional operators expand their services by integrating bikesharing into their broader offering. *Call a bike scheme, run in Germany by Deutsche Bahn*
Non-profit model	A non-profit organisation is either created for the operation of the service or one that folds the bikesharing service into its existing interests. *Bycyklen, run in Copenhagen by City Bike Foundation*
Advertising model	An advertising company offer a bikesharing program to a jurisdiction, usually in exchange for the right to use public space to display revenue-generating advertisements on billboards, bus shelters and kiosks. *Villo!, run in Brussels' by JCDecaux*
For-profit model	A private company provides the service with limited or no government involvement. Most free-floating services fall under this category. *Nextbike, run in German cities*

2.1.2.4 What is the role of the service in urban mobility? What are its opportunities and risks?

Efficient and accessible bikesharing schemes make cycling in the city more appealing to users. Thus, local authorities can invest in implementing and developing bikesharing schemes to **reap the health and social benefits of cycling**, which have been extensively observed and analysed in the literature [15].

When compared to motorised transport systems such as shuttle services, the **implementation and operational costs** of bikesharing schemes are much lower. At the same time, bikesharing can positively contribute to public transport use and access thanks to its potential to **broaden the catchment area of public transport** services [16]. Moreover, bikesharing schemes encourage users to use a low-carbon transport mode for short trips that would otherwise be made by car or a motorised two-wheeler, especially in developing cities [17]. Accessible and functional bikesharing services also have a positive impact on users' behaviour, as it encourages a shift towards more regular bicycle use for daily mobility.

Depending on the layout of the system, there is a risk of resulting in a neutral measure in terms of modal shift, **taking most of the trips from public transport** and active modes instead of taking trips from private cars [1]. In addition, free-floating systems can **distort the use of public space** if no specific regulations are set up [18].

2.1.2.5 What are the conditions for the success or failure of bikesharing services?

There are many success and failure stories among bikesharing systems. For instance, the pioneer **Amsterdam** scheme relied on a limited number of free-floating "white bicycles" that could be used by anyone for free and then left to other users anywhere in the city. The system proved to be a failure because of **theft and damages** to the bicycle fleet. In 1995, **Copenhagen** introduced a large-scale public bike programme called "Bycyklen" (City Bikes), which allowed users to access sturdy, shared bicycles at specific locations throughout the city via a coin-operated system. The following year, a solution to the vandalism problem was found in **Portsmouth**, United Kingdom, where a small bike-share system limited to university students relied on individualized magnetic-stripe cards, which allowed them to be **tracked** when they were not returned. This was the first example of "third generation bikesharing" and paved the way for the development of more efficient and economically viable bikesharing systems across the world. In 2010, the literature identified approximately 100 bikesharing schemes in operation in 125 cities around the world [14]. In the years that followed, the number of bikesharing schemes worldwide multiplied, with **Guangzhou** (China), **Buenos Aires** (Argentina), **Mexico City**, **London** and **Melbourne** establishing city-wide schemes. In 2013, **New York**'s bike-share system launched with 6,000 bikes was a first-of-its-kind system since it uses no public funding, given that it is fully paid for by corporate sponsorships. Up to date, organisations monitoring the development of bikesharing schemes (such as *MetroBike LLC*) worldwide count around 900 bike-share systems currently in operation. The **support from local governments** (e.g. by developing cycling infrastructure) [19] and **accurate communication strategies** [20] seem to be crucial success factors.

2.1.3 Micromobility services

2.1.3.1 What is it?

Micromobility services can be defined as a transportation solution based on small, lightweight vehicles that are shared among multiple users [21]. It is arguably one of the latest and most disrupting trends that is impacting the mobility landscape in cities, as it has been remarked in the workshops conducted in the framework of MOMENTUM. In particular, the fast adoption of electric scooter services, which started being introduced in cities worldwide only after 2016, is a prime example of this trend and therefore stars in this section.

2.1.3.2 How does it work? What are the enabling technologies?

Micromobility systems intend to provide a solution for short trips within determined boundaries. Vehicles are distributed across such boundaries or *geofences,* and customers can use a smartphone application to find, unlock an pay the trip. Trip rates typically incorporate an initial flat fee plus a per-minute charge. Following this, as it is the case with all shared mobility systems, the main technologies that enable micromobility schemes are **GPS positioning** and **smartphone applications** [22]. GPS tracking allows users to quickly identify the closest vehicle and companies to oversee the trips that are performed within a city. User-friendly mobile applications are the gateway to the service to a wide number of users, which can effortlessly book a vehicle and pay automatically for their service within seconds. In addition, the **electrification of scooters** has played a key role in the emergence of these solutions. Powerful and capacious batteries have dramatically increased vehicles' lifespan and performance. Hand brakes have been refined to be safer and more responsive. Due to the high number of companies offering e-scooter services, the competition for the development of innovative technologies is fierce.

2.1.3.3 Who provides micromobility services?

Unlike bikesharing schemes, which were established and developed mostly by local public administrations, e-scooter sharing services are mostly run by **for-profit private operators**. The first dockless electric scooters appeared in Paris in June 2018, when US-based company Lime officially launched its e-scooter service in Europe. As of 2019, 19 scooter sharing operators are estimated to be operating across the continent. The high number of operators can partially be explained by the low barriers to entry the micromobility market and the low cost of scaling up assets compared to other shared mobility solutions such as shared electric cars [23].

2.1.3.4 What is the role of the service in urban mobility? What are its opportunities and risks?

As cities face rapid population growth, the mobility demand is on the rise and pressure on existing transportation networks is growing. Against this backdrop, micromobility schemes have the potential to **complement cities' public transport networks** and offer a valuable solution for the first and last mile [22]. Furthermore, micromobility could be a powerful tool in the fight to **increase access to transportation** for some discriminated communities [22]. For that reason, e-scooters operators have engaged in cooperation agreements with city authorities to contribute to their transport accessibility goals [24]. However, some providers have failed to meet city-mandated benchmarks for numbers of vehicles and numbers of trips originating in areas with the most need [24]. Beyond the first and last mile role, micromobility services offer a sustainable **alternative to short car trips**, so they can prove to be beneficial in reducing air pollution and congestion [22]. The number of trips that constitute the potential demand of micromobility solutions is high: trips of less than 8 kilometres account for more than half of total trips in the European Union [23].

However, most public transport trips are also short and therefore are potentially susceptible to substitution by micromobility. This is even clearer in the case of walking and cycling. As a result, many argue that e-scooters pose a **threat to healthy active mobility** behaviours and **to the use of public transport**. Micromobility is also challenging governance procedures. The rise of e-scooters was not always coupled with the introduction of clear rules on where and how such vehicles could be used, which often resulted in **conflicts on the use of public spaces**, in particular on the use of sidewalks [22]. **Safety**, for both riders and others, has been another key concern in many cities. Although the safety of shared e-scooters is yet to be comprehensively assessed in comparison to other transport modes, local authorities have pressed micromobility providers to encourage and improve safety, by increasing helmet availability or modifying vehicle designs in order to cope with uneven pavement [22]. Finally, e-scooters **design features limit the pool of potential users**—people with certain disabilities, for example, could find a scooter difficult if not impossible to use. For that reason, companies such as Lime or Jump are exploring innovative design features to make the service more accessible and inclusive.

2.1.3.5 What are the conditions for the success or failure of micromobility services?

As it is the case with all privately-led shared mobility services, it is still unclear if micromobility companies will be able to achieve profitability, since they rely in their remarkable capability to raise funds [25, 26]. However, there is already enough evidence to compare the different approaches taken by local authorities. Whilst some cities are waiting for national or federal legislation, others are taking a leading role in setting up a regulatory framework for these new services and actively cooperating with the operators [22]. Among other issues, **data sharing agreements** [22, 24, 27] and **clear regulations on the use of public space** [22, 24, 26] seem to lead the discussions.

Brussels, Belgium

The Belgian capital is one of the cities that are showing a positive attitude towards micromobility, as a bet to offer residents a sustainable alternative to private car. There are currently around 5,000 free-floating e-scooters, 1,800 bicycles and 750 mopeds in operation. In early 2019, the city introduced a law for micro-mobility that applies to all providers across the 19 communes of the Capital Region [28]. Brussels has opted for a license model with a set of conditions related to parking, the concentration of vehicles in certain areas, enforcement mechanisms and liability in case of wrongdoing [29]. Currently, the regional agency Brussels Mobility is monitoring the way these services are being used, in terms of indicators such as frequency of trips.

Madrid, Spain

The city of Madrid constitutes another good example of a city building a comprehensive regulatory framework for new mobility services. In October 2018, the municipality adopted a regulatory framework for new mobility services, including e-scooters [30]. It set out a basic definition for e-scooters and a 30 kph speed limit for such vehicles. The regulation attributed e-scooters the right to circulate on cycle paths and lanes, as well as on city streets within the 30 kph zones. It introduced the obligation to carry a plate for vehicles operating on other roads. Circulation in pedestrian areas, sidewalks and bus lanes is not allowed under any circumstances. Strict parking requirements were also set out, allowing micromobility vehicles to park on the sidewalks only in exceptional cases. To date, 18 e-scooters operators have been granted licenses to operate in Madrid.

Lisbon, Portugal

Up to date, 9 e-scooter companies are running operations in Lisbon. The city has adopted an approach based on a flexible regulation and active dialogue with operators [24]. Accordingly, private operators could access the market freely on the condition to meet regularly with city officials and report on issues related to the operation of vehicles. Based on these exchanges, the city drafted a Memorandum of Understanding for micromobility operators setting out basic rules with regards to parking, safety and data collection, among other issues. The city has launched an awareness campaign to promote good practices in the use of new mobility services in the city, *Partilha Lisboa* (Share Lisbon), to which all new mobility services operators have actively contributed.

2.1.4 Ridehailing

2.1.4.1 What is it?

Ridehailing services, also known as *ridesharing*, *Transportation Network Companies (TNC)* or *ridesourcing*, are based on mobile applications that match costumer demand for a ride with private drivers or drivers of vehicles for hire through GPS tracking [31].

2.1.4.2 How does it work? What are the enabling technologies?

Ridehailing services are enabled by the same technological developments that support the rest of shared mobility services, namely **GPS positioning** and **smartphone applications**, which underpin matching process between riders and drivers. In this sense, they can be seen as an update of taxi services. However, **shared economy** principles imply a key difference with traditional taxi, since it offers citizens the possibility of using their own car as the vehicle to be used for rides, without going through taxi license systems [32]. Moreover, it is understood that **CAV technologies** will transform ridehailing services in the future [33].

Registered customers use a mobile application to request a ride, by setting their pickup location and entering their destination. A fare quote is given to them. Users can then track registered vehicles and accept the quote for the ride, waiting for the matched driver to accept. Once accepted, the passenger will receive information on the driver and the car, which they can track on the map. The passenger is notified on his smartphone of the imminent arrival of his driver. After pickup, the app will show the driver the route, using GPS navigation. Some of these trips can also be shared with customers that are looking for rides with similar destinations. Payments are handled through the service provider directly by billing the rider's credit card that is linked to the app. A rating system asking the driver to rate the rider and vice-versa allows maintaining service quality and trust. After the ride the passenger immediately receives an invoice on his smartphone stating the exact route, distance and time travelled. For every ride sold the platform gets a commission. Pricing is flexible and companies usually increase the fares during peak hour services or special events or whenever demand is high (surge-pricing) [34]. Most services also allow clients to split the fare with a co-passenger, further reducing the cost for the passengers.

Table 2 – Key differentiating aspects of ridehailing versus similar mobility solutions

Ridehailing	Carpooling	Carsharing	Taxi
A **chauffeur** drives its **own vehicle**.	A person demanding that trip drives their own vehicle.	The user drives the vehicle from the operator's fleet.	A chauffeur drives a registered taxi vehicle.
The trip is **only performed if requested on-demand** by a mobile application.	The trip is performed in any case by the driver, additional passengers can request in advance.	The trip is only performed if the user unlocks and uses a vehicle.	The trip is only performed if requested through taxi service procedures.

2.1.4.3 Who provides ridehailing services?

Ridehailing systems are **privately owned**. The service is generally delivered under entrepreneurship schemes and start-ups that are experimenting in order to respond to a need and gain market share quickly, without focusing in profitability [25]. In terms of regulation, the jurisdiction in charge of these services is unclear as they challenge several regulatory frameworks, especially labour laws and taxi regulation.

2.1.4.4 What is the role of the service in urban mobility? What are its opportunities and risks?

Ridehailing is sometimes framed as a necessary **evolution of taxi systems**, whose lack of competence incentives was leading to disadvantages for passengers in terms of price and quality of service. In any case, ridehailing services have come in addition to taxi services and not as a substitution, since the number of licenses has not been modified due to their emergence [33]. In this context, the key question is to whether the trips covered by ridehailing services replace private car rides or sustainable options. The effects in terms of reduction of car trips are still unclear, but empirical evidence indicates a **very limited impact on car ownership** [35]. Moreover, there is evidence that users **substitute certain public transport trips** with ridehailing services, especially if bus or rail services have limited quality in terms of frequency and travel times [35]. In addition to this, many trips would have been made by walking or cycling, so ridehailing services **may affect the modal share of active mobility** [35]. **Data unavailability** for cities is also regarded as a risk for sustainable urban mobility planning [35].

2.1.4.5 What are the conditions for the success or failure of ridehailing services?

TNCs develop all over the world, supported by financial funding in a similar fashion to micromobility [25]. What varies from countries to countries and even cities to cities is the attitude towards their implementation. UITP [31] mapped 4 different responses, as can be seen in Figure 1.

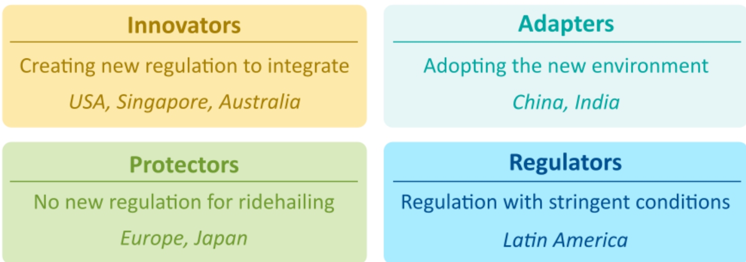


Figure 1 – Approaches of authorities to ridehailing solutions. Source: adapted from [31]

San Francisco is the cradle of ridehailing. To develop these companies required an accommodative regulatory framework as they were opposed by cities heavily regulated and politically active taxi operators. In consequence, TNCs were operating illegally before engaging into an **aggressive lobbying** and coalition building process. At the beginning, they argued that they had no need to comply with state and city's regulation as they were only connecting riders and drivers. This standpoint led them to ignore regulators earlier warnings before seeking support from elected senior officials. Their strategy was then to convince regulators to implement a more favourable regulation and put a hold on enforcement actions. Over this process, TNCs won the backing of San Francisco's Mayor who was supportive for two reasons. First, TNCs constituted a popular alternative to the unreliable taxi market. Second, the Mayor was keen to retain technologies companies involved in the "sharing economy" at a time were the effects of the Great Recession were still acutely felt. As the Mayor was responsible for appointing the board of the San Francisco Metropolitan Transport Agency (SFMTA) in charge of regulating taxis, he was also able to prevent the agency from shutting down the TNCs. This is how San Francisco embraced the development of new services. This was not without raising the resistance of taxi's operators and challenging the way this market was organized, the medallion scheme in particular. This political outcome allowed TNCs to continue to grow in California and expand internationally.

An interesting case is the approach of **Singapore's** Land Transport Authority (LTA). They rely in ridehailing services to provide door-to-door solutions complementary to scheduled public transport services. LTA decided to adopt a "light-touch" regulation approach to guide and shape the development of new services towards integration. Singapore contrasts with European countries because TNC or ridehailing companies own the fleet of vehicles, given the high price of cars. This facilitated the process of progressive licensing of the services and the collaboration between LTA and ridehailing companies, which in turn has improved traditional taxi services [31].

2.1.5 Demand Responsive Transport (DRT)

2.1.5.1 What is it?

Demand Responsive Transport (DRT), also known as *microtransit*, *ridepooling*, or *on-demand buses/shuttles/minibuses*, are IT-based shared transport services operated by a company with professional drivers with no fixed schedule, not necessarily fixed stops, and dynamic routing. Vehicles can range from cars to large SUVs to vans to shuttle buses. DRT serves multiple passengers independent from each other using dynamically generated routes, and may expect passengers to go to common pick-up or drop-off points [36].

2.1.5.2 How does it work? What are the enabling technologies?

DRT is not a new mobility solution, since already from the 1960's the concept was developed to serve rural areas in the UK [37]. Before the Internet era, these services were based on telephone requests, so they have been also known as *dial-a-ride*. Nowadays, DRT typically works through **smartphone applications** that match passengers in demand for a ride with free seats in a vehicle shared with other passengers that are looking for rides with similar destinations. As a consequence, **GPS positioning** is a relevant enabler of these services in their current form. From the customer perspective it requires downloading an app. Passengers download the app on their smartphone, register and choose the payment method. Passengers enter the origin and destination of the trip and the app provides them with the price. The app provides the passenger with the pick-up point and pick the passenger up within minutes. Some services have "virtual" stops while other services use scheduled public transport stops. Passengers with similar destinations share the ride and are dropped at the agreed destination. In terms of pricing/fares, different pricing systems exist at the moment: (i) dynamic pricing, depending on distance or time; (ii) fixed fares, normally associated to public transport ticketing system or (iii) mixed pricing, with a fixed price as a lower threshold that can increase due to distance or time. Most of them offer a discount if you travel with someone else. Some services do also offer passes. Similar to the case of ridehailing, there is hope that **vehicle automation** will ease the implementation of these services in the near future [38].

2.1.5.3 Who provides DRT services?

DRT is either run as part of the **public transport operator** services or in competition with existing public transport lines by **private companies**. Private actors and entrepreneurs can take the initiative to deliver the service but might clash with existing regulation and legislative categories. A promising practice is when public actors, that is a municipality, a Public Transport Authority or even a traditional Public Transport Operator work in partnership with entrepreneurs to increase mobility options for the citizen, contributing to the car-lite city vision.

2.1.5.4 What is the role of the service in urban mobility? What are its opportunities and risks?

Within urban mobility options, DRT offers a space-efficient flexible service. Looking at it from a public transport point of view, different applications can be envisioned [36, 37, 39, 40]:

- **Complementing the public transport supply in time**: during operational times where the demand is too low for higher capacity transport options, e.g. evening & night times, Saturdays and Sundays.
- **Complementing the public transport supply in space**: in certain low-density areas where demand is low, e.g. suburban or rural areas, industrial areas, etc.
- **Offering additional services**: either as a premium service or for special needs, such as for disabled people.
- **Replacement of inefficient public transport lines**: especially when low demand does not justify the use of large vehicles neither from an economical nor from and ecological point of view and aiming at providing better service for the customers. In some cases, it can also offer better service with for instance direct connections, instead of a trip with 2 or 3 transfers.

2.1.5.5 What are the conditions for the success or failure of DRT services?

In general, DRT services are not profitable, so they are usually highly subsidized by authorities [36, 37]. In any case, many Public Transport Authorities (PTAs) have considered these systems as a valuable contribution to their supply networks. The minimisation of costs is obviously a success factor among the existing experiences, which can be achieved through an accurate management of the system. A common goal in this direction is to **minimise empty trips** [39]. The **coordination with scheduled public transport** is also relevant in those areas where the service intends to replace low-demand services [36, 39]. Moreover, tailored **communication strategies** seem crucial to release the potential demand of the services [39]. Many of the unsuccessful implementation examples have in common the lack of commitment among stakeholders to deploy a **large enough fleet** to make the service attractive [39].

In **Germany**, DRT schemes are developed in several cities across the country such as Berlin, Hamburg, Hannover, Frankfurt or Stuttgart with the overarching goal of complementing public transport. At the moment there is no homogeneous legal framework for DRT which is subject to approval for concession either for car rental services or for public transport. In Stuttgart DRT is reckoned as regular public transport service which operates 76% downtown and 24 % outside the city. The public transport operator is responsible for regulatory approval, control, branding and marketing, demand data, customer services and ticketing while the private entrepreneur cares about the platform and the routing, the fleet management, the label and the app, the technical aspects of ticketing etc. The project started in June 2018 as an experimentation before being optimized in summer 2019 with unified service area and expansion of service times in the evening to the whole week. From December 2019 the service is expected to be 24/7 overall the whole Stuttgart. Cooperation with other strategic partners as well as the electrification of the vehicles are part of the plan.

In Australia, DRT pilots are implemented in **Sydney**. The objectives of the pilots are to identify and test new service delivery models, identify technology requirements, improve customer outcomes and achieve better value for money. There are currently 11 pilots in Sydney which include operators, software and vehicles providers. The pilot of Sydney's Northern Beaches started in November 2017 and consist of a feeder service that brings passenger to bus lines. The Moree Pilot comprises 3 route services that have been replaced by DRT. Patronage has increased more than 1,000%. It provides access to isolated communities. Overall customers are more satisfied than when compared with bus. Areas of improvement should be the integration with the traditional public transport's fare and ticketing system.

2.1.6 Urban Air Mobility (UAM)

2.1.6.1 What is it?

Urban Air Mobility (UAM) is a form of passenger and cargo transportation within metropolitan areas based on highly automated and efficient air vehicles [41, 42]. UAM represents a disruptive improvement of traditional helicopter transportation [43]. On the one hand, UAM embraces unmanned aerial systems and electric propulsion. On the other hand, UAM intends to operate on an on-demand basis and requires a control framework for high density airspace management to ensure safe operations in an urban environment.

2.1.6.2 How does it work? What are the enabling technologies?

UAM is based on two technological advancements:

- **Vertical Takeoff and Landing vehicles (VTOL)**, which are aircrafts capable of vertically taking off and landing, removing the need for runaways [44]. VTOL vehicles dedicated to UAM are generally foreseen as highly automated, including the possibility of being fully autonomous. Moreover, these vehicles usually avoid to be dependent on a single part to fly, substituting helicopter rotors with multiple smaller propellers arranged in an organised pattern above and/or around the body of the vehicle (drones), or occasionally along a fixed tiltable wing (VTOL vehicles) [41]. This change is enabled by Distributed Electric Propulsion (DEP) and contributes to decrease noise and greenhouse gases (GHG) emissions compared to helicopters [45]. In addition, VTOL design is based on the use of light composite materials and the application of 3D printing technologies in order to achieve large-scale and low-cost production [41].
- The **adaptation of Air Traffic Management (ATM) to urban environments**. The proliferation of drones has pushed aviation authorities to extend their scope to low-level airspaces, developing specific conceptualisations for it (e.g. U-Space). The technological challenge is to provide a safe and efficient framework for operating UAM in a context with high traffic density and complexity, ensuring the compatibility of both cooperative and non-cooperative users [41].

2.1.6.3 Who provides UAM services?

At the moment, **private agents** are the ones most interested in operating UAM services in the future. Many of the companies that are involved in the development of VTOL vehicles have taken the first steps to establish themselves as UAM operators (e.g. Airbus, Ehang) while others have initiated partnerships with other companies from the mobility ecosystem (e.g. Boeing-owned Aurora and Uber). However, public authorities are starting to cooperate with these stakeholders to develop pilot projects that will precede full-scale operations.

2.1.6.4 What is the role of the service in urban mobility? What are its opportunities and risks?

In principle, UAM is conceived as a tool for **solving road congestion** problems and **cutting travel times** through a zero-emission alternative [45]. However, it is clear that both travel demand patterns and contribution to sustainable mobility will vary depending on vehicle features, prices and door-to-door travel times [46]. Giving the road congestion problems and the proliferation of urban sprawl, UAM concept seems more popular in US than in Europe, since long commute trips are the most likely to be attracted by this mode. The initiatives in Europe regarding drones and cities are more focused in applications such as **urban delivery** or **emergency transport**. In the absence of full operational systems, stated-preference surveys show that potential users seem particularly interested in trips to airports and recreational trips [42]. Indeed, some precursor experiences based on helicopters are focused on niches such as trips among airports within a metropolitan area [45]. In addition, model simulations provide evidence that UAM has a potential for providing a cleaner way to perform certain trips in metropolitan areas, especially those that are longer, e.g. between suburban areas and urban cores [47]. In general, the stakeholders involved in the workshops and the Delphi poll conducted in MOMENTUM expressed their scepticism about the possibility of a popularisation of UAM services as a widespread mode across European cities.

2.1.6.5 What are the conditions for the success or failure of UAM services?

At the moment there are no commercial services fulfilling all basic characteristics of UAM (e.g. the use of VTOL vehicles), but there are some precursors across the world:

- Voom services in **São Paulo** and **Mexico City**: Airbus launched this booking platform for helicopter providers in 2016 to increase the availability of this mode in congested cities. The prices are up to 80% less compared to traditional helicopter services [41].
- **New York**: there are several operators offering helicopter services between airports and Manhattan, Uber being one of them [48].

Apart from these previous experiences, there are some relevant pilot projects or initiatives regarding UAM in preparation for the incoming years:

- **Paris**: one of the high-profile cases in Europe is the initiative launched by Airbus and RATP (Paris' public transport operator) for 2024 Olympic Games. The pilot project will focus in services between Charles de Gaulle airport and the city centre [49].
- The **European Innovation Partnership on Smart Cities and Communities** (EIP-SCC) has launched an initiative related to UAM with 43 members, including a manifesto aiming to foster demonstration projects.
- **New Zealand**: Kitty Hawk, the manufacturer of Cora eVTOL vehicle, has reached an agreement with the Government of New Zealand for supporting their certification process, with the goal of starting operations in 2022 [41].
- **Uber Air** programme: following Voom example, Uber intends to expand its ridesharing platform concept to UAM. The company is preparing demonstration projects in Dallas, Los Angeles and Melbourne to start operations in 2023 [50].

These cases show the relevance of **public-private partnerships** between aviation regulators, transport authorities, manufacturers and potential private operators for supporting UAM initiatives.

2.1.7 Connected and Autonomous Vehicle (CAV)

2.1.7.1 What is it?

Connected and Autonomous Vehicles (CAVs) are characterized by communication technologies and artificial intelligence systems capable of performing part or all of the driving tasks, based on inputs from onboard sensors, infrastructure and other vehicles. This concept is not only applicable to cars. Actually, many initiatives have focused on public transport vehicles, such as autonomous buses [51, 52]. In this sense, an alternative concept with a broader approach has been proposed: **Connected and Automated Transport** or **CAT** [53]. This concept has been emphasized by policy-makers in the workshops conducted in MOMENTUM.

2.1.7.2 How does it work? What are the enabling technologies?

The idea of driverless cars is far from new, but it has not been until recent times that the industry started to push towards this innovation with the aim of commercializing fully autonomous vehicles [54]. CAV technologies are based on introducing systems able to manage the relation of the vehicle with other vehicles, the infrastructure and the environment. This includes **sensoring** and **connectivity** functionalities, **autonomous decision-making processes** and subsequent **control and actuation procedures** [55]. It is widely accepted that the best approaches to CAV implementation will require **adaptation in the infrastructures**, for instance to enhance guidance systems functionalities [53]. Other major changes, such as the need of a centralised traffic management procedure, are yet to be discussed [53].

The US-based Society of Automotive Engineers (SAE) published in 2014 a definition for several elements of the CAV context and a taxonomy consisting in five levels that have become widely used [56]. Under its terminology, vehicle movements are guided by Dynamic Driving Tasks (DDT), that encompass both the motion of the vehicle and the Object and Event Detection Responses (OEDR). DDT take place in a given Operational Design Domain (ODD), which refers to the environment where the vehicle is moving (e.g. a dedicated lane, a traditional road...). According to what extent DDT is assisted by automation, SAE defines five levels (Table 3).

Table 3 – CAV automation levels. Source: adapted from [56]

Level 1	An automation system controls either lateral or longitudinal motion of the vehicle within a given ODD, but the driver is expected to perform the remainder of driving tasks.
Level 2	An automation system controls both lateral or longitudinal motion of the vehicle within a given ODD, but the driver is expected to perform the remainder of driving tasks.
Level 3	Passengers become "fallback-ready users" of the automated driving system within a given ODD and intervene only when requested from this system.
Level 4	Passengers are not expected to intervene in any case within a given ODD.
Level 5	Passengers are not expected to intervene in any case, regardless of the environment.

2.1.7.3 Who provides this technology?

Traditional vehicle manufacturers are promoting innovation programmes for the provision of this technology, but **other players are entering the market**, such as technology companies. For instance, Google has heavily invested in research programmes towards the development of CAV concepts, leading to the establishment of a subsidiary company called Waymo. Apart from manufacturers, the highest automation levels require also adaptations from several infrastructures. This involves **road authorities**, but also other public and private agents, such as mobile phone operators that provide 4G and 5G connectivity [52].

2.1.7.4 What is the role of this technology in urban mobility? What are its opportunities and risks?

There is a growing interest in analysing what will be the role of CAVs in urban mobility and how it can be included in the urban mobility planning processes, since it may have important impacts already from low implementation rates [57]. At the same time, it is uncertain to what extent car ownership, parking needs, or distance travelled would evolve [57, 58]

Automation is perceived as an opportunity for a **more efficient public transport**, since it can contribute to more dynamic systems and decrease operation costs [59]. CAV technologies can secure the viability of public transport innovations, such as DRT, and **facilitate the management of ridehailing** systems [58]. In addition, automated cars can increase traffic safety if the technologies are sufficiently reliable, making **easier to implement traffic calming** measures such as shared spaces [60]. Depending on the business and ownership models underlying CAV deployment, it may contribute also to **reduce the need of urban space for parking** cars [51, 52].

However, CAV technologies involve some risks for sustainable urban mobility. If automation is fully applicable to private cars at low prices, it may increase the attractiveness of this mode, leading to more congestion due to **modal shift from public transportation and active mobility** [57, 59]. Moreover, it can enable people living in metropolitan areas to move even further from inner cities, **extending suburban areas** and sprawl [52]. Apart from these spatial effects, there is a concern about the transparency and competence rules in the CAV market. Some commercial strategies may **increase inequalities in mobility and accessibility**, since vehicles from each manufacturer may cooperate among each other to cut their travel times at the expense of others [60]. In addition, many risks have been identified from a cyber-security perspective. **Software attacks** affecting the vehicle normal operation can compromise data privacy and safety itself [61]. As it occurs with any innovative technology with strong implications in safety terms for the user, there is a risk that potential design failures and **driver premature overconfidence** situations may lead to major accidents, which could cause a reduction in the attractiveness of autonomous driving [62]. Finally, the full predefinition of the driving process requires to solve **moral dilemmas** such as victim preference in irreversible situations, whose answer is far from reaching consensus [63].

2.1.7.5 What are the conditions for the success or failure of CAVs?

Many vehicles already incorporate some functionalities that are in line with first levels of automation. However, highest levels depend not only on vehicle developments but also on cooperative infrastructure based on ITS systems, which requires the involvement of public authorities. Most European countries have launched **programmes for supporting CAV innovations**, testing and implementation. Furthermore, the EU is willing to embrace large scale demonstration pilots able to evaluate the maturity of CAV technologies [53]. In urban contexts, US cities have been more active in promoting CAV. For instance, **Boston** has designated a large-scale area as a testing for CAV, with gradual expansions to mitigate initial safety concerns and collaboration with ridehailing companies such as Lyft to provide services based on autonomous vehicles [64].

Successful conditions for the implementation of CAV can be grouped in two areas: **user acceptance** and **management**. In terms of acceptance, there are still open questions regarding how users can feel safer and be attracted by these vehicles. Current automation experiences generally require drivers to remain almost as alert as in manual vehicles and have shown limited safety improvements [65]. In terms of management, it is clear that public-private partnerships are a must to conduct pilot projects capable of demonstrating the benefits and outcomes of this technology [64].

2.1.8 Mobility-as-a-Service (MaaS)

2.1.8.1 What is it?

Mobility-as-a-Service (MaaS) is a model for the provision of transportation services based on the integration of various forms of transport into a single package accessible by end-users on-demand [66]. MaaS intends to **bundle a series of mobility services** that are not owned by the end-user, to provide a **navigation application** with multimodal functionalities covering the entire trip chain, and to include a **booking platform** that centralises end-user interaction with booking and ticketing procedures of the different service providers. The progressive implementation of MaaS functionalities can be visualised through different levels [67], as shown in Figure 2.

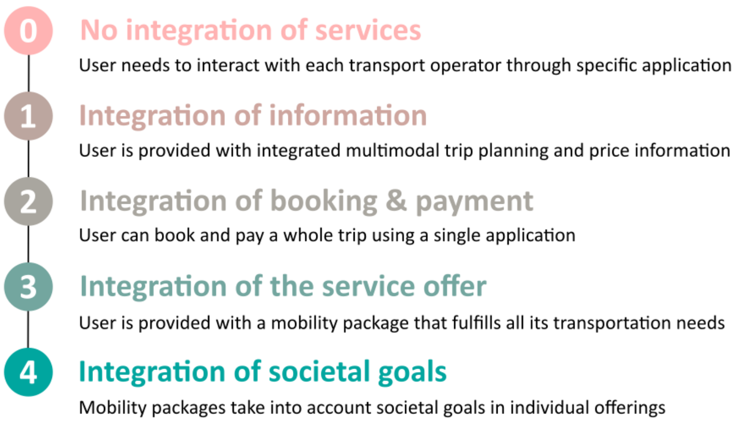


Figure 2 – MaaS topology, adapted from [67]

2.1.8.2 How does it work? What are the enabling technologies?

Internet-based and wireless technologies enable the main requirements for the provision of MaaS platforms [26]. As it is the case of the emerging mobility services themselves, smartphone applications would be the interface between end users and MaaS providers. In their most simple form, MaaS apps are mostly navigation apps, since they provide integrated multimodal trip planning together with price information.

However, when most advanced MaaS frameworks start to be deployed, additional enablers appear. Basically, there is a need for **interoperable systems** between the different mobility operators and the MaaS provider. As it happens with innovative payment methods, interoperability includes not only the technological aspects but also clear legal and financial procedures between all parts.

2.1.8.3 Who provides MaaS?

A **MaaS operator** acts as a broker between the customer and the different mobility service providers. By means of an app, he provides an overview of the service offer to the end user, collects the reservations and bookings, informs the end user before and during their trip, and settles all payments between the different parties involved [40]. At the moment, both private and public stakeholders are developing MaaS applications.

2.1.8.4 What is the role of MaaS in urban mobility? What are its opportunities and risks?

MaaS offers several opportunities for urban mobility. Firstly, it can **promote sustainable travel and reduce its environmental impact**. By improving the integration of transport services, MaaS could reduce private car ownership. Also, by enabling a more transparent presentation, situational awareness about available services improves, which could increase the use of public transport and shared services. Secondly, it can **improve the efficiency of existing transport services and resources**. For instance, excessive demand in peak-hours can be redirected to under-used routes or other transport modes. This increases available capacity and can help to reduce congestion. Thirdly, it can **provide better accessibility to people with disabilities or reduced mobility**, since MaaS offers a personalized door-to-door approach including a wider variety of travel options which increases accessibility especially for people with reduced mobility. Finally, MaaS applications collect valuable **data for transport planning**, such as data about intermodal trips [68, 69].

At the same time, there is a risk that MaaS can backfire and lead to less sustainable travel, in case it promotes **modal shifts from active modes and public transportation to other modes** [40]. Following this, MaaS could accentuate some of the potential risks of merging mobility forms. Empirical evidence regarding the impact of MaaS is to this day inconclusive and limited [70]. Whether there is a shift towards sustainable travel or away from it, depends largely on the set of available MaaS products and their attractiveness.

2.1.8.5 What are the conditions for the success or failure of carsharing and motosharing services?

Europe has hosted several MaaS projects, from which the following are good examples [68]:

Whim – Helsinki, Finland

Whim, which is in operation from 2016, allow users to plan their trips, book mobility services and get electronic tickets. It includes services like taxis, rental cars, bikesharing and public transport. It has been observed that the users of Whim tend are more likely to use multimodal options, integrating taxi and public transport more often than other travellers. In addition, they tend to choose more frequently bikesharing as a solution for the first and last mile in combination with public transport trips. The results indicate that most users are replacing cycling and walking trips with public transport and taxi. This implies that there are no major differences in the use of private car among Whim users and the rest of the population.

UbiGo - Gothenburg, Sweden

UbiGo was a Swedish pilot that ran between 2013 and 2014, in which 70 households paid their transport costs upfront by choosing prepaid bundles based on their own needs. It was observed that the participants made considerably more use of carpool services and public transport. The use of private car among participants who owned one fell by 50%. However, the group that participated in the pilot was selective and not representative of the entire population. This makes it difficult to draw any general conclusion.

SMILE - Vienna, Austria

This pilot was organized in Vienna by the city utility company and its transport operator in 2015. SMILE integrated a wide array of transportation solutions. With SMILE, users could plan their trips, book mobility services and get electronic tickets. Half of the participants were found to increase their use of public transport, while only 10% and 4% reported an increase in the use of bikesharing and carsharing, respectively. Crucially, around 20% of the participants indicated a decrease in the use of private car.

These experiences and the related literature show that there are two main conditions for a successful implementation of MaaS [71, 72]: (i) a MaaS operator must **be able to set up its services** in a city or region; (ii) users must be **willing to change their current mobility behavior** and start using MaaS. With regard to the first condition, MaaS can succeed if a wide range of transport modes are available, operators are willing to share their real-time data and are open to third parties for selling their services via e-ticketing [70]. While these aspects are mainly technical and regulatory in nature, the ultimate success of MaaS depends on its perception by the user. Iyt is difficult to change travel behaviour without a trigger for doing so, especially for recurrent trips. Studies have reported four fields where MaaS can offer added value [40]: **cost savings**, use convenience through clear and **user-friendly applications, freedom of choice** not only in terms of modal choice but also in terms of vehicle choice, and high **customisation** levels.

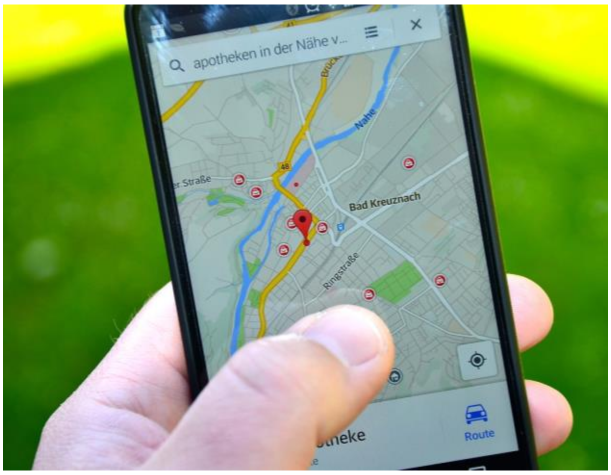
2.1.9 Navigation services

2.1.9.1 What are they?

Navigation services, also known as *Advanced Traveller Information Systems (ATIS)*, provide online mapping and routing assistance, among other aspects, through mobile applications. In recent times these navigation apps have replaced printed road maps and timetables of transport services for a significant part of the population. Navigation apps are already amongst the most used apps on smartphones, e.g., Google Maps, is amongst the most popular 5 apps by number of downloads and frequency of usage [73].

2.1.9.2 How do they work? What are the enabling technologies?

It has been acknowledged that **GPS positioning** has been a key enabler of emerging mobility services, but its role is even more central in the case of navigation services. GPS based car navigation premiered at the beginning of the 1990s in Japan, but a real breakthrough in development and production arrived after the USA ended the 'Selective Availability' program in May 2000, when high-precision GPS signal became publicly available. In the pre-smartphone era development focused on integrated or handheld in-car units (e.g. TomTom, Garmin). These were off-line devices with an on-board mapping database (kept recent by factory updates or via memory-card purchases), and were only capable of giving the fastest route towards a chosen destination.



With the breakthrough success of the **smartphone**, the stress shifted from hardware and static data to actual navigation services that rely on continuous connection to the internet. The information was enriched, since users could get real time traffic information (e.g. congestion) and corresponding routing suggestions, based on advanced algorithms that run in the cloud and not on their devices. By using the app, travellers also provide traffic flow data and have the chance to report dangerous situations such as accidents, that can be immediately shown to other users of the app (e.g., in Waze). In addition, navigation services started to include public transport, cycling and walking information and routing, since their use ceased to be restricted to those drivers equipped with GPS in their cars. In this line, the **standardisation of public transport supply data** is also a key enabler of the multimodal navigation apps [74]. General Transit Feed Specification (GTFS) developed by Google and Transmodel, promoted by the European Union, are some of the most known standards. The **improvement of routing algorithms** and their deployment and running in the cloud (where the computational capabilities are much higher than in on-board device) is also behind the success of navigation services. While basic car-routing is a straightforward task, the inclusion of real time traffic and multimodal route planning, with input from time-dependent multi-criteria searches, is definitely necessary to enable the navigation services of the future [75]. Emerging mobility solutions raise the complexity even further, since it concerns journeys that combine schedule-based transportation with unrestricted modes (i.e. walking, cycling and driving) and services where availability might be strongly time and demand dependent (e.g. taxi and shared mobility services).

2.1.9.3 Who provides navigation services?

Most used navigation services are run by **private companies**. Companies such as Google, Apple, Here or Baidu (in China) will likely remain the largest catalysator of their evolution. The upcoming local MaaS providers are also a relevant player to take into account, as well as all the agents that have to feed with information these navigation apps (e.g. public transport operators).

2.1.9.4 What is the role of the navigation services in urban mobility? Which are their opportunities and risks?

While being restricted to road traffic, the main role of ATIS was to **allow drivers to cut their travel times** by enabling alternatives to congested routes [76]. Amidst the current atmosphere of climate consciousness, our society **looks for alternatives of passenger car use**, and for better ways of car use, which puts multimodal transit, along with smart and optimised route planning in the spotlight [77]. The **MaaS** approach relies heavily in the potential of navigation services. Comprehensive and easily accessible mobility services (where accessibility is driven by better and better navigation apps/services) will help us exploit the existing fleet in a more efficient way, realise a modal shift away from private car use, and facilitate the development of future-proof transportation options. Initiatives such as TM2.0 aim to release the potential of navigation services for traffic management [78], and gamification strategies may increase the use of sustainable modes [79]. **Indoor navigation** paves the way for an extended routing experience, that actually works as a door-to-door trip planner. This could be very useful in, e.g., navigating large metro stations with multiple entrances and exits, or managing the crowdedness of certain hotspots by re-routing people over alternative points. High precision, location-aware technology would also be highly beneficial for **guiding visually impaired** individuals. Risks can be summarised under the following keywords:

- A **mismatch between the intended road hierarchy and routing recommendations**: Waze have reportedly and repeatedly routed large amounts of traffic over residential roads (e.g., [80]), which are simply not designed to handle such a massive volume of vehicles. This causes not only nuisance in the form of noise and air pollution for residents, but also leads to a faster degradation of the infrastructure [81].
- **Uncontrolled network use can cause unexpected spill-back effects**: drivers following an alternative suggestion around a congested road segment could block an even larger portion of the network, leading to an overall higher total travel time. Alternative roads and flexible responses to congested situations are good, but they need to be better regulated.
- **Monopolisation and segmentation**: depending on the commercial agreements between mobility service providers and navigation service providers, some transport options may not be available in certain navigation apps. Moreover, there may be incentives to route people towards a certain service depending on the commercial relation between those providers, independently on the impacts for the sustainable mobility in the city.

2.1.9.5 What are the conditions for the success or failure of navigation apps?

The example of Google Maps and Waze illustrate the best how navigation apps became important parts of our everyday lives. Recently, local MaaS providers (and applications) have started to appear, but their development and future success depends heavily on how policies and regulations can accommodate the needs of a rapidly changing mobility landscape.

An important parameter in making a successful navigation service is **personalisation**. Users appreciate customisation options that have an influence in the suggested alternative routes and modes, powered by trained intelligent algorithms that learn from the behaviour of individual users, leading to suggestions that match the users' needs better and better over time [77]. In this sense, widely used platforms, as Google Maps or Waze, have a competitive advantage since the data provided by other (similar) users have shown to improve personalisation of route suggestions.

With technology society needs to change too. People will have to make conscious choices, aware of not only the personal (time and monetary) but also the societal cost (including energy use and emissions) of their travels. Apps are being developed where users can see what is the **healthiest route** for cycling or walking (in terms of air pollution), which promotes slow modes not only by showing their health benefits, but also by showing the **amount of energy and emissions** that can be saved by not taking the car for the trip in question. This is something that should be included in a multimodal trip planner too, where trade-offs are not only calculated in time and costs, but also in health and environmental benefits and impact too.

2.1.10 Innovative payment methods

2.1.10.1 What are they?

In recent years, several new payment procedures have been implemented in some public transport networks. In general, this concept groups all methods that have appeared after the last consolidated innovation in ticketing systems, which were contactless cards [82]. Therefore, it includes smartphone-based ticketing as well as the direct payment and validation with credit cards (EMV-based ticketing).

2.1.10.2 How do they work? What are the enabling technologies?

Payment tools have evolved in the last decades from traditional models based on purchasing physical tickets (e.g. paper, coins...) to payment methods that have integrated latest technological and administrative advances. The first evolution that improved ticket purchase and validation were magnetic strips, which were largely deployed during the 1970s and 1980s [82]. This method was surpassed by contactless cards in the early 2000s, which allow passengers to board vehicles or to enter to service stations in a much more agile way compared to previous contact systems [83]. The last decade has given way to two key innovations in the ticketing context: (i) **Near-field communication (NFC)** technologies, which have multiplied the number of devices capable of supporting payment transactions [84]; and (ii) **operators' openness to payment tools from external agents**, eliminating the need for a card issued by the operator or transport authority related to the service [85]. Both innovations have resulted in two growing new payment and validation methods: **smartphone-based ticketing** and **EMV-based ticketing**. The former consists of incorporating service tickets to mobile apps, while the latter consists of taking advantage of the standards developed by the payment card industry to enable direct contactless payment and validation from bank debit and credit cards.

In addition to the solutions based on NFC systems, it must be highlighted that **emerging mobility solutions** such as shared vehicles or ridesharing schemes also change the way transport services are paid. These services are accessible from smartphone applications that do not require contact or near field communication between the mobile device of the user and the vehicle. Payment is processed by the application and the system unlocks the vehicle when it checks that the user meets the conditions for performing a trip.

2.1.10.3 Who provides innovative payment methods?

The decision of implementing a new payment method is in the hands of **transport operators**. EMV-based ticketing is often developed in collaboration with **financial companies** that provide credit cards (e.g. Visa, Mastercard...), under contracts that include the creation and maintenance of payment gateways. The utility of smartphone-based ticketing depends also on the share of mobile phones with NFC capabilities, although this is constantly increasing.

2.1.10.4 What is the role of this trend in urban mobility? What are its opportunities and risks?

Payment tools are key elements in mobility services. The usability and agility of payment methods contributes to a faster and more attractive transport service. Given its broad application in the last decade, it has become clear that any contactless technology enables a series of advantages in transport ticketing in comparison to previous methods such as magnetic strips. The main opportunities that innovative payment methods bring about for public transport systems are the following [83, 85–87]:

- Reduced **maintenance costs** for transport operators.

- Reduced opportunities for **fraud**.
- Increase in **commercial average speed** of services where validation takes place on-board.
- Facilitated **interoperability** among different transport systems and operators, and even beyond transport services (e.g. integration with other public services).
- Increase the **flexibility of fare policies**, by applying fares to each user depending on the number of trips observed during a certain period.
- Since each transport user holds a unique payment tool (e.g. smart card, mobile device...) it is possible to extract valuable information about **use patterns**.

In addition, smartphone and EMV ticketing have specific advantages to be added to those from contactless systems. For instance, visitors **do not need to purchase the specific card** of the transport system to access the services. This alleviates one of the perceived drawbacks of the replacement of single paper tickets with contactless cards [85].

One of the main disruptive features of the most innovative solutions is that transactions may not be reflected in the physical payment tool: while in traditional ticketing the number of tickets purchased or used it is registered in the payment tool itself, this is not the case in EMV ticketing. This introduces **challenges related to the legal rights and obligations** that are associated to a transport ticket holder, such as compulsory travel insurances [85]. Moreover, certain agents have expressed concerns about the **potential misuse by third parties** of all the data generated by these transactions [83, 88]. Finally, smart ticketing solutions can lead to financial exclusion of certain users, since bank accounts are needed [83].

2.1.10.5 What are the conditions for successful or unsuccessful implementation of innovative payment methods?

Most of Europe regions and metropolitan areas are considering the introduction of smartphone-based and/or EMV payment methods for public transport services. The existing experiences regarding the introduction of innovative payment methods show that a **simple and user-friendly framework** is vital for the success of the initiatives [87]. Two specific cases are outlined here:

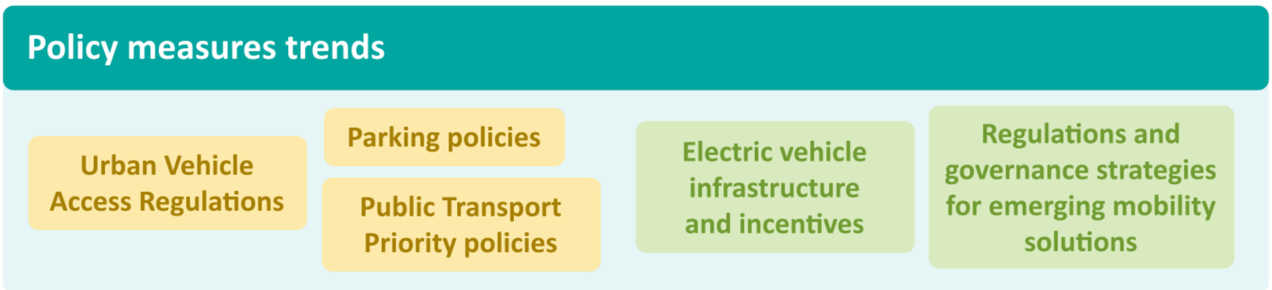
- **Transport for London (TfL)** case is perhaps the best known among the sector. The large number of visitors to London motivated this transport authority to find solutions that are less costly for sporadic use and easier to understand by end-users. Following this, TfL selected EMV payment as the most suitable tool, with the aim of cutting the costs in fares collection up to 6% of the revenues. TfL model can be regarded as "aggregated pay-as-you-go" [89]. Under this approach, users can make several multimodal journeys touching in or out with the contactless credit card. At the end of the day, the daily charge is processed by settling the journeys made, and the charge can be checked in the bank statement. By April 2019, 55% of the trips were paid by this system [90]. TfL itself has identified as a key success factor the high level of integration of transportation services in Greater London [91]. Thanks to this, the implementation has been easier across all modes.
- **Wrocław**, Poland has recently initiated the operation of the new payment system based on a versatile platform that includes smartphone, EMV and contactless card methods. This initiative has a background of pilot projects as early as 2011 that took advantage of the early adoption of contactless payments in Poland [92]. This suggests that broad implementation of technologies that enable these innovative payment methods is a key successful factor.

2.2 Policy measures trends

It is clear that supply innovations are transforming urban mobility, but policy measures are also a key element in the changing landscape of transportation in cities. Mobility management is not a minor issue for local governments and related governmental stakeholders, rather it appears frequently at the spotlight of public policy discussions in cities. This demonstrates the need for a continuous improvement of modelling and decision support tools that provide policy-makers with evidence-based strategies to achieve sustainable mobility goals.

The section examines the application of several policies that public administrations promote for managing urban mobility. For each policy, the **technical and societal implications** of their implementations are reviewed. The section also looks at the **opportunities, risks and successful factors of each policy**, in a similar fashion to what is done for supply innovations in the previous section. Examples from several urban areas illustrate the strategies that cities follow towards a successful application of the measures included in these policy packages.

The selected policy measures combine strategies that have a long history among sustainable mobility planning in Europe with the relatively novel public responses to the supply innovations reported in this document. The first group includes the case of **access** and **parking regulations** for private vehicles and the case of the **public transport priority** measures. Those cities listed among the early adopters of these solutions are already familiar with the successful implementation of these measures. However, the inclusion of these in several guidelines for mobility planning have increased the interest in them across Europe. It has to be noted as well that the maturity of ICT solutions has enabled new ways of deploying such measures. Moreover, the emergence of new mobility solutions requires some adaptations of these consolidated strategies. As a consequence, it is worthwhile to revisit them. The second group includes the **electric vehicle infrastructure and incentives**, and the **regulation and governance frameworks for emerging mobility solutions**. These two policies are the response of public bodies to the supply innovations explored in the previous section, and therefore are very relevant to the conceptual framework of MOMENTUM.



2.2.1 Urban Vehicle Access Regulation schemes (UVAR)

2.2.1.1 What are they?

Urban Vehicle Access Regulations schemes (UVAR) are a collection of policy measures restricting or discouraging the use of cars and other motorised vehicles over certain areas. The main motivations behind UVARs are usually structured around three cornerstones: (i) improving air quality (e.g. Madrid), (ii) reducing congestion (e.g. Milan, London, Stockholm), and (iii) raising revenues via an urban road tolling network (e.g. Norwegian system) [93].

2.2.1.2 How do UVARs work?

UVARs implemented in actual cities usually contain a mix of access regulations, restrictions, and tolling schemes, balanced according to the local situation. The most important types are **Low Emission Zones (LEZ)** and **Urban road tolls**. Where congestion is critical urban tolls might have a stronger role, while where air quality is the most problematic, emission-based access regulations tend to dominate the policy package. Most LEZs apply more stringent criteria for diesel cars than for petrol ones. These usually exclude older diesel vehicles first before extending the restrictions to more recent generations. Urban road tolls, also known as *urban road pricing* or *congestion charges*, use pricing mechanisms to make users conscious about the impacts that they impose on society and environment when they drive. This way users pay for their externalities (e.g. pollution), which consequently encourages the redistribution of demand. LEZs are often combined with other urban road charging schemes. As an example, in some LEZs polluting vehicles might also enter, but have to pay more for access.

Other schemes, which are not regulated by payment or emissions, are sometimes referred to as **key Access Regulation Schemes (Key-ARS)** [94]. This includes several schemes such as pedestrian streets and areas, zones where a permit is required to drive in to a given area (e.g. access only for residents), zones where access is only granted for certain vehicle types or weights (e.g. only vehicles under 3.5 tn) or zones where access is restricted at certain times of the day.

Several techniques have been adopted to regulate the vehicles access to urban infrastructure [93]:

- **Cordon-based**: vehicles are not allowed to cross a cordon, which might vary by time, direction of travel, vehicle type, and location. This is both applicable for full access restrictions and for urban road tolls.
- **Point-based**: vehicles are not permitted to cross a specific point in the network (without payment, or specific type of vehicles), e.g., a bridge, or enter a specific section of the city.
- **Area license-based pricing**: a fee is charged for driving within an area.
- **Distance or time-based**: a simple pricing scheme based on the time or distance a vehicle spends along a congested route or a specific area.
- **Occupancy-based**: when vehicles with a higher occupancy (buses, taxis, cars with more than one occupant) get access to specific lanes or pay less to enter a given area.

These measures can be enforced by cameras, physical barriers or local authority officers. The implementation of UVARs is often accompanied by circulation plans to manage the expected changes in traffic patterns. The plans often include the redesign of the streets where traffic is expected to decrease, promoting active mobility and prioritising public transport. Parking restrictions are often set up in combination with UVARs, as well as speed limits, in order to reduce the resuspension of fine particulate matter from road surfaces [95].

2.2.1.3 Which are the opportunities and risks of UVARs for cities?

Among the aforementioned three main motivator factors for UVARs (improving air quality, reducing congestions, and raising revenues) it must be acknowledged that the **need for clean air** plays a prominent role. There are more than 480,000 premature deaths annually in the EU due to air pollution [96]. The human health damage from air pollution is estimated between 427 and 790 billion Euros per year. Transport emissions account for 60% of NO2 concentrations in cities, and diesel cars are responsible for almost 75% of this. Diesel emissions have been classified as carcinogenic by the World Health Organisation [97]. As there are no sufficient actions to clean up the existing fleet, cities have taken the lead to make air pollution levels safe.

Congestion costs nearly 100 billion Euro, or 1% of the EU's GDP each year. The marginal external costs generated by trucks, cars, and motorcycles driving through dense urban regions during the peak hours is much higher when compared to the one of buses or trains travelling through non-urban areas in off-peak periods, and therefore UVARs are an opportunity to reflect the differences in the generated externalities on the pricing structure for different vehicle types. This in turn can **raise funds for sustainable mobility**.

Risks are mainly embedded in the growing diversity of different regulation schemes which are being implemented across the EU. This diversity can hamper the achievement of economies of scale and contribute to a **fragmentation of the single market**. To deal with this risk, studies have delivered guidelines to assist policymakers in the successful UVARs implementation. Basing bans blindly on Euro classes is also somewhat controversial, as even some Euro 6 diesel cars emit more than 10 times the legislative NOx limit in real-world use conditions [98].

There are also some concerns about the social impacts of LEZs, since the cleanest vehicles are not affordable for everyone. In addition, some LEZs open the room for special exemptions that can be purchased (e.g. daily-passes). This would imply that LEZs **are more restrictive to low-income population**. Similarly, those **business who do not have the financial capacity to renovate their fleets** may be more affected than bigger companies [99]. Carefully selected subsidy packages specifically crafted for the most vulnerable set of citizens is a good practice to follow to ease their transition. The implementation of UVARs usually raises concerns about the fact that restrictions tend to **affect those living outside the UVAR zone** and have to commute into it while most external benefits are enjoyed by the people living inside of it. Finally, the installation of cameras raises **privacy concerns**.

2.2.1.4 What are the conditions for the success or failure of UVARs?

The first European LEZ was introduced in Sweden in 1996 (Göteborg, Malmö, and Stockholm), targeting the most polluting diesel trucks and buses in the city centres. Currently more than 260 LEZs exists across 12 EU member states, of which 250 concern passenger cars. While most of these can be found in the Western EU, several Central and Eastern European cities are considering the introduction of some sort of LEZs.

General congestion pricing schemes are much less common compared to LEZs or other access regulations, but significant examples exists through various parts of Europe [100], e.g. in **London** (introduced in 2003), **Stockholm** (since 2007, following a test period in 2006), and **Milan** (in operation since 2008, with a shift from pollution to congestion charging in 2012). Each of these cities use cordon charges, where automated ANPR cameras control access to the city centres. In each location there was a **wide political and public debate before setting up** a permanent system, in Stockholm and Milan even a referendum was held. In each case, at the time of introduction citizens were not in favour, but **after implementation the public opinion has turned**. The gross revenues (excluding fines) in these two cities are around 2.5-3.5 times higher than the operating costs. Each of these schemes were supported by a **substantial increase in public transportation**. As a result, car traffic has decreased (-20% in London and Stockholm, -35% in Milan) thanks to a modal shift towards public transport (+10% in London, +12.5% in Milan). In contrast with common opinion, there was no significant effect on retail or property values. Congestion initially decreased by 30% in London, but since the city have turned the reclaimed road space into bike lanes and pedestrian areas, it has returned to similar levels as before (but still including less vehicles on the road). Reduction in traffic also reduces the number of chargeable passengers, which has a significant effect everywhere.

2.2.2 Parking policies

2.2.2.1 *What are they?*

Sustainable mobility depends on achieving the best balance between all modes of transport, reflecting the advantage of each mode in relation to the different circumstance of each individual journey. Parking policies are a group of instruments that aims to restore this balance in cities where car dominates by regulating or restricting the space available to cars to discourage its use in certain areas.

2.2.2.2 *How do parking policies work?*

There are several policies to improve parking management from a sustainable mobility perspective. Firstly, it is common that cities enforce regulations for setting up **parking time restrictions and charges** that deter commuter parking at specific locations (mainly in the central areas of cities). Secondly, restrictions are often accompanied with **Park & Ride (P&R) schemes**, that consist in the provision of parking facilities outside the congested areas, connected with fast and comfortable public transport services to large transport hubs inside the city. The use of these facilities is promoted through combined tickets (day tickets and longer subscriptions) for parking and public transport access [101].

Parking policies should be formulated and implemented in the framework of a broader cooperation involving various affected stakeholders, including the local (city level) and regional (broader agglomeration level) public transport providers, and the representatives of the authorities that are responsible for land use, road networks, and urban planning, etc.

2.2.2.3 *Which are the opportunities and risks of parking policies for cities?*

Private cars are immobile 95% of the time [101]. Cities suffer from intrusive, anarchic parking that blights the urban landscape and impedes the passage of other vehicles, buses, bicycles and pedestrians. In this line, parking policies are an opportunity for cities to **achieve a better usage of public space**. In addition, it is widely acknowledged that parking restrictions are a key measure to **make private car less attractive** as a modal choice in comparison to other modes [102]. Park & Ride schemes can also **increase the demand of public transport in suburban areas**, which are often too disperse to generate substantial demand in the immediate access and egress area of stations and stops [103].

Apart from some of the risks already mentioned for UVARs and that are also applicable to parking policies, the **planning and design of P&R** facilities and incentives have to **avoid an unintended promotion of car usage** [103, 104]. Parking space should be strategically located such as near PT stations, encouraging people to use PT and leave their car where parking is not at the expense of more valuable land uses. Allocating space to parking without an underpinning policy consists in making car use relatively easy and convenient, increasing the car-dependency of cities.

2.2.2.4 *What are the conditions for the success or failure of parking policies?*

There are many examples of parking policies that can provide insights on which aspects seem more crucial to achieve a successful contribution to sustainable mobility [105]:

Kuala Lumpur, Malaysia

Kuala Lumpur is the largest city and national capital of Malaysia. It covers an area of 243 km2 and is among the fastest growing metropolitan regions in South-East Asia. The P&R was first established in 1997 and is managed by the Land Public Transport Commission. P&R sites are usually located within 300m of PT stations and equipped with a pathway to the station. Mobility services available at P&R are Bus and Taxi. PT frequency at P&R is every 2 minutes during peak hours. Theft and robbery are among the perceived security risks associated with P&R. Preventive measures include Panic/alarm buttons, security guards, CCTV and dedicated ladies parking spaces. Authority believes new technologies will allow a better P&R promotion that will enhance awareness among users regarding nearest P&R location as well as available bays. It also believes that there would be no impact of autonomous vehicles on parking policy.

Akershus county, Norway

Akershus County, which surrounds Oslo, is the second largest City County of Norway after Oslo. It covers an area of 4,918 km2. The P&R was first established in 1985 and further development is still in progress. P&R is managed by various operators and authorities: Norwegian National Rail, Public Roads, Municipality PT Operator and County Council. Monthly users benefit from low rates for both P&R and PT. Priority access to available spaces is given to commuters with monthly tickets. Mobility services available at P&R sites are mostly Train and Bus. PT frequency at P&R ranges from 10 to 30 minutes. No special security risks are associated with P&R except bicycle theft. Authority believes new technologies may provide a lot of possibilities if decisions are taken at a political level to use market mechanisms to optimise P&R capacity. Authority believes autonomous vehicles will reduce the need for P&R in the short term while they will likely rearrange the whole transport system in the long term.

Barcelona, Spain

Barcelona is the capital city of the Catalonia Region in Spain and covers an area of 101 km2. It is one of the leading worldwide tourist destinations. The P&R was first established in 1990 with a regional focus on train station parking to encourage multimodal mobility. Further development is in progress to incorporate peripheral Barcelona district locations. P&R is managed by various operators and authorities: Àrea Metropolitana de Barcelona, Autoritat del Transport Metropolità, Transports Metropolitans de Barcelona (PT Operator) and other municipal administrations. P&R is usually free for local residents. Authority is looking into developing a combined P&R+PT rate that would be cheaper than the intercity parking rate. Mobility services available at P&R sites are mostly Train, with direct connections to the stations and street signage. PT frequency at P&R is every 15 minutes. No special security risks are associated with P&R. Authority believes new technologies will allow a better P&R promotion that will enhance awareness among users regarding nearest P&R location as well as a better integration with the mass transport system. Authority expects the use of autonomous vehicles will have an important impact on PT and P&R in the long term since it will probably reduce the need of parking spaces. They also believe it will affect mobility as a whole, although not in the short term yet.

2.2.3 Public Transport Priority policies

2.2.3.1 *What are they?*

Public Transport Priority schemes are part of the combined package of measures that numerous European cities have implemented with the goal of reducing car use over time. Given that surface public transport services are those sharing space with cars, Public Transport Priority concern these surface modes. The fundamental idea behind these schemes is increasing the relative competitiveness of public transport modes by giving buses and trams priority and better access on the road, resulting in a decrease in travel times compared to individual motorised transport [106]. The challenge is often to allocate more space to buses at the expense of cars. They are often combined with land use policies such as Transit Oriented Development (TOD) [107]. One of the most successful form of Public Transport Priority schemes is the deployment of Bus Rapid Transit (BRT) Systems, which deserves a specific focus.

2.2.3.2 *How do Public Transport Priority policies work?*

BRT Systems consist of large buses that run on **dedicated lanes** and stop at **well-defined stations**, and include a technology that enables passengers to **pay before boarding** [107]. They offer mass transport services at lower costs than rail-based modes, reaching the same levels of capacity, comfort and safety while retaining the flexibility of a bus with fairly short implementation times. Taking BRT as the most advanced measure towards Public Transport Priority, there are other partial measures (e.g. dedicated bus lanes, traffic lights priority) that improve average commercial speed of surface public transport [108].

Some cities are better prepared than others to deploy and accommodate BRT systems. Decision-makers should assess to what extent their conditions will support or constrain their development. In general, where public transport networks are still underdeveloped, BRT and related measures require first to create a market for it, a process that involves the reform of the traditional bus and paratransit sector [107]. Public Transport Priority schemes are usually implemented by Public Transport Authorities (PTAs) in cooperation with local governments, since the redesign of street sections is often a responsibility of urban planning departments.

2.2.3.3 *Which are the opportunities and risks of Public Transport Priority policies for cities?*

Public transport is a major driver for urban sustainable mobility, thanks to its high efficiency moving people from one place to another. After years of decision-making that systematically favoured road infrastructures and cars, it is now pressing to reconsider the way we provide transport in relation to the city. The implementation of priority measures on roads is therefore an opportunity to increase the **performance of buses and trams**, in terms of travel times and reliability [108].

The implementation of priority measures must be accompanied with studies (e.g. simulation and modelling tests) that proves the benefits for the public transport operations without implying **the reduction of road safety conditions**, not only for private cars but also for pedestrians and cyclists [108]. In addition, the creation of **spatial barriers to active mobility** by hard separation measures of bus lanes from the rest of the street must be avoided. By dedicating special attention to these issues, the advantages of BRT and similar measures can be reinforced [109].

2.2.3.4 What are the conditions for the success or failure of Public Transport Priority policies?

There are numerous existing examples of successful measures concerning Public Transport Priority that can serve as an inspiration for future implementations. The following experiences reveal that aspects such as **cooperation between public administrations**, the introduction of BRT together with **urban renovations** and the **enhancement of bus services** using the priority functionalities are key elements for the success of these interventions [107].

Manchester, UK

"The city of Manchester is implementing a bus priority package, with over 25 miles of key bus routes that have been either created or enhanced, making the scheme one of the largest investments in Greater Manchester's bus network in decades. The scheme comes with an integrated public transport network that comprises the first guided busway, new buses, cycling and pedestrian improvements. The benefits of the bus priority package are shorter journey times, more punctual and reliable bus services, better passenger travel experience, increased access to employment, improved connectivity to health care and residential appeal of local communities served by the scheme." [107]

Nantes, France

Nantes Metropole launched its Busway line in 2006 [110]. Operated with CNG articulated buses, its infrastructure is 100% dedicated to performance with right-of-way lane and priority at all crossroads. To face line saturation, 2019 will be a major step forward for the Busway with the upgrade of the line with fully electric double articulated buses with opportunity charging. Busway is perceived as to be an overwhelming success, as after 10 years ridership has more than tripled, and more than 92% of the customers have perceived a service improvement. The new service attracted new customers: people with new types of motivations behind their travels (leisure, shopping, etc.), and people who would have taken the car for the same journey before Busway (25% of the users). A survey showed that the perception of the Busway is even better than of the Tramway.

Montreal, Canada

In Montreal, the scope of the project is broader than the Busway of Nantes. It includes 11 km of reserved lanes in Montreal and Laval, 17 BRT stations (15 in Montreal; 2 in Laval) and 1 incentive parking facility (750 places) [111]. Yet the improvements extend to Municipal Infrastructures: i.e.: water and sewage upgrade, roadway reconstruction, public utilities displacement as well as improvements to Public Property with new lighting, new intelligent traffic lights and planting of hundreds of trees. The project is a consequence of the collaboration of the following stakeholders: *Autorité Régionale de Transport Métropolitain* (ARTM) that is the PTA, the city of Montréal, the transport ministry of Quebec with the City of Laval, the organisations in charge of infrastructures and public transport operators for partners as well as the boroughs.

2.2.4 Electric vehicle infrastructure and incentives

2.2.4.1 *What are they?*

Transport is one of the economic sectors with a higher contribution to greenhouse gases emissions. In this context, its electrification is a key factor for achieving global emission targets. The adoption of electric vehicles is promoted by several institutions through a series of incentives targeting both industry and end-users. In the first case, the incentives seek a commitment from manufacturers to develop more efficient and attractive electric vehicles. In the second case, the measures try to make electric vehicles more appealing to consumers, by counteracting the potential drawbacks of such an emerging technology through rewards or facilitating the use of the vehicles. Among these, electric vehicle infrastructure, namely battery charging or swapping points, is one of the most relevant measures to promote electric vehicle adoption.

2.2.4.2 *How do electric vehicle infrastructure and incentives work?*

There are three main types of road electric vehicles [112]: (i) Plug-in Hybrid Electric Vehicles (PHEV), as a transitory type that combines combustion and batteries; (ii) Battery Electric Vehicles (BEV), powered by plug-in batteries; and (iii) Fuel-Cell Electric Vehicles (FCEV), powered by hydrogen. While FCEV provides higher ranges and faster charging, the costs of FCEV are currently too high for expecting a fast market uptake in comparison to those of BEV [113]. Therefore, most incentives focus on **BEV promotion**.

Incentives to industry focus on **funding research projects** to improve the **capacity and charging speed** of batteries [114] which is a key feature in BEV attractiveness [115, 116]. Incentives to consumers take two complementary approaches: (i) **positive discrimination**, which includes policies such as special discounts in parking and toll fees, access to dedicated lanes, purchase grants or tax exemptions [112, 117]; or (ii) **deployment of charging infrastructure**, which intends to alleviate the **range anxiety**. This refers to the fear of not being able of completing a trip due to the lack of battery [115]. Following this, the features of electric vehicle infrastructure (number and distribution of charging sites, charging speed...) should guarantee that any intended trip is not going to be disrupted or modified due to the lack of battery. Residential in-house charging, which currently accounts for around 80% of total charging [118], seems not enough to alleviate range anxiety at least today, given that only a few years ago have BEVs started to provide ranges far above the average daily distances (e.g. around 30 miles for US [115]).

Charging points are usually classified in two groups [114]: (i) "normal" or **"slow" charging points**, whose transfer power is equal or less than 22 kW; and (ii) "high power" or **"fast" charging points**, whose transfer power is higher than 22 kW. It is considered that the viability of BEV depends on the deployment of fast charging points, since slow ones are not an effective incentive for a higher implementation of BEV [116].

In any case, the feasibility and implications of large charging networks is still unclear. **Public- and private-owned systems coexists** but the business model supporting these networks is still far from consolidated due to the low implementation rates of BEV [119, 120]. Most of the private initiatives rely in additional revenues (e.g. parking fees) or are promoted by big corporations that can afford such a strategic investment [118, 121].

2.2.4.3 *Which are the opportunities and risks of electric vehicle infrastructure and incentives for cities?*

While the modal shift to clean collective transport has a broader capacity of reducing the contribution of urban transport to local air pollution, BEV can still play a role in improving air quality by substituting ICEV in those trips where car becomes the only viable mode choice (e.g. in low-density suburban areas). As a result, the deployment of electric vehicle infrastructure and additional incentives is an opportunity for **reducing local air pollution**. Moreover, BEV and the associated infrastructure brings also the opportunity of **cutting noise pollution** levels [112].

Even with fast charging points, the time required for the charging operation is longer than the associated to a conventional car refuelling operation, so **queueing management** will be an issue at charging sites if BEV implementation levels become higher [116]. In addition, the **impacts of BEV-related electricity demand on urban power grids** are under study [115, 119]. This will depend very much on the temporal dimension of the daily demand for charging vehicles, i.e. to what extent do demand peaks coincide in time with traditional electricity demand peaks [122]. This opens the room for managing strategies to attempt a more even temporal distribution of the charging demand [123].

2.2.4.4 What are the conditions for the success or failure of electric vehicle infrastructure and incentives?

As discussed above, electric vehicle infrastructure is still anecdotal compared to the spatial coverage and density of refuelling infrastructure. European Union have set as a target to have 1 charging point per 10 EV [112]. However, tackling with range anxiety is not only a matter of the number of charging points but also of its **distribution across the territory**. In this line, electric vehicle infrastructure deployment emerges as an interesting facility location problem. Extensive research has been conducted to identify strategies and models capable of determining the optimum location of charging sites [115, 116, 124]. If the agents providing the infrastructure follow the outcomes of these studies its deployment and evolution is likely to be more successful than if no evidence-based guidelines are taken into account.

Another condition for the successful implementation of these systems is the **development of standards for the infrastructure**. These standards are basic for enabling charging interoperability, and therefore for achieving a seamless use of the charging infrastructure [121]. In addition, it is important that the data about the location, features and status of charging sites is shared among all stakeholders involved in the market, so that end-users can actually be aware of all the options for BEV charging [121].

Regarding specific experiences that can serve to gather lessons learnt, it is useful to look at the country with highest implementation rate of BEV in the world, which is **Norway**. There, BEV accounts for 6-7% of the private car fleet [116]. At the moment, any other country is far from these figures. Indeed, 25% of European BEV sales during 2018 took place in Norway [118]. The official goal is to achieve a 100% share of electric vehicles by 2025, including PHEV. There are several aspects interesting from Norwegian case:

- The effectiveness of specific incentives can be related to **very local aspects** [125]. This is specially the case for positive discrimination measures. For instance, discounts in tolls or priority access to dedicated lanes would only have an effect in areas where trips actually would make use of such benefits. This highlights the role of cities in adapting BEV incentives to the local contexts.
- **Positive discrimination incentives can be very attractive**, even more than electric vehicle infrastructure among crucial early adopters [120]. Indeed, despite its outstanding BEV market uptake in comparison to other countries, Norway is not the country with higher charging point per BEV rate.
- Among positive discrimination incentives, it has been found that **tax exemptions** were particularly attractive [125].
- The role of public initiative in introducing electric vehicle infrastructure is crucial, especially for ensuring that **charging sites reach also low-demand areas** [120, 121].
- Users perceive as important that registration and payment procedures for charging operations are kept **simple** [120].

Other countries are also putting efforts in deploying electric vehicle infrastructure. For instance, **Estonia** intends to ensure fast charging points each 40-60 km on all important roads, together with all municipalities above 5,000 inhabitants [112].

2.2.5 Regulation and governance strategies for emerging mobility solutions

2.2.5.1 What are they?

The emerging mobility services reviewed in this document are changing the urban mobility landscape. Cities generally embrace these emerging mobility services, as they offer an alternative to private car-use and hence they can help in the shift towards more sustainable urban mobility. However, some of these emerging mobility services are seen to cause unintended negative effects, as the reviews included in Section 2.1 unveil. Cities are therefore taking measures by introducing regulation for new mobility services. This is also included in public procurement, since cities are taking steps to take into account new elements to control shared mobility services, in order to align these new mobility services with the city's urban mobility policy goal [126].

2.2.5.2 How do regulation and governance strategies for emerging mobility solutions work?

Local governments typically implement regulations for sharing mobility systems by introducing an **obliged license** for the operation of the service. These licenses mainly target free-floating shared systems, and have the form of a Service Level Agreement (SLA). These SLA's stipulate a number of requirements that a contractor must fulfil, for example [18]:

- **Open data & data sharing**: with this requirement, data can be collected about the usage of the system. Data provide insights into the people who utilize the system, the volume of users, and when and where the system is used. It reveals the popular origin sites and destinations, an information which is useful in optimizing operations and policy-making [26]. The SLA can specify conditions about the data (e.g. frequency, quality, data standard, delivery format, etc.).
- **Geographical coverage**: regulations on geographical coverage can specify that vehicles must be sufficiently spread over different areas, such that an adequate service level for the user is achieved. Other regulations on geographical coverage do the opposite, and specify areas where no vehicles can be parked.
- **Maximum number & minimum use**: in order to limit the use of public space, a maximum number of vehicles per operator is generally defined. Other regulations to limit the use of public space are requirements on the minimum use of a vehicle. For example, each vehicle must be used once a day on average. This helps to match supply and demand.
- **Quality & maintenance**: the quality of the vehicle must be assured, both at the time of deployment as during operation. This regulation typically includes specifications on the obliged disposal of damaged vehicles.
- **Tracking system**: all vehicles must be equipped with a tracking system.

2.2.5.3 Which are the opportunities and risks of regulation and governance strategies for emerging mobility solutions?

As it is detailed in Section 2.1, some of the emerging mobility services may lead to unintended negative effects. This is the case today with for example free-floating bikes and e-scooters, which create problems in various cities: anarchic occupation of public spaces, traffic accidents, increased vandalism, littering, etc. These problems can also lead to increased costs for cities. For example, there are some cases where cities had to remove 'orphan' bicycles after a bike provider quit operations. Finally, it is not always clear whether a new mobility service is in line with a city's urban mobility policy goals. For example, the effect of free-floating carsharing systems on other modes such as public transport and walking or cycling is not always clear, and can in some cases **work against policy goals**. Therefore, it becomes logical for public authorities to regulate these new mobility services.

However, regulation also bears some risks: strict regulations can lead to some **operators leaving the market**, or even make the service impossible. Regulations can also limit competition and lead to **monopolistic situations**.

Both of these issues can cause a **slower uptake** of innovative mobility solutions in those market niches where the contribution to sustainable mobility is real (e.g. first and last mile complementarity with public transport).

2.2.5.4 What are the conditions for the success or failure of regulation and governance strategies for emerging mobility solutions?

Apart from the variety of regulatory approaches that are explored through the implementation examples of the different supply innovation trends in Section 2.1, is it worthwhile to highlight some cases that provide additional information on the actual strategies that cities are following to manage the deployment of emerging mobility solutions:

Vienna, Austria

In 2017, dockless bike providers such as oBike and ofo went to Vienna, and overflooded the city with more than 2,500 bikes at its peak [18]. This led to parking problems and conflicts with sidewalk users. The city administration initially responded by publishing parking recommendations. These recommendations had insufficient effect, and the city issued stricter regulations: operators need to register and can have a maximum number of bikes, bikes cannot park certain areas, and operators have to remove wrongly placed bikes within 4 hours from first notice. In 2018, oBike and ofo stopped their operations in the city, leaving only one remaining private operator.

Leuven, Belgium

In Leuven, new regulation is implemented for providers of shared, free floating bikes and scooters. Providers need to obtain a license to operate within the city and only a limited number of bikes is allowed. Each bike needs to be of sufficient quality to prevent theft and vandalism, and needs to be equipped with a tracking device. Normal bikes must be used on average at least once every 2 days. Each operator must provide an API to allow MaaS providers to make use of the system, and must provide data on the occupancy of bicycles according to GBFS+, an open standard for bikesharing systems.

Hamburg, Germany

Hamburg has a bikesharing system, where the service provider needs to fulfil certain specifications according to an SLA. This SLA defines the number and location of stations, the minimum number of bikes at each station, functionalities of the customer interface, maintenance requirements, etc. These requirements are enforced by use of financial incentives and fines.

3. Urban mobility futures

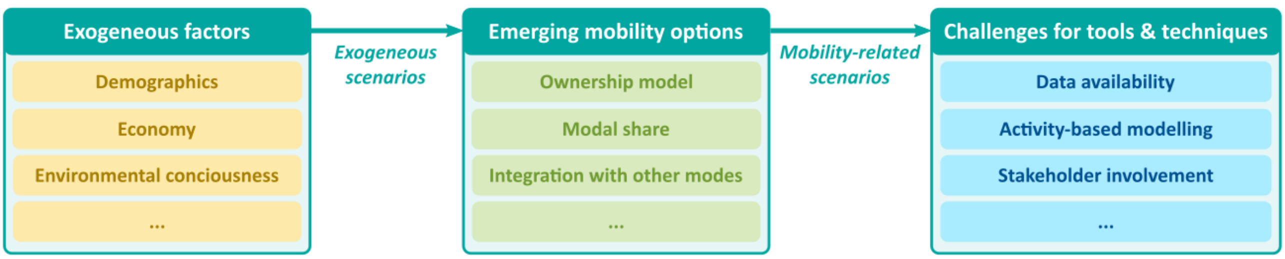
Given its numerous implications, cities have a commitment to manage urban mobility in a way that reconciles the diverging interests to maximize the benefits of the different mobility solutions. However, this is not only a matter of managing current situation: cities have also to select and prioritise measures for the future. The product of this task is often a planning instrument (e.g. a SUMP) which necessarily entails hypothesis about how urban mobility could evolve in the next decades.

If urban mobility planners have traditionally struggled with setting accurate future frameworks for transportation in cities, this challenge becomes even more salient due to the supply innovations trends reviewed in Section 2. As MOMENTUM project seeks to adapt transport planning tools and techniques to such mobility innovations, it is necessary to explore what will be the role of emerging mobility solutions and associated trends in the following decades.

This is undoubtedly a highly uncertain question, crossed by numerous subtle factors and conditions that are not easy to forecast. Instead of providing a closed prediction on the evolution of mobility innovations and their impacts in the strategies used by transportation practitioners, this Section **provides a series of exploratory scenarios**. This allows MOMENTUM to **come up with the envelope of all plausible adaptations and improvements that transport planning tools and techniques will require** in the following decades.

Specifically, this exercise has been conducted through two group of scenarios that serve to analyse two different uncertainty levels:

- **Exogeneous scenarios**, which propose different **alternative futures for a series of relevant exogenous variables** (e.g. demographics, economics, etc.) to reflect upon **the evolution of new mobility solutions** in relation to those variables (e.g. for a given socio-demographic situation, what is the expected penetration of vehicle automation?). Section 3.1 establishes these scenarios and provides insights on the implication that the alternative futures would have for emerging mobility solutions, through the results of the Delphi poll conducted in the project.
- **Mobility-related scenarios**, which set up a range of different **possible futures for emerging mobility solutions** to reflect upon the **impacts in transport planning tools and techniques** depending on the level of implementation of such solutions (e.g. for a given modal share of the emerging mobility solutions, which improvements in transport models are needed?). Section 3.2 suggests these scenarios and puts them in relation to the expected impacts in tools and techniques, using the results of the Delphi poll.



The examination of both levels, which intends to unveil the determinants of these relations, puts MOMENTUM project in a privilege position to **anticipate the most plausible requirements that policy-makers will pose to transport planning tools and techniques**.

3.1 Scenarios for the evolution of urban mobility in Europe

The task of setting up exogeneous scenarios to depict the plausible contexts where urban mobility will operate can become a rather arbitrary exercise. In order to avoid this drift, it is possible to resort to previous scenario-definition processes conducted by the scientific community. This section motivates the use of climate change scenarios as a basis for alternative urban futures and presents the four scenarios envisaged for European cities.

3.1.1 Shared Socioeconomic Pathways (SSPs) and their applicability to urban mobility context

3.1.1.1 Climate change research: a valuable source for scenarios

Among the research fields with more activity in the last decades, anthropogenic climate change research is likely the one that most relies on scenario-definition processes for producing future impact assessments relevant to policy-making. The continuous effort among this research community to produce a wide variety of scenarios can be exploited as a valuable starting point for scenario-definition for other sectors [127]. This can be the case of transport, and more specifically, urban mobility, given the **strong relationship between this sector and the causes and effects of climate change** [128].

The generation of scenarios addressing climate change has been guided by the research demands gathered within the International Panel on Climate Change (IPCC). Until 2008, the research community worked with comprehensive emission scenarios that consisted of sequential cause-effect alternative futures, that start from certain assumptions on socioeconomical factors followed by correlative emissions that lead to certain effects and impacts on climate. In 2008, the IPCC decided not only to revise the scenarios including corrections to hypotheses and data updates, but also changing this structure. From this point, climate change future studies work with two groups of scenarios that may converge after their full development and dissemination [129]:

- **Shared Socio-economic Pathways (SSPs).** The main factors of these scenarios are population, GDP and urbanisation rate, together with a narrative including "demographic, political, social, cultural, institutional, life-style, economic, and technological aspects" [130]. SSPs are meant to represent different levels of mitigation and adaptation challenges towards climate change [130].
- **Representative Concentration Pathways (RCPs).** The main factor of these scenarios is the radiative forcing, which IPCC uses for quantifying the changes of energy flows into the Earth system caused by greenhouse gases [131]. RCPs are meant to be a representative cluster of all scenarios in the literature with regard to the evolution of the components of radiative forcing, which are greenhouse concentrations and land uses [132].

The main reasons behind this move were to shorten the long processes required by the sequential approach [129] and to attend the need to explore with more detail certain relations that were demanded by scenario users [129], such as adaptation measures effects [132]. The latter is the analogous motivation for creating two scenario groups in the MOMENTUM project, i.e., give room for a closer exploration of the most uncertain relations.

3.1.1.2 SSPs as a basis for exogeneous scenarios for urban mobility

In this context, it is clear that the SSPs developed by the climate change research community have a great potential for inspiring exogeneous scenarios that provide several alternative contexts where urban mobility will have to operate, in a way that they are challenging, plausible and relevant [133]. As mentioned above, SSPs represent future societies that face different levels of mitigation and adaptation challenges towards climate change. There are five scenarios that can be located in two axes, as shown in Figure 3.

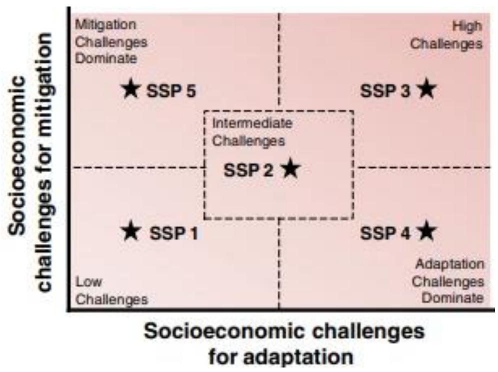


Figure 3 - SSPs in the "challenge space". Source: [130]

Briefly speaking, SSP1 imagines a future where Sustainable Development Goals guide society at all levels and thus the evolution of socioeconomic variables allows an environmental and social sustainable growth. SSP3 presents a fragmented future with high rivalries among countries that led to limited growth and governance capacity for achieving global agreements, which implies insufficient technology for adaptation and lack of efforts for mitigation. SSP4 is characterized by a two-speed society: (i) an upper class that adopts sustainable life-style and policies that are able to mitigate part of the anthropogenic climate change, and (ii) a lower-income group, both globally and within countries, which is not able to adopt adaptation measures given its material restrictions. SSP5 assumes that technology improvements boost economy and society trust in adaptation measures for coping with climate change, achieving social convergence at consumerist life-styles that accelerate emission levels. SSP2 is introduced as a 'middle-of-the-road' scenario reproducing intermediate challenges for adaptation and mitigation.

SSPs have a number of advantages for using them as a basis for urban mobility exogeneous scenarios:

- There is a **growing body of literature** about the implications of SSPs in specific topics, providing numerous references for the values of indicators that are applicable to urban mobility under the different scenarios.
- **IPCC will publish its sixth round of reports** on the basis of SSPs in the next two years. Hence, the dissemination of SSPs will continue along the execution of the MOMENTUM project. IPCC scenarios are usually the ones most known among public opinion [127].
- By using SSPs the **climate change perspective** becomes transversal to all elements in the MOMENTUM exogeneous scenarios, which is relevant given the importance of this challenge during the next decades.
- The **number of scenarios** contemplated in the SSP framework is five, which falls under the range proposed for the number of MOMENTUM exogeneous scenarios (3 to 5).

SSPs have also some limitations that have to be taken into account:

- The use of SSPs in fields that are not climate change research is always open to **mismatches between the needed contents** for the scenarios [127]. However, it is expected that the high relation between climate change and transport will limit this effect.
- SSPs are global alternative futures that need to be **downscaled** to European urban areas for being relevant to urban mobility. Downscaling is problematic since it generally assumes that the downscaled scenario will not deviate significantly from the original scenario [134]. In this case, the scenario-definition process takes advantage of the valuable work of Kok et al. [127] in downscaling global SSPs to Europe, and also of recent studies that have worked with SSPs at the urban level [135, 136]. In addition, the **involvement of stakeholders through the Delphi poll and the workshops** during the MOMENTUM project provided an opportunity to improve the adjustment of the alternative futures to the European urban context.

3.1.1.3 Tailoring SSPs to urban mobility context

While SSPs provide a good basis for developing MOMENTUM scenarios, there are still aspects to analyse more in detail before developing tailored versions applicable to the urban mobility context.

Firstly, it is important to evaluate to what extent there is a need for **additional factors** to be considered. As discussed by Kok et al. [127], when applying SSPs to related sectors there are some parameters that might be missing from the original narratives. In the case of urban mobility, it has been considered that the following aspects needed further assumptions:

- **Evolution of the urban form**. It is well-known that land uses interact with transport supply and demand. While SSPs include urbanisation among its definition variables, they do not address how population is allocated in urban areas. However, it can be argued that the narratives and quantitative features of SSPs allow the definition of a correlative trend in urban form evolution. The evolution of consumption preferences and the population pyramid can be related to preferred residential settlements and availability of land for other purposes. Following this, Terama et al. [136] used a Regional Urban Growth model that allocates population dynamics across available land depending on residential preferences observed in each scenario, and provides a correlative estimation for the rate of residential developments over industrial and manufacturing developments.
- **Evolution of the balance between pride of ownership and shared economies**. A contextual factor that is perceived as relevant for new mobility forms is to what extent shared economy is going to challenge ownership models, especially with regard to vehicle ownership. This aspect is not addressed by studies based on SSPs, but it is possible to look at the factors behind the intensity of the pride of ownership or conversely, the adoption of shared economy [137]. It is unclear how some factors operate. For instance, non-dependence is seen both as a driver for the pride of ownership [138] and as a driver for adopting sharing economy [139]. In any case, two differential aspects seem clear: shared economy adoption is related to a motivation for saving money [139], and is driven by a trust-based collaborative lifestyle [140]. Since economic prosperity and incentives to collaboration are central elements to SSPs, there is an opportunity for formulating an evolution of the pride of ownership in contrast to adoption of shared economies for each scenario.
- **Evolution of the digital divide.** Many of the disruptive mobility forms rely on technological advances not only for the vehicles or the infrastructure, but also for the interaction of the end users with the service providers. As demonstrated in Section 2.1, mobile devices and internet access are key enablers for the emergence of new mobility solutions. While SSPs do not address the evolution of the digital divide, this can be related to demographics. Moreover, it has been found that there is a strong relation between income and the access to technology [141]. Both aspects guide the role of digital divide in each scenario.
- **Evolution of e-commerce**. Shopping trips generation rates might be reduced due to the generalisation of e-commerce, as recent evidence suggests [142]. While e-commerce is not directly addressed by SSPs, there are many factors included in these scenarios that have an impact on the potential evolution of e-commerce. Societal trust, technology advances, urbanisation rate, education, consumerism, interest in diverse products and availability of a wide range of payment methods has been linked to e-commerce adoption [143, 144].
- **Evolution of telework**. As it is the case for shopping trips, work trips generation rates can change if teleworking gains popularity [145, 146]. There are several socioeconomic factors underlying telework adoption that are included in the SSPs. Telework is feasible in job positions that are largely based on ICT, generally in the service sector. The technological development achieved by future societies may ease telework or expand its application to other sectors [147]. Furthermore, it has been observed that telework is more frequent in households with children [148], so a link with fertility can be established as well.

Table 4 - Factors of the exogeneous urban mobility scenarios

Factor	Type	Inclusion in SSPs	Sources and evolution
Population growth and ageing	Quantitative	Yes	Modelled by International Institute for Applied Systems Analysis (IIASA) model and discussed in Kc & Lutz [149].
Education levels	Quantitative	Yes	Modelled by IIASA model and discussed in Kc & Lutz [149].
Urban population growth	Quantitative	Yes	Modelled by US National Center for Atmospheric Research model and discussed in Jiang & O'Neill [150].
GDP	Quantitative	Yes	Modelled by International Institute for Applied Systems Analysis (IIASA) model and discussed in Crespo Cuaresma [151].
Technological development	Qualitative	Yes	Included in O'Neill et al. [152] narratives.
Environmental consciousness	Qualitative	Yes	Included in O'Neill et al. [152] narratives.
Consumption levels	Qualitative	Yes	Included in O'Neill et al. [152] narratives.
National social inequality	Qualitative	Yes	This factor was already included in O'Neill et al. [152] narratives but is further explored by Rao et al. [153]: • **SSP1**: **low** • **SSP2**: **medium** • **SSP3**: **medium-high** • **SSP4**: **high** • **SSP5**: **low**
Land use in cities, urban form	Qualitative	No	Terama et al. [136] conclusions about urban form preferences shifts and density changes: • **SSP1**: **urban + suburban preference / increasing density in both urban and suburban areas** • **SSP2**: **not addressed** • **SSP3**: **suburban preference / decreasing density in suburban areas** • **SSP4**: **urban preference / increasing density in urban areas** • **SSP5**: **rural + suburban preference / decreasing density in suburban areas** SSP1, SSP3 and SSP5 are also addressed by Rohat et al. [135] for Houston case, leading to same conclusions with regard to urban sprawling and urban vertical development.

Factor	Type	Inclusion in SSPs	Sources and evolution
Pride of ownership vs. shared economy	Qualitative	No	Based on trust evolution among citizens and corrected by economic growth in SSP4 and SSP5 cases: • **SSP1: much higher trust + higher growth → lower pride of ownership** • **SSP2: medium trust + medium growth → medium pride of ownership** • **SSP3: much lower trust + stagnated growth → high pride of ownership** • **SSP4: lower trust + medium growth → medium pride of ownership among higher class, high pride among lower class** • **SSP5: medium trust + much higher growth → high pride of ownership**
Digital divide	Qualitative	No	Haight et al. [141] concludes that the digital divide intensity is strongly related with income apart from age.
E-commerce	Qualitative	No	Based on consumption patterns, trust and technology: • **SSP1: low consumption + high-tech advances + high trust → moderate expansion of e-commerce** • **SSP2: medium consumption + medium tech advances + medium trust → moderate expansion of e-commerce** • **SSP3: medium consumption + stagnated tech advances + much lower trust → limited expansion of e-commerce** • **SSP4: unequal consumption + high-tech advances + lower trust → moderate expansion of e-commerce** • **SSP5: very high consumption + high-tech advances + high trust → wide expansion of e-commerce**
Teleworking	Qualitative	No	Based on technology advances, job positions based on ICT (associated to tertiary education levels) and demand for telework due to children care, which is associated to fertility rates [149]: • **SSP1: high-tech advances + high rate of tertiary educated + low-medium fertility → moderate expansion of telework** • **SSP2: medium tech advances + medium rate of tertiary educated + medium fertility → moderate expansion of e-commerce** • **SSP3: stagnated tech advances + low rate of tertiary educated + low fertility → limited expansion of telework** • **SSP4: high-tech advances + low rate of tertiary educated + low-medium fertility → moderate expansion of telework** • **SSP5: high-tech advances + high rate of tertiary educated + high fertility → wide expansion of telework**

With regard to the **temporal scope**, SSPs provide great flexibility given that quantitative models providing support to their figures are publicly available and can be applicable to any temporal scope from today to 2100. In the context of MOMENTUM project, it has been considered that **2030 and 2050 are reasonable candidates**, since they coincide with the different energy and climate change and clean mobility objectives of the European Commission and could then be a temporal scope to look at. The farthest was selected (**2050**) to ensure that all possible challenges to transport planning tools and techniques are considered in the discussions guided by the scenarios.

Finally, it must be noticed that **the inclusion of a 'middle-of-the-road' scenario has been discarded**. It is understood that SSP2 "lacks its own identity as almost all elements change moderately" [127]. Indeed, some of the studies took as reference for downscaling scenarios do not address this alternative future (e.g. [136]). In addition, this allows to keep an even number of scenarios, which avoids confusion of the central scenario with a best-estimation scenario [129].

3.1.2 Alternative exogeneous futures for European urban mobility

The result of the tailoring process explained above is a set of four alternative futures for the context of European urban mobility. The quantitative figures associated with each scenario are calculated using the models for each variable included in Table 4, setting 2050 as the temporal scope.

3.1.2.1 Scenario 1 - Mixed compact cities in a sustainable Europe – SSP1

European society shifts towards sustainability driven by the generalisation of environmental concerns and the popularity of sustainable development goals in public opinion. Changes are reflected both in urban daily life, with lower consumption and higher trust among citizens, and in urban governance, with higher cooperation between authorities. Access to public services is generalised limiting urban segregation and inequalities. The strong efforts for completing the energy transition have boosted European economy, with cities demanding many qualified workers for the green industry. Renewable energies and small-scale storage solutions provide relatively cheap and versatile energy to European cities. The benefits generated by high-tech green industry are reinvested in improving public services, increasing social equality across urban areas. Improvements in life expectancy of all population layers result in an elder population, but with a limited digital divide thanks to the integration measures. Speciality products are delivered by green e-commerce but convenience products are based on proximity and purchased through local consumer communities. Telework is a feasible tool for improving work-life balance, but it is not highly demanded. Pride of ownership is declining and urban citizens seek collective solutions to daily-life problems. Urban sustainable life-styles are popular and accessible, attracting people to densified urban cores. The high demand for residential areas impacts suburban rings, that become much denser, and are also attractive for certain people given the proximity to natural parks. There are almost no greenfield developments. Mixed compact developments within urban cores host offices and high-tech industry.

EU GDP/PPP annual average growth: **+3.0%**
EU population total growth: **+6.9%**
EU urban population growth: **+20.7%**
EU population over 65 years (rate): 19.7% in 2018 → **33.8%** in 2050
EU population aged 30-34 years with tertiary education: 40.7% in 2018 → **70.5%** in 2050

3.1.2.2 Scenario 2 - Stagnant individualist cities in a nationalist Europe – SSP3

European society becomes dominated by a climate of distrust where individual and national interests have priority over collective and global targets. Environmental concerns are a residual driver for citizens, so people consume as much as their limited economic resources enable. Few households have managed to improve their living conditions, even in the upper classes. Clean energy research programs suffered from a lack of funding, so fossil fuel dependency remains stable. Tensions between global regions have an extraordinary impact on energy prices in Europe given the lack of own resources. E-commerce becomes standard for speciality products but the limited growth is a barrier for a definite expansion. Telework is only used by qualified workers. Elderly people have limited access to the latest technological developments. Ownership is not only related to a certain social status but also key for feeling safe given the successive economic crises and the security concerns in cities. The degradation of urban cores intensifies and there is limited demand for living in dense areas, which are associated with high crime levels and high pollution. Urbanisation rate slows down in Europe and the increasing need of national supply of food and energy have reactivated rural areas and the suburban ring of small cities, where low-density developments become more and more extensive. Industries remain in current locations and do not need more space due to the economic stagnation. However, offices and institutions tend to move from urban cores to suburban areas.

EU GDP/PPP annual average growth: **+0.9%**
EU population growth: **-9.1%**
EU urban population growth: **-4.0%**
EU population over 65 years (rate): 19.7% in 2018 → **31.3%** in 2050
EU population aged 30-34 years with tertiary education: 40.7% in 2018 → **31.9%** in 2050

3.1.2.3 Scenario 3 - Segregated green cities in an unequal Europe – SSP4

European society is unable to limit the growth of inequality in the continent. On the one hand, a highly educated cohort achieves high incomes thanks to the flourishing green economy. Business and political power are concentrated in this exclusive population layer, which is worried about climate change. On the other hand, large sectors of the society fail to improve their conditions due to limited public education investments. They struggle to access a European labour market where old low-tech industry is not generating as many jobs as in the past. There is progress in the energy transition towards renewable sources, but these are still not accessible to everyone due to high prices. Elites rely on e-commerce for almost all products but face-to-face trade still holds for the rest of the population. Similarly, upper classes are familiar with telework, while unemployment and precariousness are the rule among lower income communities. The limited fertility rates lead to an ageing population. Retirees from higher-income classes have much better access to technology than those from lower-income groups. While ownership is not trendy among urban upper-class, larger lower-income population perceives ownership as positive for achieving social status. The taste of upper classes for creative environments have fuelled the completion of gentrification processes in European urban city centres, limiting suburban growth and low-density developments both in large and small cities. Lower-income groups tend to live in high-density neighbourhoods with stretched social services. Leading high-tech industry settles in the renovated industrial areas within the urban cores, since proximity to the workplace is highly valued by qualified workers.

EU GDP/PPP annual average growth: **+2.5%**
EU population growth: **-1.1%**
EU urban population growth: **+9.3%**
EU population over 65 years (rate): 19.7% in 2018 → **32.9%** in 2050
EU population aged 30-34 years with tertiary education: 40.7% in 2018 → **26.5%** in 2050

3.1.2.4 Scenario 4 - Sprawling technological cities in a vibrant Europe – SSP5

European society experiences a period of prolonged growth thanks to the development of climate change adaptation technologies and the cheap energy prices. There is no special consciousness on the effect of the lifestyle on the environment, since technology keeps most people away from the consequences of the nature degradation. As a result, consumption trends move towards resource intensive lifestyles. Fossil fuels are still the main energy source since the exploitation of new deposits is now possible and much cheaper than before, opening the room for the large-scale extraction of shale gas. This benefits European countries and cheapens energy. There is extensive and promising research related to adaptation measures to issues such as sea level rise or extreme weather effects, with big investments in new smart infrastructures. E-commerce and teleworking boost allow people to live in small cities and work for companies based in big cities, causing small cities to grow above average. Face-to-face commerce is residual. The high fertility rates spurred by good economy perspectives limit European population ageing. The efforts to enhance human and social capital limit digital divide, although rapid changes in technology make it hard to keep the pace for some elder people. Given societal convergence, pride of ownership is not related to social status but to a strong sense of freedom in cities and their surroundings. Suburban areas become attractive and host the major part of the urban population growth in large cities. Larger properties are highly demanded and therefore many rural municipalities become suburban.

EU GDP/PPP annual average growth: **+4.9%**
EU population growth: **+18.1%**
EU urban population growth: **+33.4%**
EU population over 65 years: 19.7% in 2018 → **30.7%** in 2050
EU population aged 30-34 years with tertiary education: 40.7% in 2018 → **70.6%** in 2050

3.1.3 Evolution of new mobility options across the scenarios

As explained in Section 1.2, the exogeneous scenarios are used in the Delphi poll to assess the potential of emerging mobility solutions and their associated innovations. The aspects covered for each scenario included the following topics:

- **Basic mobility indicators**: car ownership, trips per person and average trip distance.
- **Vehicle automation** penetration rates among different fleets.
- **Shared mobility services** evolution: modal shares, trip induction, modal shifts and provision models.
- **Urban Air Mobility services** evolution: modal shares, trip induction, modal shifts and provision models.

The results of the Delphi reveal the possible outcomes of the different scenarios for urban mobility and also which aspects generate a wider dispersion of opinions among transport experts.

3.1.3.1 Basic mobility indicators

The Delphi poll explores the relation between each scenario and three basic urban mobility indicators: **car ownership**, **daily trips per person** and **average trip distance**.

The results show that sustainable futures (Scenario 1) are perceived by the experts as linked to decreases in car ownership, average trip distance and even trip generation rates. On the contrary, the remaining scenarios would lead to increases in the three indicators, although less intense than the decreases associated to Scenario 1 (Table 5). The variable that produces more diverging opinions and also more differences between the four scenarios is car ownership. Conversely, trips per person seem to remain more stable across the alternative futures.

Nevertheless, Scenarios 3 and 4 are associated to a higher relative dispersion, where somewhat contradictory drivers (e.g. telework versus income) may introduce additional uncertainties (Table 6).

These conclusions were already clear after the 1st Round of the poll, but the dispersion of the opinions decreased in the 2nd Round, in particular for the responses to the average trip distance estimation (-25% in the standard deviation).

Table 5 – Average estimation of basic mobility indicators

Average estimation	Car ownership	Trips per person	Average trip distance
1 - Mixed compact cities in a sustainable Europe	Moderate to large decrease	Slight decrease	Slight to moderate decrease
2 - Stagnant individualist cities in a nationalist Europe	Slight to moderate increase	Slight increase	Slight increase
3 - Segregated green cities in an unequal Europe	Unchanged	Slight increase	Slight increase
4 - Sprawling technological cities in a vibrant Europe	Slight to moderate increase	Slight increase	Moderate to large increase

Table 6 – Relative dispersion among estimations of basic mobility indicators

Relative dispersion trend	Car ownership	Trips per person	Average trip distance
1 - Mixed compact cities in a sustainable Europe	Low dispersion	High dispersion	Medium dispersion
2 - Stagnant individualist cities in a nationalist Europe	High dispersion	Medium dispersion	Low dispersion
3 - Segregated green cities in an unequal Europe	Very high dispersion	Very low dispersion	Low dispersion
4 - Sprawling technological cities in a vibrant Europe	Very high dispersion	Very high dispersion	Very low dispersion

3.1.3.2 Vehicle automation

The Delphi poll deals with vehicle automation, by asking about the expected evolution of this technology across different fleets: **private cars**, **shared cars**, **buses** and **Demand Responsive Transport vehicles**. In addition to the penetration rates, the participants were asked about their opinions about whether private autonomous vehicles would lead to induced trips.

In general, the participants exhibit a wide dispersion of opinions in respect of vehicle automation. In the 1st Round, the average estimation of the penetration rate was of at least 15% for all vehicle types in all scenarios. The results of the 2nd Round pointed to a more conservative estimation. For instance, the penetration rate of CAVs among private cars range from 17% to 31% in the 1st Round, depending of the scenario; while it ranges from 9% to 23% in the 2nd Round. This change is mainly due to the fact that those experts that participated in the 1st Round but did not participate in the 2nd Round were those more optimistic about vehicle automation role in the 1st Round. Nevertheless, if only the answers of those that participated in both rounds are compared, the difference between both rounds also reveals that the convergence of opinions produced a decrease in the estimated penetration rate. The average results of the 1st Round are shown in Table 7 and the average results of the 2nd Round are shown in Table 8.

In any case, it seems clear that the deployment of automated vehicles would be more intense among buses and shared vehicles, and less intense among private cars. The difference between private cars and the rest of the vehicle types would take place regardless of the future evolution of urban societies. However, it must be taken into account that these figures are a result of a highly variable combination of opinions, that range from very low penetration rates (all scenarios suggested penetration rates under 5% for at least an opinion) to great penetration rates, particularly in Scenario 1 and Scenario 3.

According to the results about trip induction, which can be seen in Table 11, private CAVs would generate additional trips in any future situation, though this would be specially the case in Scenario 4 (average estimation of a 15% increase in trips generation). This conclusion accounts both for the results of the 1st and the 2nd Round.

Table 7 – Average estimation of automation penetration rate among several fleets (1st Round)

Average estimation	Private cars	Shared cars	Buses	DRT
1 - Mixed compact cities in a sustainable Europe	20-25%	45-50%	40-45%	35-40%
2 - Stagnant individualist cities in a nationalist Europe	15-20%	20-25%	25-30%	20-25%
3 - Segregated green cities in an unequal Europe	15-20%	25-30%	25-30%	25-30%
4 - Sprawling technological cities in a vibrant Europe	30-35%	35-40%	40-45%	35-40%

Table 8 – Average estimation of automation penetration rate among several fleets (2nd Round)

Average estimation	Private cars	Shared cars	Buses	DRT
1 - Mixed compact cities in a sustainable Europe	10-15%	30-35%	25-30%	25-30%
2 - Stagnant individualist cities in a nationalist Europe	5-10%	10-15%	10-15%	10-15%
3 - Segregated green cities in an unequal Europe	10-15%	15-20%	15-20%	20-25%
4 - Sprawling technological cities in a vibrant Europe	20-25%	25-30%	35-40%	35-40%

Table 9 - Relative dispersion among estimation of automation penetration rate among several fleets (1st Round)

Relative dispersion	Private cars	Shared cars	Buses	DRT
1 - Mixed compact cities in a sustainable Europe	High dispersion	Very high dispersion	High dispersion	Very high dispersion
2 - Stagnant individualist cities in a nationalist Europe	Very low dispersion	Low dispersion	High dispersion	Medium dispersion
3 - Segregated green cities in an unequal Europe	Low dispersion	Medium dispersion	High dispersion	High dispersion
4 - Sprawling technological cities in a vibrant Europe	Medium dispersion	Very high dispersion	Very high dispersion	Very high dispersion

Table 10 - Relative dispersion among estimation of automation penetration rate among several fleets (2nd Round)

Relative dispersion	Private cars	Shared cars	Buses	DRT
1 - Mixed compact cities in a sustainable Europe	Low dispersion	Very high dispersion	High dispersion	High dispersion
2 - Stagnant individualist cities in a nationalist Europe	Very low dispersion	Very low dispersion	Very low dispersion	Very low dispersion
3 - Segregated green cities in an unequal Europe	Low dispersion	Very low dispersion	Very low dispersion	Low dispersion
4 - Sprawling technological cities in a vibrant Europe	Low dispersion	High dispersion	Very high dispersion	Very high dispersion

Table 11 – Estimation and relative dispersion of the trip induction effects of private autonomous cars

Private CAV trip induction	Average estimation	Relative dispersion
1 - Mixed compact cities in a sustainable Europe	<5% increase	Low dispersion
2 - Stagnant individualist cities in a nationalist Europe	5-10% increase	High dispersion
3 - Segregated green cities in an unequal Europe	5-10% increase	Low dispersion
4 - Sprawling technological cities in a vibrant Europe	10-15% increase	High dispersion

3.1.3.3 Shared mobility services

The poll explores the future of shared mobility services in terms of **modal share**, effects on trip induction and **provision models**. In general, participants consider that shared mobility services will **cover a good proportion of trips in future European urban areas**. More than 70% of opinions raise modal share of these services above 10% in large cities, regardless of the scenario considered. The average estimation for this figure ranges from 15% in Scenario 2 to 30-35% in Scenario 1, although opinions appeared to be dispersed for most scenarios. Interestingly, there are no major differences in the estimations with regard to city size. Estimations are only slightly lower in the case of smaller cities. The 2nd Round produced less disperse results, but converging in the average estimations already obtained in the 1st Round (Figure 4 and Figure 5).

The **impacts of shared mobility services would not be the same under all alternative futures**. Participants consider that Scenario 1 opens the room for shared mobility services that compete with car instead of with public transport, which would not be the case for the remaining scenarios (Figure 6). **Trip induction rates would be low**, in any case much lower than the expectations for private autonomous cars, and only would not be negligible in Scenario 4 (Figure 7). The results did not change from the 1st Round to the 2nd Round.

The participants were asked also about the likelihood of some trends in shared mobility systems. The integration of the services in MaaS platforms is the trend regarded as most probable, with low dispersion of opinions within and among scenarios already in the 1st Round. The evolution of the other questioned trends seems to be more uncertain, since the dispersion was higher and did not decrease significantly after the 2nd Round. Some trends would depend a lot on the future scenario or present higher dispersion among opinions, such as the agreements between operators and cities to complement public transport. Consistently with the opinions related to modal shifts, Scenario 1 would likely lead to such agreements, but Scenario 2 would set a difficult context for this to happen. All scenarios would lead to an increase in prices of these services in order to reach profitability, but the dispersion is higher for this trend than for the ones related to MaaS integration and public transport complementarity.

Figure 4 - Shared mobility modal share in large cities across scenarios

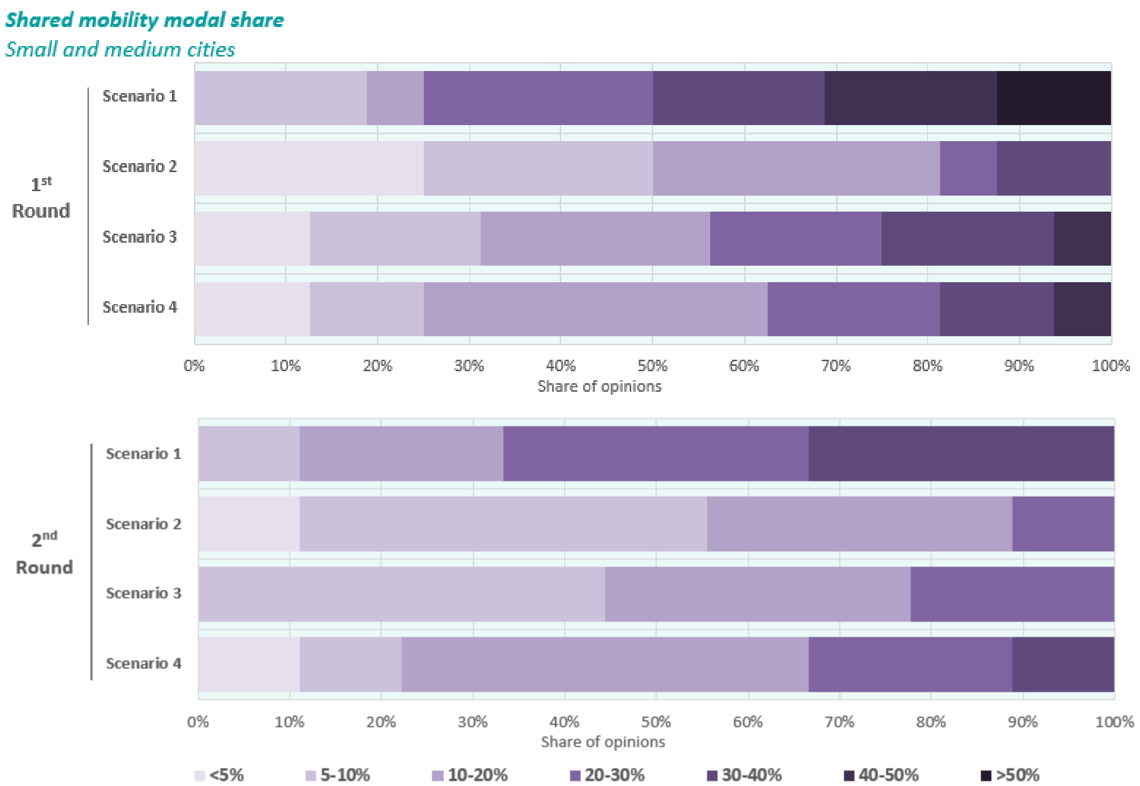


Figure 5 - Shared mobility modal share in small and medium cities across scenarios

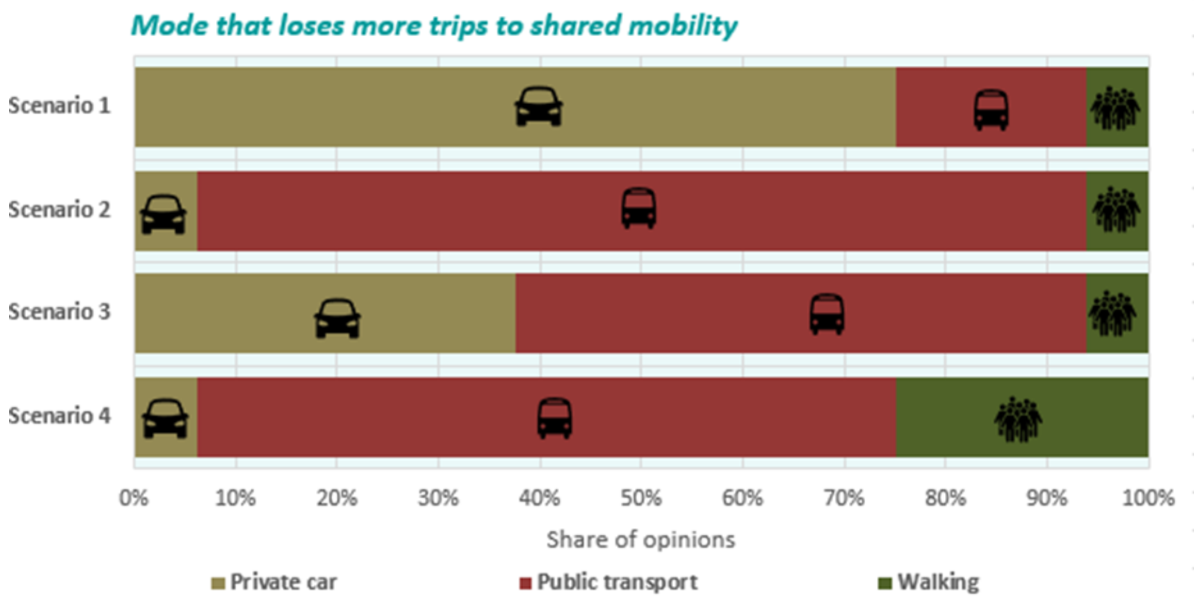


Figure 6 - Relative modal shifts to shared mobility across scenarios (1st Round)

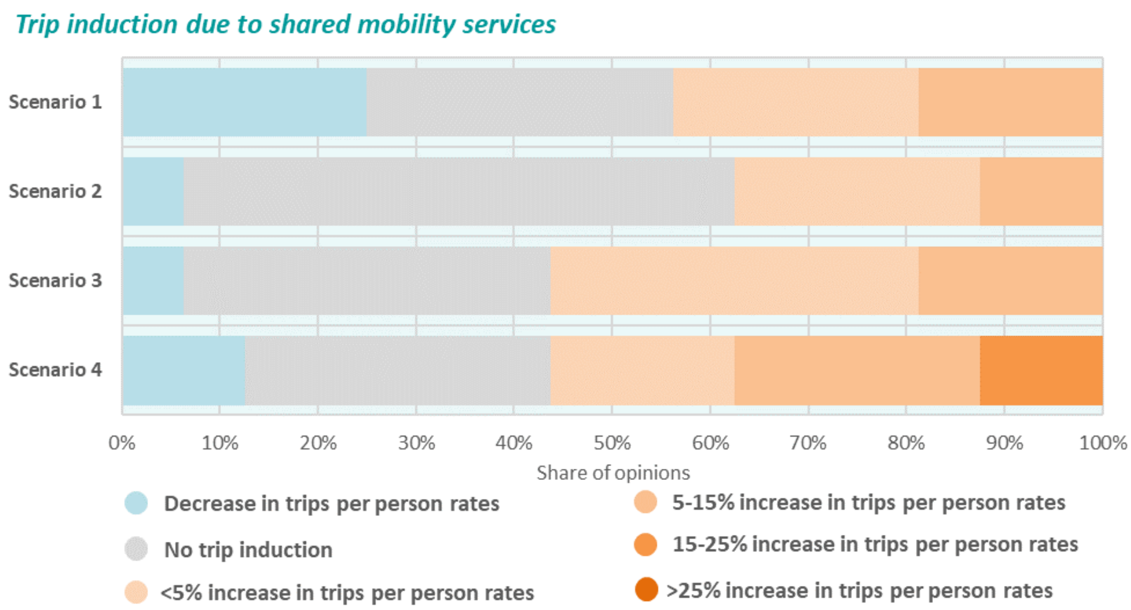


Figure 7 - Trip induction estimations due to shared mobility services (1st Round)

Table 12 – Likelihood average estimation of trends in shared mobility systems (1st Round)

Average estimation	Agreements operator-city	Cities as operators	Integration in MaaS	Carsharing = Ridesharing	Increase in prices
1 - Mixed compact cities in a sustainable Europe	Likely to very likely	Likely	Likely to very likely	Slightly likely	Slightly likely
2 - Stagnant individualist cities in a nationalist Europe	Slightly unlikely to unlikely	Slightly likely	Likely	Slightly unlikely	Slightly likely to likely
3 - Segregated green cities in an unequal Europe	Slightly likely	Slightly unlikely to unlikely	Likely to very likely	Slightly unlikely	Slightly likely to likely
4 - Sprawling technological cities in a vibrant Europe	Slightly likely to likely	Slightly unlikely	Likely to very likely	Slightly unlikely	Slightly likely

Table 13 - Relative dispersion among the estimated likelihood of trends in shared mobility systems (1st Round)

Average estimation	Agreements operator-city	Cities as operators	Integration in MaaS	Carsharing = Ridesharing	Increase in prices
1 - Mixed compact cities in a sustainable Europe	Very low dispersion	Medium dispersion	Very low dispersion	High dispersion	Medium dispersion
2 - Stagnant individualist cities in a nationalist Europe	Low dispersion	High dispersion	Medium dispersion	Low dispersion	High dispersion
3 - Segregated green cities in an unequal Europe	Medium dispersion	High dispersion	Very low dispersion	Low dispersion	Medium dispersion
4 - Sprawling technological cities in a vibrant Europe	High dispersion	Very high dispersion	High dispersion	Medium dispersion	High dispersion

3.1.3.4 Urban Air Mobility services

The poll has a section devoted to the expected evolution of Urban Air Mobility (UAM) services, with a similar approach to the previous one related to shared mobility. Participants **do not expect large modal shares for Urban Air Mobility services**. For at least half of the opinions no scenario would lead to modal shares over 5%. Scenario 4 would be the one most likely to end up in UAM modal shares over this threshold, since 50% of participants envisaged this in the 1st Round. However, this fell to 25% in the 2nd Round, as can be seen in Figure 8. Large cities would see higher modal shares than smaller cities, but the differences are not substantial (Figure 9). Dispersion of opinions is considerably lower than in shared mobility case.

There is almost unanimity in the fact that UAM would mainly **take trips from private car**, regardless of the scenario considered (Figure 10). Given that most participants do not expect a significant spread of UAM services **the effects on trip induction would be negligible**, weaker than for shared mobility services and private autonomous cars (Figure 11). The latest was confirmed in the results of the 2nd Round.

As for shared mobility, the participants were asked also about the likelihood of some trends in UAM provision. In this case, the differences between 1st and 2nd Rounds are remarkable, since the participants changed their answers towards a more pessimistic attitude towards UAM services. In any case, a common opinion among participants is to discard that UAM services prices could get cheaper and reach current taxi prices. This possibility was seen as unlikely in all scenarios already in the 1st Round (Table 14). There is little hope for agreements between UAM operators and public authorities to complement public transport. Although the dispersion of opinions is high with regard to the integration of these services in MaaS platforms, participants consider this less likely than the integration of shared mobility services. The role of cities in promoting UAM is the aspect that varies most across scenarios. Following this, the success deployment of urban air traffic management systems integrated in urban transport management, which is likely to happen in the Scenario 4 regarding the results of the 1st Round, it is seen as very unlikely in any scenario according to the results of the 2nd Round (Table 15). The possibility of cities operating UAM services themselves is also seen as more likely in Scenario 4. However, these aspects were the ones that generated most dispersion across the participants in the 1st Round (Table 16).

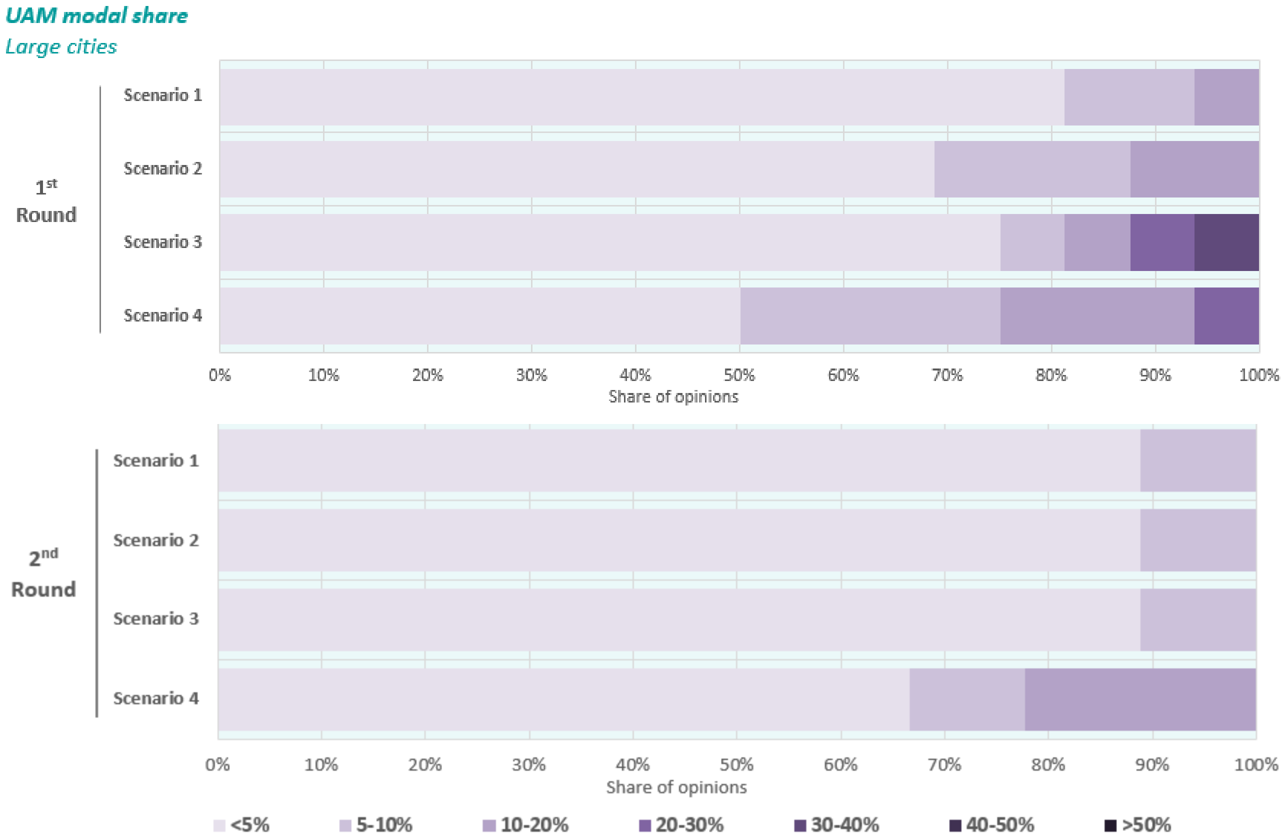


Figure 8 - UAM modal share in large cities across scenarios

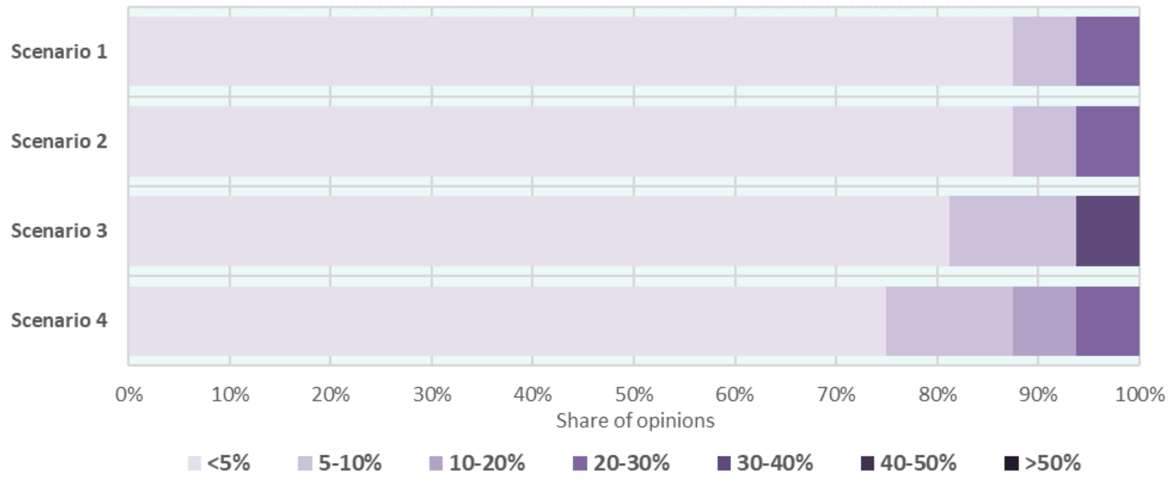


Figure 9 - UAM modal share in small and medium cities across scenarios (1st Round)

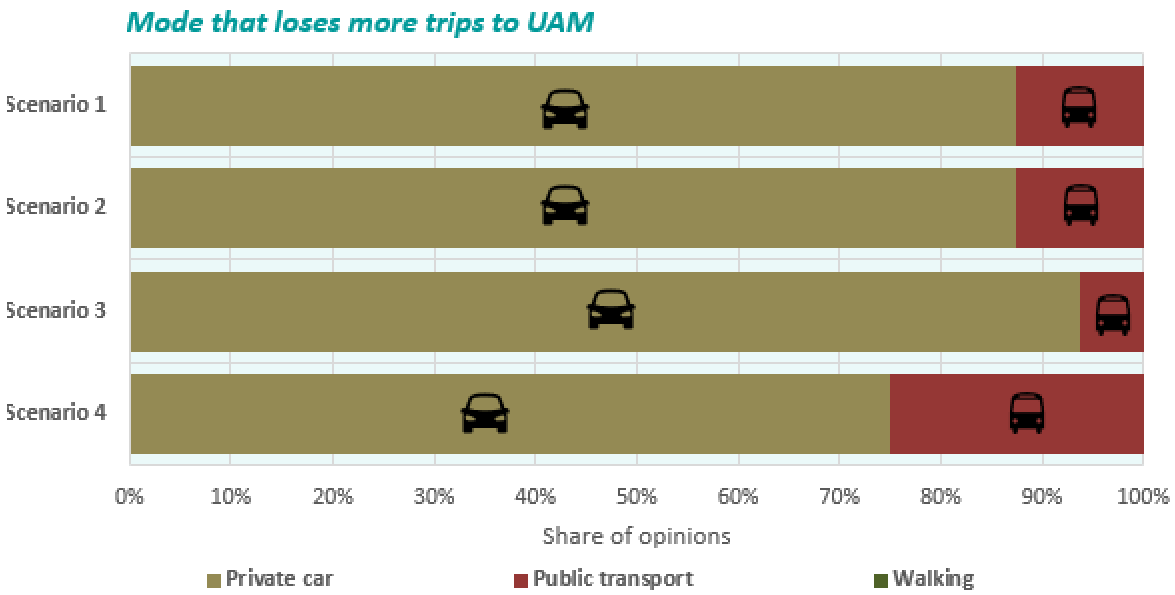


Figure 10 - Relative modal shifts to UAM across scenarios (1st Round)

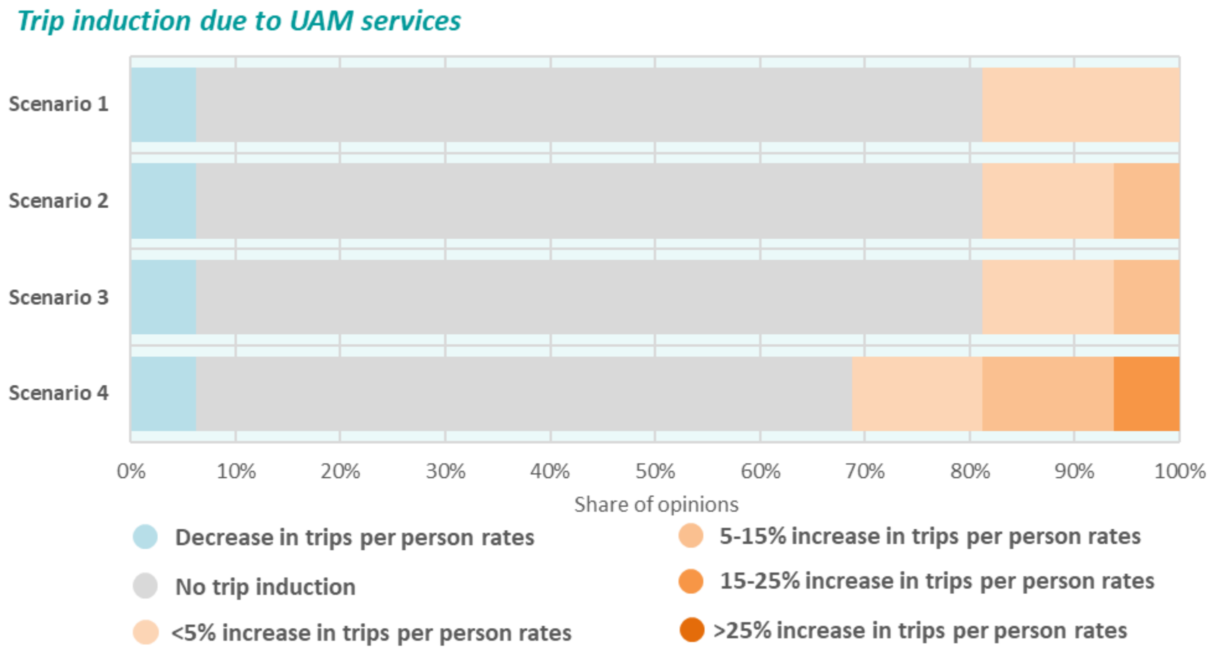


Figure 11 - Trip induction estimations due to UAM services (1st Round)

Table 14 – Likelihood average estimation of trends in UAM systems (1st Round)

Average estimation	Integrated urban ATM	Agreements operator-city	Cities as operators	Integration in MaaS	Cost as much as a current taxi
1 - Mixed compact cities in a sustainable Europe	Slightly likely	Slightly unlikely to unlikely	Neither likely nor unlikely	Slightly unlikely to unlikely	Unlikely to very unlikely
2 - Stagnant individualist cities in a nationalist Europe	Slightly unlikely to unlikely	Unlikely	Slightly unlikely to unlikely	Slightly unlikely to unlikely	Unlikely to very unlikely
3 - Segregated green cities in an unequal Europe	Neither likely nor unlikely	Unlikely	Slightly unlikely	Slightly unlikely to unlikely	Unlikely to very unlikely
4 - Sprawling technological cities in a vibrant Europe	Slightly likely to likely	Slightly unlikely to unlikely	Slightly likely	Slightly unlikely to unlikely	Unlikely

Table 15 – Likelihood average estimation of trends in UAM systems (2nd Round)

Average estimation	**Integrated urban ATM**	**Agreements operator-city**	**Cities as operators**	**Integration in MaaS**
1 - Mixed compact cities in a sustainable Europe	Slightly unlikely to unlikely	Unlikely	Unlikely	Unlikely
2 - Stagnant individualist cities in a nationalist Europe	Slightly unlikely to unlikely	Unlikely to very unlikely	Unlikely to very unlikely	Unlikely to very unlikely
3 - Segregated green cities in an unequal Europe	Slightly unlikely to unlikely	Unlikely to very unlikely	Unlikely to very unlikely	Unlikely to very unlikely
4 - Sprawling technological cities in a vibrant Europe	Slightly unlikely to unlikely	Unlikely	Slightly unlikely	Unlikely

Table 16 - Relative dispersion among the estimated likelihood of trends in UAM systems (1st Round)

Relative dispersion	**Integrated urban ATM**	**Agreements operator-city**	**Cities as operators**	**Integration in MaaS**	**Cost as much as a current taxi**
1 - Mixed compact cities in a sustainable Europe	Very high dispersion	Very high dispersion	High dispersion	Very high dispersion	Very low dispersion
2 - Stagnant individualist cities in a nationalist Europe	Very high dispersion	Medium dispersion	High dispersion	Very high dispersion	Medium dispersion
3 - Segregated green cities in an unequal Europe	High dispersion	Low dispersion	Medium dispersion	Medium dispersion	Very low dispersion
4 - Sprawling technological cities in a vibrant Europe	Very high dispersion	Very high dispersion	High dispersion	High dispersion	Low dispersion

3.2 Scenarios for the evolution of emerging mobility concepts

The conception of exogeneous scenarios and the exploration of how emerging mobility concepts would evolve under each of them needs to be complemented with the assessment of the actual impacts that each mobility innovation may impose to transport planning tools and techniques. In order to do so, a series of alternative futures for some of the concepts that are transforming urban mobility have been developed. Each concept has been associated to **two diverging or complementary scenarios**, depending on the nature of the uncertainties that have an influence in its evolution. In this context, the Delphi poll has helped to **identify which scenarios can be more challenging** in terms of data sources and transport modelling.

3.2.1 Alternative futures for mobility innovations

3.2.1.1 Alternative futures for carsharing services

Two successive scenarios are foreseen for the future of carsharing services, depending on the ownership model and its role in modal choice. In the first scenario, with a medium-term time horizon, shared fleets become essential in cities due to the difficulties for accessing private electric cars and the deployment of restrictions to pollutant vehicles. In the second scenario, with a long-term time horizon, smart mobility innovations would be integrated with housing and smart grid management.

Scenario	Description
Electric carsharing in cities as an additional mode	The generalisation of UVARs and parking management policies in the metropolitan areas constraints the use of private cars in these contexts. The high cost of electric vehicles discourages their acquisition, so electric vehicle ownership remains low. This fosters the introduction of sharing schemes through viable business models at national and EU level. Due to this fact, electric carsharing schemes become a key mode in urban areas for daily commuting, boosting its modal share up to 20-25% in large cities. Electric vehicle infrastructure has been developed at certain urban areas in combination with the deployment of sharing schemes. Multimodality becomes usual, combining mass transport for long-haul trips and individual transport for last-mile, which further increases the use of electric vehicles sharing schemes. The complexity of traveling has increased due to the multi-leg multimodal trips, so information sharing and availability and achieving smoother transfers becomes crucial. Electric carsharing is fully integrated with public transport modes and innovative mobility concepts and services increase flexibility, quality, efficiency and affordability of combined transport options.
Holistic housing-mobility solution	Urban planning follows an advanced holistic approach, since it integrates aspects such as mobility, housing, energy distribution and ICT networks from the beginning, in order to ensure high living standards. As a consequence, modern collective housing policies include electric sharing vehicle schemes as part of the house infrastructure. Energy supply and urban power grids take into account this, and balance the different electricity needs throughout the day through dedicated fare schemes. Community-based electric vehicle schemes are developed, facilitating the access and use of electric shared vehicles and contributing to the reduction in parking requirements. The national application of these standards contributes to a homogeneous modal share of electric vehicle solutions.

3.2.1.2 Alternative futures for micromobility services

Micromobility is the most recent player among shared mobility services. Two scenarios are depicted with different temporal horizons, in a similar way to what has been developed for carsharing services. In the first scenario, in a short-term time horizon (2030), micromobility systems remain independent from other transport modes and is provided by multiple third-parties, mostly replacing walking and short trips. In the second scenario, with a long-term time horizon, micromobility is integrated with other transport modes as its last mile component.

Scenario	Description
Micromobility for stand-alone short-distance trips	Micromobility substitutes other transport modes in short distance trips. Policy and safety regulations for micromobility have been satisfactorily defined in most cities. Therefore, e-scooters and similar vehicles are provided as a stand-alone service, moderately expensive and replacing daily short distance trips, mostly car and taxi rides. Micromobility modes are more appealing for new generations and car ownership has decreased since young adults turn towards a model of personal mobility consumption based on pay-per-use rather than a car purchase. Road network situation is upgraded and adapted with adequate infrastructure (e.g. dedicated lanes) for micromobility vehicles' use. In addition, and once the policy framework has become mature, operators will be able to explore new business schemes openly pursuing pilot projects and market's needs, since all of the competitors in the field are subjected to the same regulation.
Micromobility as part of a longer combined trip	Due to relatively strict regulatory frameworks, micromobility becomes completely integrated in the transport system. This integration is facilitated by MaaS platforms. Micromobility is combined with public mass transport and included in the mobility packages provided by transport authorities. The restrictions to private car use foster the use of e-scooters and similar vehicles. People use these services to reach or leave the transition stations, and also combine micromobility modes with their private car in Park&Ride solutions, particularly in smaller cities. The technology in design has evolved to be more user friendly for people suffering from motor impairment such as those with injuries, disabilities, or even just old age. Micromobility operators are in touch with local governments, regulators and other transport providers as partners to provide the most flexible, efficient, and sustainable combined transport options.

3.2.1.3 Alternative futures for Demand Responsive Transport services

Two scenarios are proposed here for the evolution of Demand Responsive Transport services. In the first scenario, with a medium-term time horizon, these services will offer a significant opportunity for cities to optimize, transform and sustain integrated transport systems. In the second scenario, with a long-term time horizon, these forms of on-demand transportation are expanded to logistics (in particular, last mile delivery) since passengers and goods share the same vehicles.

Scenario	Description
Satisfying people's needs and expectations while reducing operational costs	The proliferation of digital content and the emergence of the connected travellers allow operators to reduce operational costs while improving the Level of Service (i.e. less waiting time, more accessibility) through intelligent applications and user information services by 2030. On-demand transportation emerges as an alternative to traditional public transport services in sprawling areas, integrated (in first/last mile and supplementary function) with the backbone public transport network. Technology education and acceptance across population has increased, allowing for a better interchange of information in both directions (between the users and the operators). Citizens of suburban areas and special users' categories (ageing population, vulnerable users, etc.) are attracted by the public transport on-demand services, avoiding the use of unsustainable modes where traditional bus and railway services are not available. Efficient demand management is possible, thanks to the enhanced user visibility and the service organisation techniques that provides the user with options for different prices and seamless connectivity to other modes of transport. Cities enable greater public transport capacity and efficiency by providing door-to-door mobility information and guidance systems and by facilitating intermodal travel chains.
On-demand shared passenger/parcel transport service for all	The on-demand transport system expands to freight and goods delivery by 2050. Passengers and cargo are combined aiming at increasing the use of the network infrastructure and transport assets capacity. New vehicles able to accommodate both passengers and cargo in an efficient and comfortable (and safe) way are designed. Consequently, multiple parcels and more passengers in one vehicle are allowed. Higher visibility and transparency of cargo flow is achieved, enabling avoidance of unnecessary/empty vehicle movements in urban areas by making last mile deliveries more efficient by consolidating goods flows. Shared data, infrastructure and logistics business models for urban goods distribution are developed providing a more efficient utilisation of public transport infrastructure across both passenger and goods transport modes.

3.2.1.4 Alternative futures for Connected Autonomous Vehicles

The introduction of Connected Autonomous Vehicles to passenger car fleets will bring certain new possibilities and possible disruptions to the current transport system. CAVs will likely be a determining factor for the transport system, but differences in the level of automation and ownership can lead to entirely different scenarios. While these parameters provide the context behind the scenarios, some supporting policies, technologies, and a shift in mentality and behaviour is naturally required for a complete narrative.

Scenario	Description
People take cars	CAVs Level 4 have been slowly introduced into the car fleet starting from 2025, and picked up around 2030. Most of these vehicles are privately owned. Level 5 vehicles became available on the market in 2050. Ownership trend in CAV use is based on the limitation of autonomous features, that are limited to highways and motorways where no non-motorised traffic is allowed. This excludes car-share fleets that are more used over short-distance trips, mostly within cities. Due to the private ownership, access to these vehicles are limited to the wealthier part of society, as fixed costs (purchase, maintenance) are also covered by the individual owner/user, not only the variable costs (energy/fuel). People appreciates the time savings that CAV brings about, since the time spent in a CAV that navigates the highways on its own is not wasted time anymore. The intercity CAV traffic is not allowed to enter the inner cities, as parking space is already sparse, so here the development of P+R parkings and connected public transport/micro-transit/bike-share services is a requirement. The overwhelming majority of CAVs are electric vehicles. This, together with an improved driving efficiency, contributes further to the reduction of total emissions from cars, compared to a full non-electric, non-autonomous fleet.
Cars take people	Soon after the availability of Level 4 automation level, Level 5 also becomes available on the market. This results in autonomous vehicles being able to drive fully without human interaction over any kind of road infrastructure and in any kind of weather or traffic situation, both inside and outside the cities. In big cities large car-share fleets or micro-transit services become available, so private car ownership plummets. Improved connectivity and information sharing facilitate the integration of fleets in broad-reaching MaaS schemes. Since each mode of transport is connected, multimodal trips become more attractive. This boosts public transport use and discourages private car use. It is possible to convert a large amount of parking spaces to hubs for mobility services, or other public spaces. In small cities less people make use of car-share fleets/services, therefore the private ownership of CAVs is higher than in big cities. In small cities there is usually a higher amount of private parking available due to lower density housing structures. C-ITS equipment has been installed over various components of the traffic infrastructure, when not only car-to-car but car-to-infrastructure connectivity is considered, and/or C-ITS data beacons could be installed on Legacy Vehicles to include them in the network of connected vehicles, providing an additional level of safety on the roads. With full automation new groups of individuals get access to safe and convenient mobility services beyond the current fixed public transport lines, for example individuals with limited mobility options, children, etc.

3.2.1.5 Alternative futures for Urban Air Mobility

Urban Air Mobility (UAM) is a solution for passenger and cargo transportation within metropolitan areas based on highly automated and efficient air vehicles. Vertical Take-off and Landing vehicles (VTOL) capabilities, the regulatory framework of urban air traffic management space, the rider experience and the cost of this mode will determine the adoption and use of UAM across European cities.

Scenario	Description
Aerolimousines	The impulse of manufacturers and some companies willing to operate UAM services is pushing the regulators forward towards the implementation of this mode, but the challenges require very high levels of coordination among stakeholders and progress is difficult in some areas. The manufacturers have achieved sustainable production levels, above those of helicopters, but are still far away from car production schemes. Noise impact is similar to medium-sized trucks. Certification process follows the same procedures as standard aircrafts. European aviation authorities have conducted demonstration projects for urban air traffic management schemes in collaboration with local authorities, and have started to operate these systems in some metropolitan areas. However, there are some aspects that have not yet been agreed, which hinders the adoption of a standard system across Europe. Safety levels are better than those registered for traditional on-demand flight, but some notable accidents impact public opinion from time to time. Most large cities have explored partnerships with potential operators to adapt heliports and add some additional vertiports in suburban areas, but the complex governance structures and the lack of expertise from local authorities delays most infrastructure projects. Ridesharing companies provide services in integrated platforms with their ground modes. UAM is not regarded as part of the public transportation system of the city, but as an exclusive mode.
Flying shared mobility	There is a conviction that UAM can support profitable business models and contribute to sustainable urban mobility, so cooperation among different governance levels and stakeholders is smooth. The technological advances in composite material and distributed electric propulsion has enabled manufacturers to cut vehicle production costs and achieve high production volumes, getting closer to traditional car production standards. Noise impact has been reduced to half the levels of a medium-sized truck passing a house. Specific certification procedures have been designed for VTOL vehicles. After intensive funding of research activities and demonstration projects, European aviation authorities have set standards for urban air traffic management. Metropolitan transport authorities and aviation organisations work together to apply these standards across Europe. Safety levels have improved substantially in comparison to traditional on-demand flight, and public opinion appreciates the potential for reducing car fatalities through modal shift. Large cities receive funding from European aviation authorities to deploy infrastructure for UAM operations. Many of them have succeed in developing a vertiport network that covers airports, transport hubs and important nodes in suburban areas. MaaS aggregators, both public and private, have incorporated UAM services in some of their mobility packages. UAM achieves the same level of integration as shared mobility systems, with some cities integrating it in their transport systems.

3.2.1.6 Alternative futures for Mobility-as-a-Service

The introduction of MaaS is expected to make the life of citizens easier, it should help shift from private car use towards multimodal, sustainable transport. The determining factor for the success of MaaS lies in the four C's; cost, convenience, choice, and customisation. In our vision, two scenarios are materialising for the future. In the first scenario MaaS pilots are born inside cities, and develop on their own, providing an interface layer to the underlying independent mobility services. In the second scenario these services evolve and connect under a European MaaS framework.

Scenario	Description
Limited MaaS	MaaS providers are focused at a local level. They include services from various local mobility operators that are already present in the city (public transport, car-share fleets, bike-share, taxi companies, etc.). Organisation and pricing of the traffic services is still controlled by the individual providers, while the MaaS provider is just another interface to planning trips, purchasing tickets (that are simply bundled individual tickets of the specific transport providers), and possibly providing a limited set of fixed subscription packages. Integrated information facilitates the choice regarding the time of day, route, or the mode of transport to be used. Users can find, book, and pay for their trip at a single service point (be the MaaS app or a vending machine). MaaS offers users an alternative for individual car ownership covering their daily mobility requirements. Since the MaaS service builds on existing mobility service providers, these are not common in small cities. Seamless mobility stops at the city limits: inter-city MaaS services are not yet available as different regions have their own independent MaaS solutions that are not interlinked. Some mobility providers try to obtain exclusive contracts to serve a specific transport mode in the MaaS offering, leading in some cases to an unhealthy competition. Pricing and route options are not flexible and everyone is presented with the same options: prices are independent of the imbalance of demand and supply, while the suggested routes and modes only reflect the traffic situation, without the aim of shaping traffic demand itself.
MaaS unlimited	MaaS services evolve into a connected European-level network. Interregional multimodal transport becomes a convenient option. MaaS services are also used to intelligently shape the spatial and temporal traffic demand over all available modes. MaaS stakeholder groups involve a wide array of tightly cooperating players from mobility providers to local and regional governments, who are all strongly involved in the planning, design, operation, and maintenance of transport services, networks, and infrastructure. Supply and demand are now combined with goals such as reducing the use of cars or promoting liveability in the cities. MaaS is seamless even beyond single city limits, and reaches regions that would be impossible to serve with traditional public transport routes. Users pay for a service from A to B irrespective of the modes that take them there. It is not a bundle of individual tickets any-more over fixed lines or modes, but a single mobility offer from A to B. MaaS covers all available means of transportation. In the offerings of a MaaS app, a multitude of parameters are considered capturing the elements that are needed to design a package that fits a given person's needs. Individual mobility patterns, attitudes and perceptions, together with current service levels, define the price of an individual offering. Public transport services are still the providers of the high capacity backbones of MaaS services in the form of trains, trams, and metro lines. As demand for MaaS increases the traffic over these lines will increase too.

3.2.2 Impacts to cities and their transport planning techniques across the scenarios

The Delphi poll conducted in the project provides a source of information for assessing the impacts of emerging mobility solutions and the related innovations in urban transportation and the techniques and tools that cities use for managing and planning it.

3.2.2.1 Future impacts in cities

The participants in the Delphi poll were asked about their views about the factors and impacts of emerging mobility solutions for cities. In the 1st Round, this was evaluated through open-ended questions, that served to gather all the possible answers to this issue. In the 2nd Round, the factors and impacts identified were prioritized by the respondents.

First, the participants provided their opinion on the **current factors underlying the emergence** of these mobility solutions. A wide range of aspects was covered by the panel, among which the following stand out:

- The collaboration between public authorities and private operators.
- The potential that authorities see in these solutions for complementing public transport services, reducing congestion, limiting air pollution or increasing accessibility.
- These services provide a great flexibility for attend mobility needs of citizens.
- The lack of specific regulations opens the door.
- The specific geographical configuration of the city.
- The existence of high-density areas in the inner city that generate demand.
- The existence of low-density remote areas that can be served by on-demand transportation services.
- The broad use of technology by citizens.
- The taste for new experiences that lead citizens to try these services.

In addition to this, the participants share their opinions on the **successful factors for the implementation** of emerging mobility solutions. The following aspects arise, from most to less frequent:

- The deployment of Urban Vehicle Access Regulations (UVARs) that make these solutions attractive to the detriment of car use, as well as parking regulations.
- The reliability of services for end users.
- The affordability of services for end users.
- The cooperation between operators and cities to deploy the systems.
- The management of public space to ensure that all user rights are preserved, and that active mobility modes are prioritized.
- The integration of the management and planning of new solutions in urban mobility planning processes.
- The acceptance from users to new mobility concepts brought by these solutions, so they feel comfortable with using these services.
- The cooperation with public transport services, e.g. first and last mile support.
- The electrification of the vehicles used by these solutions.
- The extension of the coverage areas of the services to suburban areas.
- The reduction of the size and weight of the vehicles.
- The evolution of demographics and environmental concerns among society.

Figure 12 shows the results of the 2nd Round with regard to the priorities among the aforementioned factors.

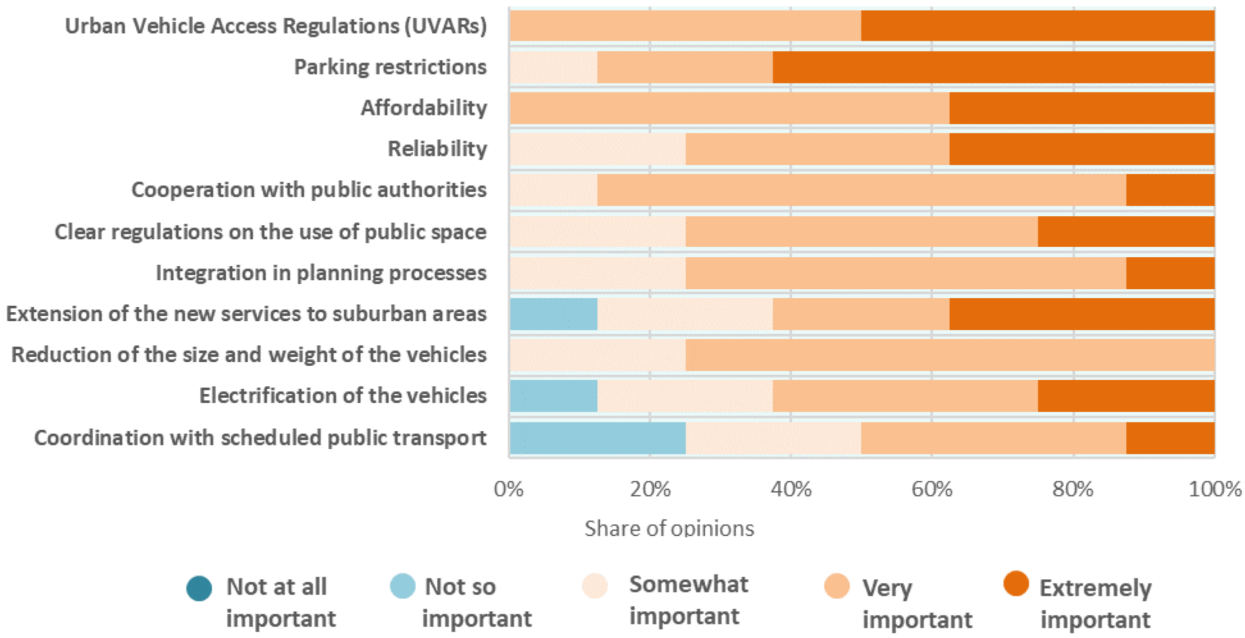


Figure 12 – Importance of certain factors for the successful implementation of new mobility options

The participants also were asked to reflect upon the main **current impacts** that these solutions have in European cities. 25% of them reported no impacts but were aware that they may have impacts in the future. Among those that cited effects of these solutions, negative aspects prevailed. These were the impacts reported from most to less frequent:

- Modal shift from public transport services.
- Modal shift from active mobility modes (i.e. walking and cycling).
- Public space consumption, leading to conflicts with pedestrians in sidewalks and with other traditional modes.
- Short life time of micromobility vehicles drive cities away from sustainable mobility principles.
- Increased pressure to public authorities for adaptation to new solutions.
- Vandalism.
- Trip induction.
- Increase of accessibility.
- Car ownership decrease.

Interestingly, the answers to the **future impacts** of emerging mobility solutions were by far more positive, with few exceptions that report that no positive impacts are to be seen. The impacts foreseen from most to least frequent were the following:

- A reduction in private car use and ownership. This would lead to an increase in walkability of inner-city areas, less need for parking space, less congestion and better air quality.
- An improvement of accessibility, especially in suburban areas.
- A replacement of scheduled public transport services, especially in low-density areas.
- A reduction in the dependency of urban mobility in fossil fuels.
- An improvement in road safety.
- An improvement of the overall economic performance of the city.

- A series of regulatory challenges for public authorities.
- Modal shifts from traditional modes to emergent modes.

In the 2nd Round, these impacts were grouped in an adverse group and a positive group, for the experts to order them in terms of importance. Figure 13 and Figure 14 show the results.

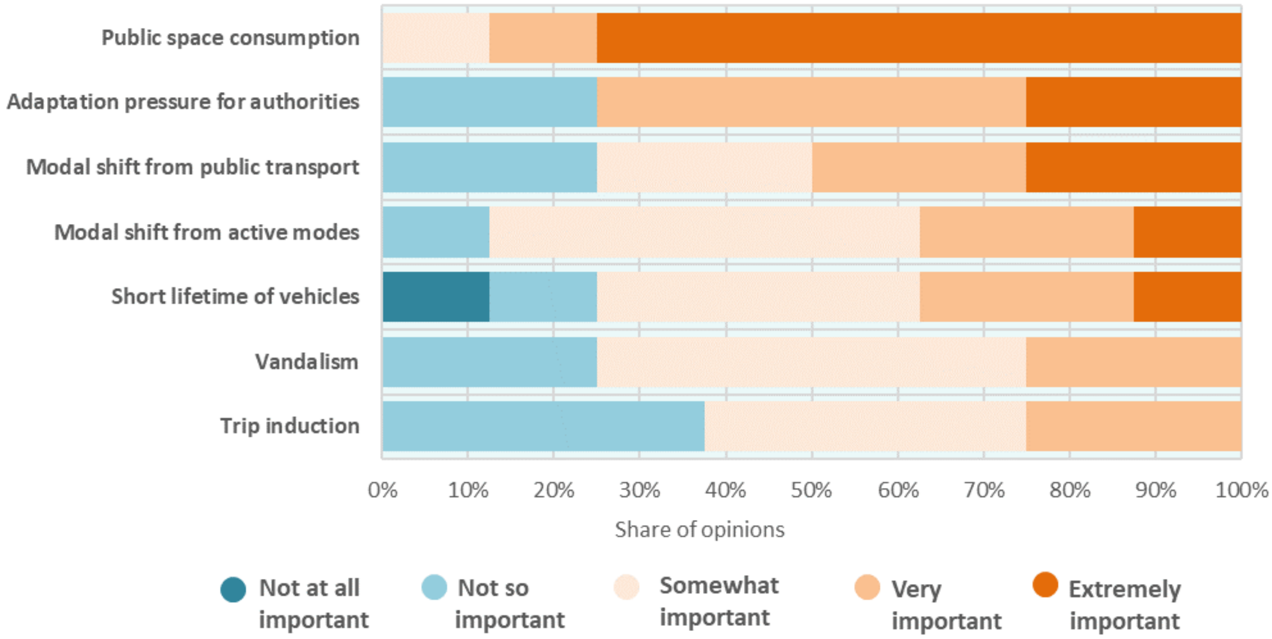


Figure 13 – Importance of certain adverse impacts of new mobility options for cities

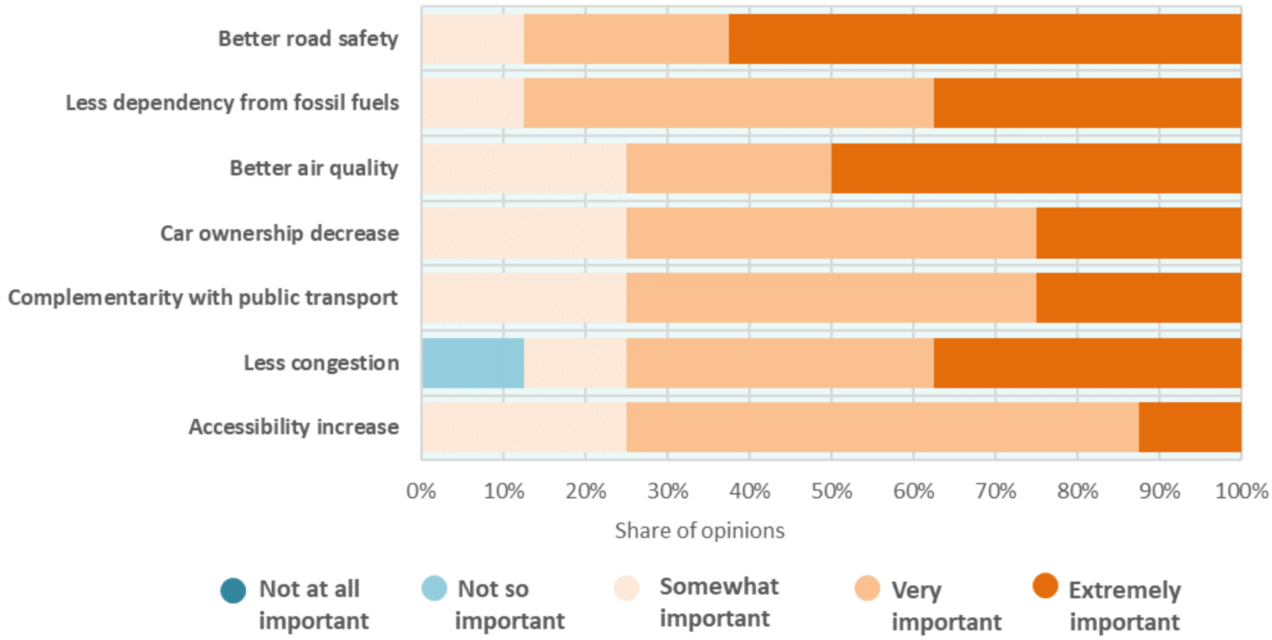


Figure 14 – Importance of certain benefits of new mobility options for cities

3.2.2.2 Future impacts in transport models

Apart from the factors or impacts in urban mobility systems, the Delphi poll addressed also the implications of these emerging mobility solutions in transport planning tools and techniques (e.g. data sources, modelling tools, decision support platforms…).

Participants consider that some of the innovative mobility solutions already represent a challenge for these techniques, as can be seen in Figure 15. In particular, shared mobility systems, micromobility and Mobility-as-a-Service would already require adaptations in transport models. Other solutions, such as UAM or CAV are seen less challenging at the moment. However, at least 25% of the respondents consider that each mobility solution is already imposing challenges to the techniques.

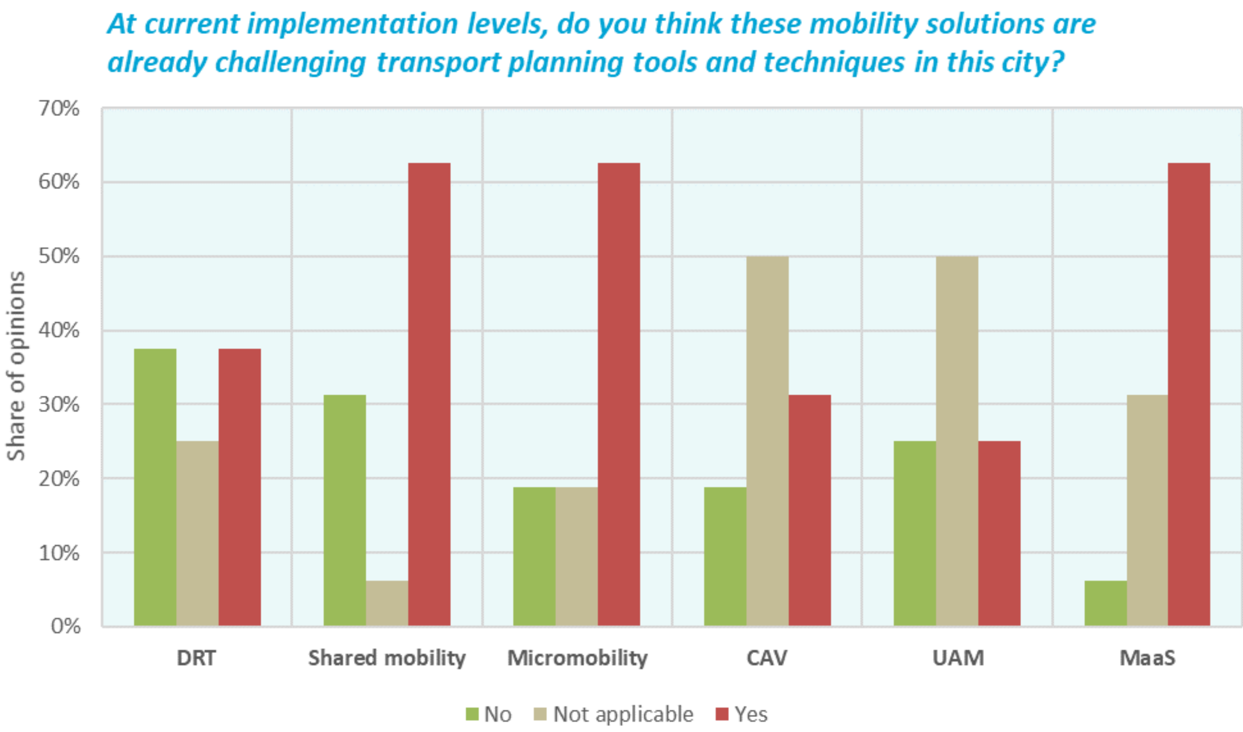


Figure 15 – Impacts of emerging mobility solutions in transport planning tools and techniques (1st Round)

Participants were asked about from what modal share do they consider essential to include these solutions in transport planning techniques. In view of the results (Figure 15**), the achievement of a 5% of modal share seems to represent a breakthrough** in how these solutions should be considered.

This question was also presented as a temporal matter (Figure 17 for the 1st Round, for the 2nd Round). For DRT, shared mobility systems and micromobility this is expected to happen in the next decade, so participants agree that they will be considered by transport planning techniques between 2020 and 2030. On the contrary, CAV and UAM would follow a much slower path towards their inclusion in these tools and techniques. The majority of the panel considers that this will not happen before 2030, and still between 10-20% consider that this will not happen. The 2nd Round repeated the question differentiating between shared vehicle systems (e.g. carsharing) and ridesharing, for the case of shared mobility. Both follow a similar path, although ridesharing inclusion is expected to take longer.

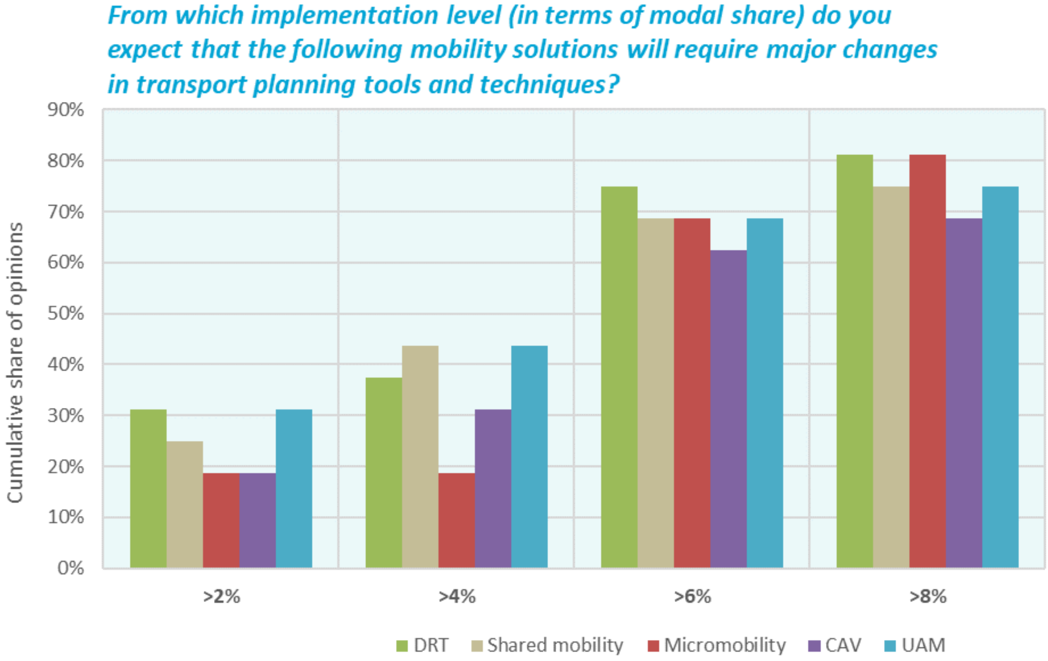


Figure 16 – Modal shares that would require major changes in current transport planning tools and techniques (1st Round)

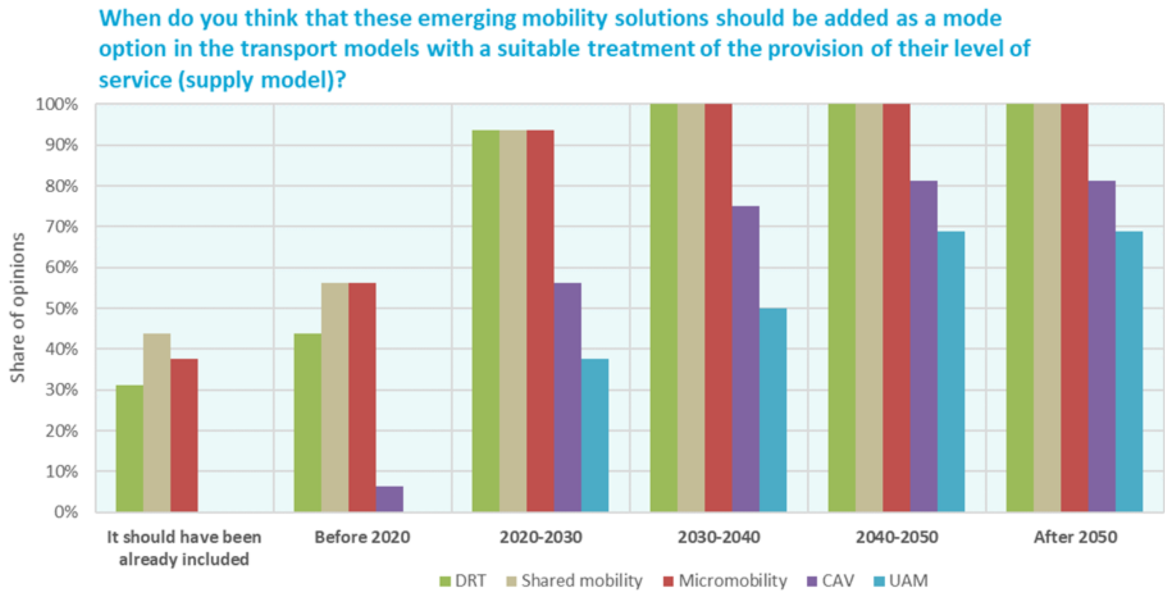


Figure 17 – Decade when emerging mobility solutions should be considered in transport planning tools (1st Round)

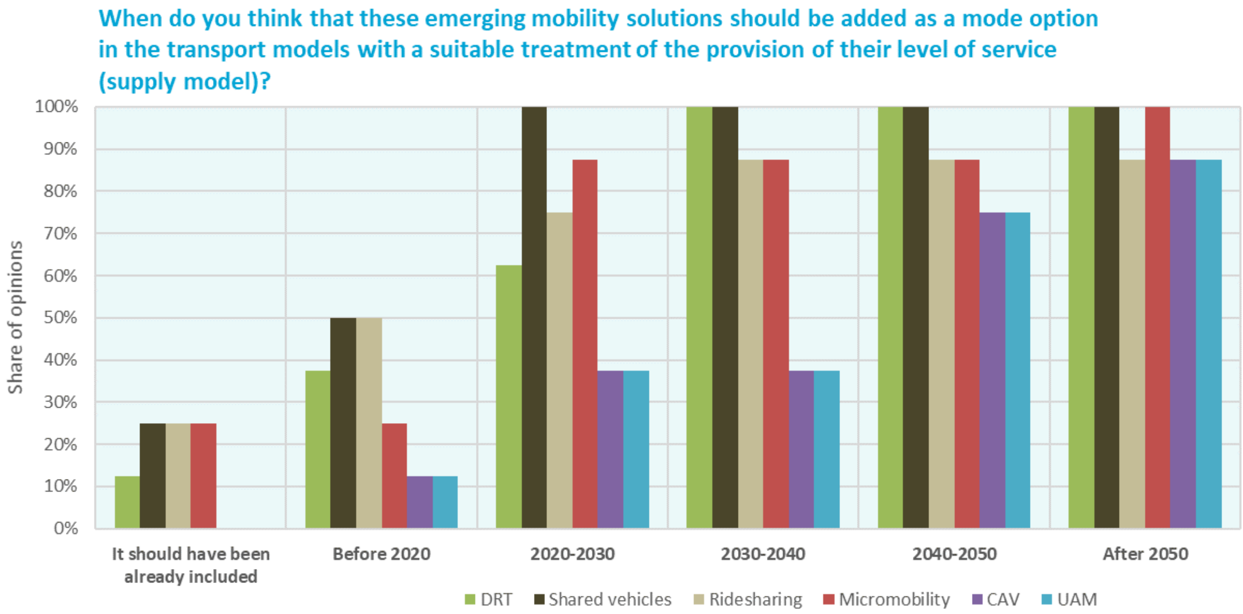


Figure 18 - Decade when emerging mobility solutions should be considered in transport planning tools (2nd Round)

The identification of research gaps and challenges among transport data sources, modelling tools and policy cycles is also of utmost interest for the project. With regard to the **gaps**, the panel provided a wide range of ideas. **Data sharing** between operators and policy-makers was highlighted by many respondents. Apart from this repeated issue, the following gaps seem to be relevant:

- The **lack of solid and stable agreements** with operators introduce uncertainties to the approaches needed for coping with these solutions. There is a lack of **monitoring tools** and **normative models** that would be valuable for policy-makers and regulators.
- The **limited cooperation of urban planning and transport planning** is also perceived as a gap in relation to this particular issue of emerging shared mobility services.
- The nature of the new options requires **disaggregated demand modelling approaches** taking into account improved behavioral models and the household context, e.g. in terms of car availability.
- The dynamism of shared mobility supply requires improvements in **supply modelling techniques** to be useful for the management of these systems.
- The **lack of models for assessing specific impacts** of these solutions, such as **empty trips modelling** or **car type choice** in shared mobility systems.
- The **lack of strategies for data fusion**, e.g. generation of synthetic populations from mobile phone data and household survey data.
- The **limited real-life data available** for performing analyses.
- The **lack of skills** by transport planners to deal with the advances in transport modelling tools.

Once again, the 2nd Round served to prioritize these gaps in terms of importance for the accurate modelling of the new mobility options. Figure 19, Figure 20 and Figure 21 collect the results of this process.

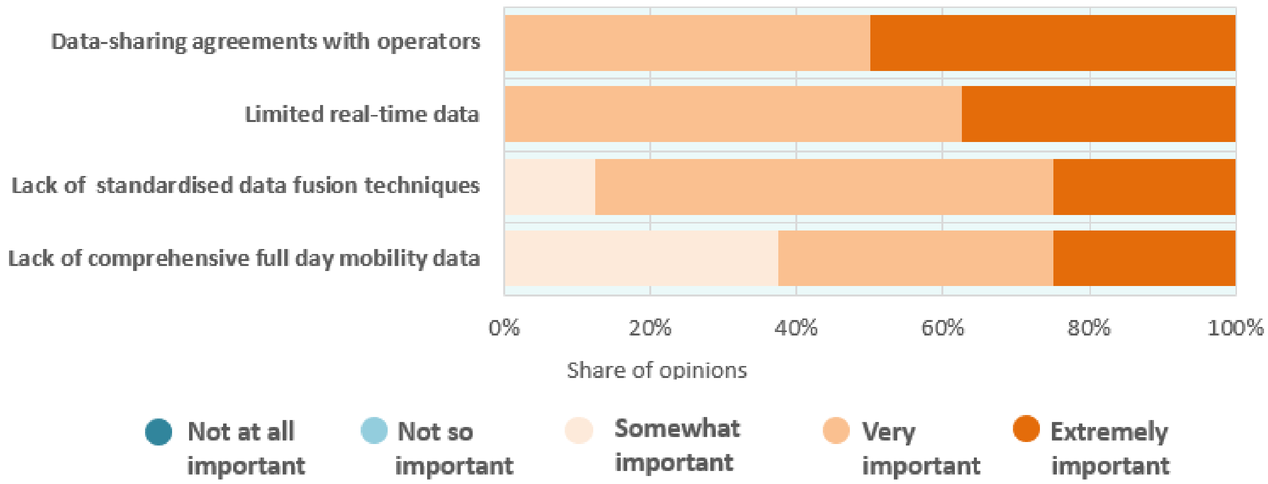


Figure 19 – Importance of transport data sources gaps for modelling new mobility options

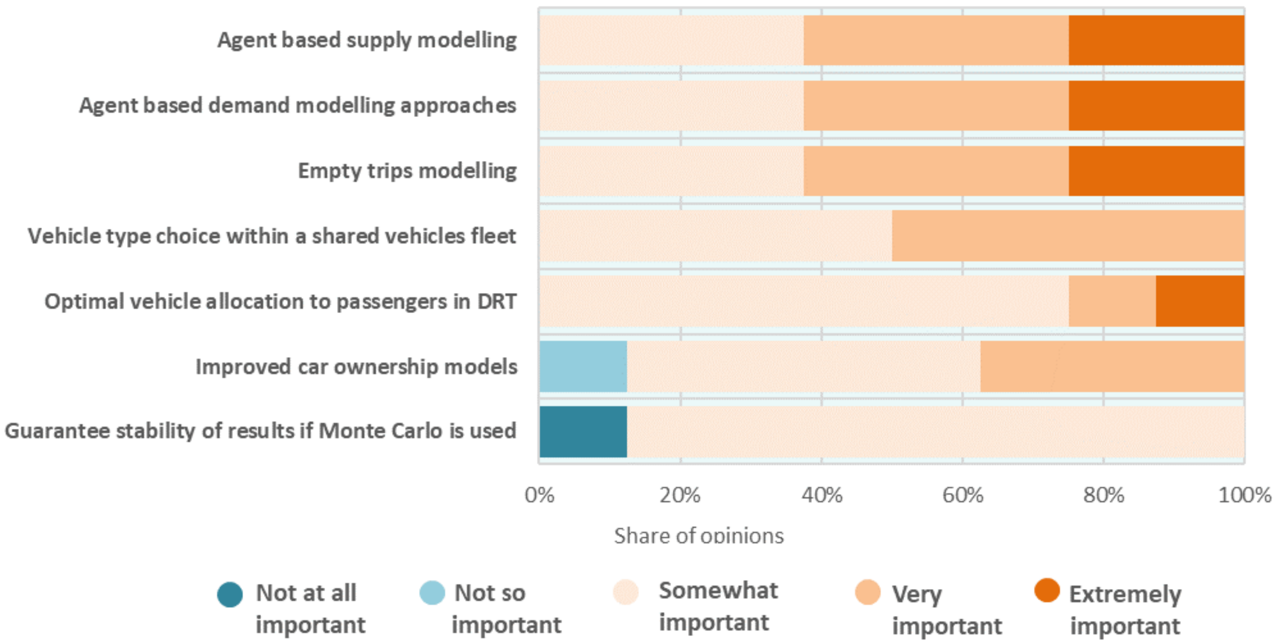


Figure 20 – Importance of transport modelling gaps for modelling new mobility options

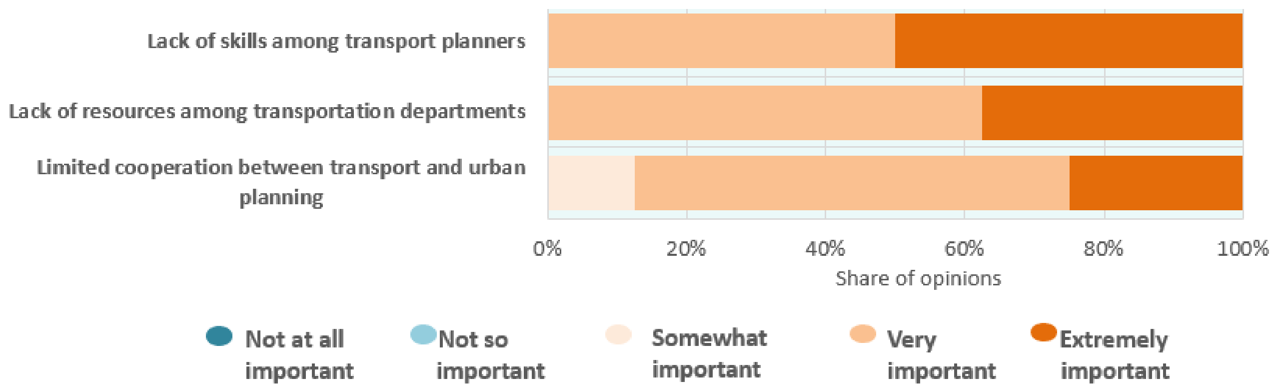


Figure 21 – Importance of urban mobility planning cycle barriers for modelling new mobility options

The **indicators** that the experts consider as interesting for the future transport planning tools are the following, from the ones most frequent to the ones less frequent:

- Emission level indicators.
- Safety measures.
- Accessibility measures, particularly related to the potential improvement of accessibility in suburban areas.
- Modal split changes, particularly the served demand by new mobility services.
- Public space consumption.
- Load factor of shared vehicles.
- User profiling of new mobility services and inclusiveness measures.
- Costs per mile.
- Empty kilometers travelled.
- Car ownership changes.
- Trip generation changes.
- Energy consumption changes.
- Spatial coverage of new mobility services.
- Comprehensive indicators related to urban life quality.

Figure 22 shows how the experts rate each category of indicators in the 2nd Round.

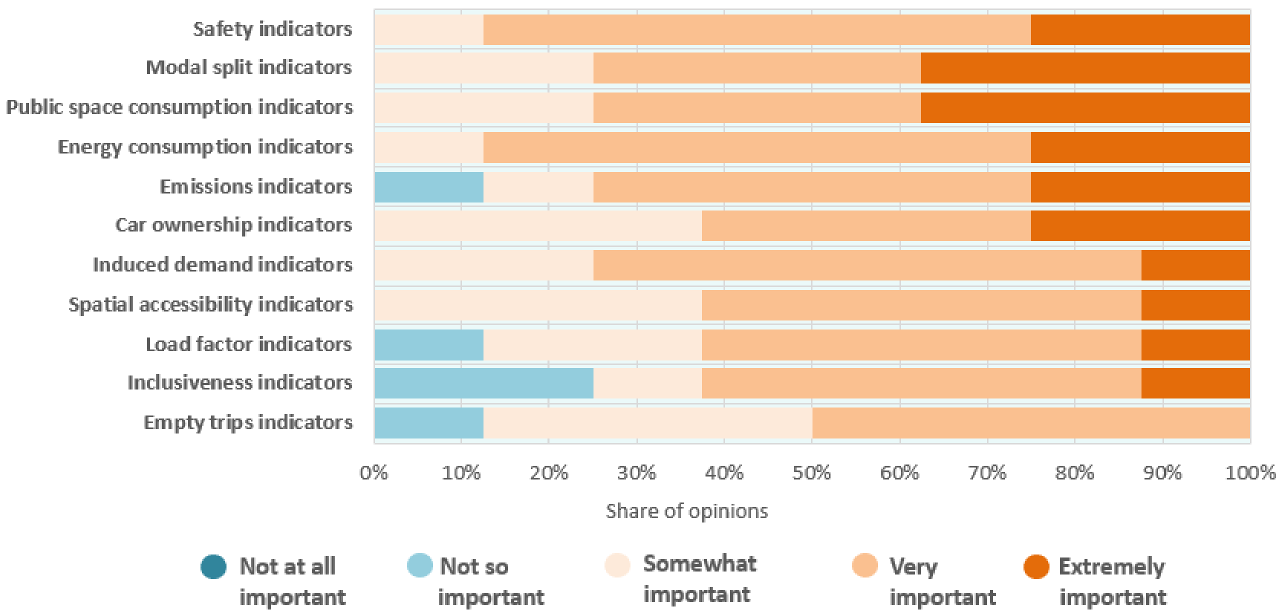
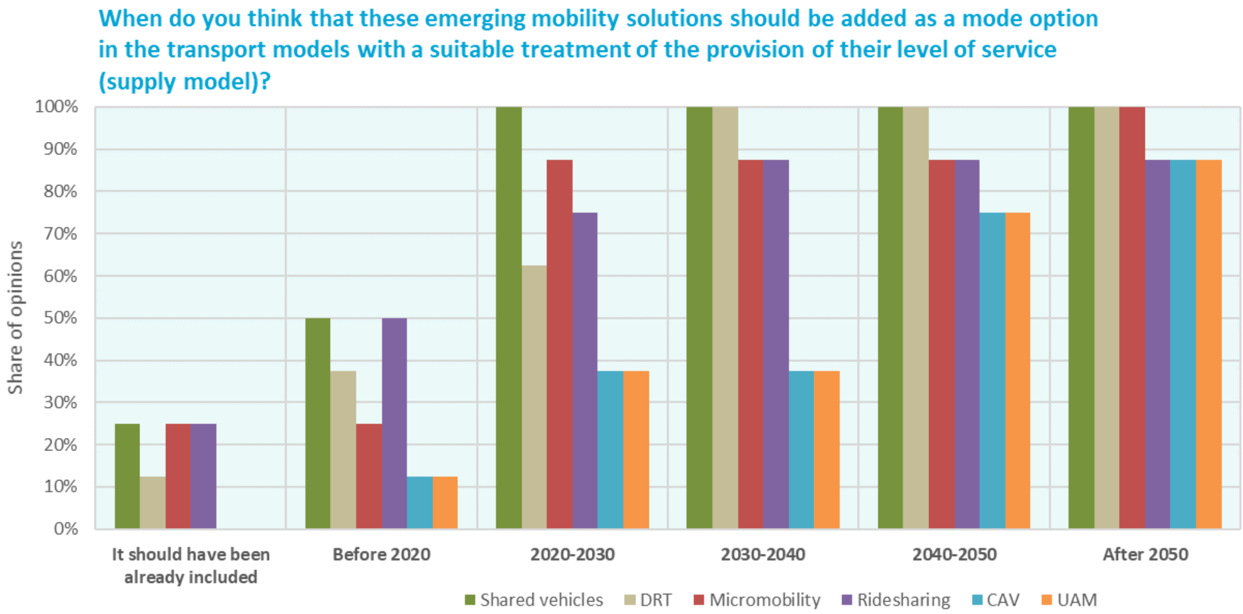


Figure 22 – Importance of different categories of indicators as priority outputs for new mobility options modelling


When do you think that these emerging mobility solutions should be added as a mode option in the transport models with a suitable treatment of the provision of their level of service (supply model)?
Share of opinions
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
It should have been already included
Before 2020
2020-2030
2030-2040
2040-2050
After 2050
Shared vehicles
DRT
Micromobility
Ridesharing
CAV
UAM

4. Present and future of transport data sources

Evidence-based policies with impact on urban transport systems require reliable information about mobility patterns and travel demand. The obtention of such information is often a headache for practitioners: data availability, the resources for collecting data and the skills for analysing it are often limited. The proliferation of mobile devices and sensorisation techniques suggests that many useful data is already being collected: the key is to have access to it and to extract from each source the most valuable information.

The traditional approach for the collection of travel demand information is based on surveys (household travel surveys, vehicle intercept surveys, on-board transit surveys, etc.). Surveys provide rich information on mobility patterns and the underlying behavioural drivers (e.g., travellers' sociodemographic characteristics, trip origin and destination, trip purpose, modal choices), but they have intrinsic problems, such as incorrect and imprecise answers, and they are expensive and time-consuming, which limits the size of the sample and the frequency of update. This leads to many urban mobility plans being developed on the basis of incomplete or outdated information.

During the last decade, different studies have shown the potential of new, opportunistically collected data sources to overcome some of these limitations. Transport modellers have begun to integrate the information extracted from these new sources. However, a number of challenges are yet to be fully overcome to exploit the full potential of these emerging data sources.

Section 4 reviews the present and future of travel demand data sources, grouped in six categories: **sensor vehicular data**, **floating vehicular data**, **sensor personal data**, **floating personal data**, social media **data** and **mobility surveys**. It must be clarified that these categories do not intend to establish a taxonomy, but to organise the review in a way that similarities and differences between different datasets are highlighted.

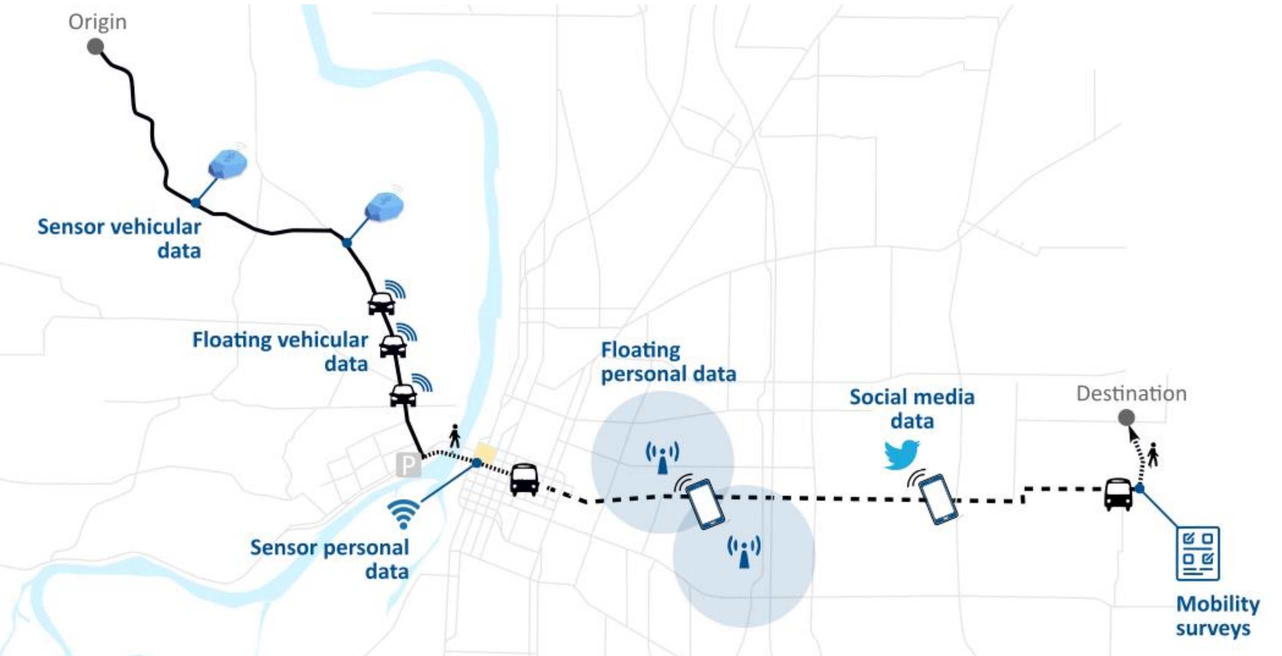


Figure 23 – The role of different data sources through a standard trip within any city

4.1 Sensor vehicular data

4.1.1 What is sensor vehicular data?

Sensor vehicular data comes from any type of vehicle detector located in a fixed position of the road, able to capture different traffic measures. This category of sensors can be divided into two main categories [154]:

- **Point detectors**, which obtain the traffic measurements at specific points in the road network [154]. There are several technologies that serve this purpose. **Pneumatic tubes** are extensively used to perform temporary counts. **Single loops** consist on a magnetic loop embedded in the asphalt and they can only provide the flow and the occupancy of the road; whereas **double-loop detectors** (two magnetic loops very close to each other) can provide instant speed and vehicle length apart from the two previous measures. **Video cameras** with image detection methods [155] also fit within the point detectors category. They are gaining interest in recent years because of their lower installation and maintenance costs, higher accuracy and its capability to detect motorised and non-motorised traffic as well as vehicle behavior.
- **Interval detectors**, which provide a measure of the travel time between two points. This category includes systems such as **Automatic Number Plate Recognition (ANPR)** [156], **Bluetooth** [157] and **Wi-Fi** [158] based-detector sensors. This type of devices usually works by identifying the vehicles at the beginning and the end of the studied segment and then by calculating the travel time from this data. Furthermore, they are also a source of local Origin/Destination matrices [159].

The **format** of the datasets generated by these detectors depends on the specific characteristics of the device. In this way, for points detectors, datasets are structured in table format (one table per sensor) with one row per period, and where each row contains aggregated measurements (flow, avg. point speed, avg. occupancy, etc.) over the time interval. The duration of the time intervals usually goes from 5 minutes up to one hour, and the aggregated measurement may be provided by vehicle type. Regarding interval detectors, the raw data obtained from these sensors have a transactional format that includes the identification of the sensor that registered the event, the timestamp of the event, the identification of the vehicle (plate number for ANPR and MAC identifiers for Bluetooth and Wi-Fi based-detectors), and some additional information (e.g. signal strength for Bluetooth and Wi-Fi). In some occasions, due to privacy issues (as it will be explained below), the format of the data is similar to that of point detectors, but with aggregated values referred to a road stretch instead of a point.

With regard to **privacy issues**, each type of device has different implications. Some detectors do not identify each vehicle but only count them (e.g. point sensors) but others track plates or MAC identifiers, so the information is more sensitive as it is related to a single vehicle. Therefore, anonymisation techniques, as the aggregations explained above, must be applied. Furthermore, this data source is **usually proprietary and owned by public or private authorities**, the former being more common than the latter. Despite its proprietary character, some initiatives have appeared recently aiming to make the information obtained from this data source category publicly available in open data portals. One of the most known ones is the PeMS repository [160] from California's Transport Department, but similar initiatives are present in cities such as Madrid [161], Paris [162] or Brussels [163]. However, there is still room for improvement since many cities and authorities are still reluctant to share this data with the general public.

4.1.2 What are the opportunities and shortcomings of sensor vehicular data?

The use of sensor vehicular data in the domain of travel behaviour and mobility pattern analysis is wide and frequent. In the case of point detectors, it is one of the primary data sources of many travel behaviour and demand analyses, because of its **current wide deployment in roadways**, its **robustness versus external factors** (especially for **loop sensors**) and its accuracy. However, the use of interval detectors has been less common due to their less widespread deployment [154], although they share many of the benefits with the previous category. The emergence of connected vehicles will extend the applicability of interval detectors.

Some examples of application are **travel time** estimation [164–166], **traffic volume** estimation [167, 168], estimation of **origin-destination matrices** [169–171], **traffic monitoring**, **segmentation of road user** classes [172], monitoring of **vehicle occupancy** [173] or **automatic incident detection** [174] just to name a few.

One recent trend that is worth mentioning here is the **increasing detection capabilities of video-based vehicle detection systems** [175]. Recent advances in hardware and computer vision approaches are making the use of this type of devices more and more popular. The main advantage of these devices lies in the multitude of use cases that are enabled by automated video-image-processing methods and their applications. Some examples are [155, 175]: automatic incident detection, multi-modal traffic count, law enforcement, toll collection, speed camera, vehicle behaviour analysis, etc.

The general shortcomings of these sensors are mainly their **limited coverage of the road network**, particularly in minor roads and their **high installation and maintenance costs** in comparison with other data sources such as Floating Car Data (FCD) [176]. Furthermore, each type of device has its additional shortcomings. In this sense, loop sensors are **prone to malfunctioning**, being inoperative from 25% to 30% of the time [177]. Bluetooth and Wi-Fi sensors show problems [171] with **data reliability and processing** because of issues related to their penetration rate, mode discrimination and detection quality; Whereas, ANPR and video-based traffic detection systems are **susceptible to external factors** such as weather and poor light conditions.

Data accessibility could also be a problem in some cases since, as discussed above, it is proprietary data, and some organisations are not willing to provide it, especially in the case of those devices that track individual vehicles, because of the sensibility of the raw data they produce.

4.2 Floating vehicular data

4.2.1 What is floating vehicular data?

Telematics systems have been developed to acquire and transmit vehicle data for decades. The measurements may cover a wide variety of variables, for instance instantaneous vehicle speed and fuel consumption. The same technology has been utilized to also track the location of vehicle fleets, which is recorded from **Global Navigation Satellite System (GNSS) receivers** operating onboard road vehicles. Traditionally, the receiver was a dedicated GNSS device but nowadays more modern, **general-purpose smart devices can be used**, that may not be connected to the car itself, like a common smartphone, a tablet used for navigation or even a tracking-enabled wearable gadget. Spatiotemporal datasets recorded while a vehicle is moving and containing the coordinates of the vehicle, are known as Floating Car Data (FCD).

FCD might be recorded during the utilisation of any kind of road vehicle, from the navigator systems of privately-owned cars to tracking systems of commercial fleets (taxis, busses, trucks, carpooling and carsharing vehicle fleets, free-floating bikes and electric scooters, etc.). Hence, it is interesting to remark that **shared mobility services often collect this type of data from their fleet**. It is nowadays regarded a simple, relatively cheap and widespread technology [178] as most vehicle fleets have already incorporated tracking systems leveraging satellite-based radio navigation, and at the same time GNSS-enabled devices have penetrated society in unprecedent levels.

Raw FCD are structured and contain records with spatiotemporal information of high granularity, as the exact timestamp and coordinates are the main dimensions of records. Often, more fields might be available reporting the instantaneous vehicle speed and/or acceleration (both magnitude and orientation), altitude and dilution of precision. Several studies have also utilized case-specific FCD features, for example the occupancy state and trip origin-destination of taxis, the transport schedule of a truck or emissions/consumption data.

The **recording frequency** varies significantly and depends on several factors, for instance the system's design, its purpose, limitations posed by the underlying communication system and its bandwidth, data transmission cost, sensor energy consumption among others [179]. The FCD frequency, as reported in most studies, typically ranges from low values of one record per minute, up to sixty records per minute (1Hz). Recording frequency is found to affect the performance of algorithms that try to map each datapoint with a specific road and travel direction, commonly known as map-matching algorithms. Tracking the exact route of a vehicle is simpler and more accurate when consecutive points are dense and the temporal difference between them is up to 10 seconds. On the other hand, in cases of less frequent sampling, the temporal and thus spatial distance between successive datapoints increases and more complex map-matching algorithms should be applied to reconstruct the travelled path to certain confidence levels [180, 181].

4.2.2 What are the opportunities and shortcomings of floating vehicular data?

The **decreasing cost** and **widespread use of sensors** and Internet of Things (IoT) has resulted in a growing trend in FCD penetration, which is expected to last or grow bigger with the arrival of further technologically advanced and autonomous vehicles. FCD is regarded as one of the main sources of **real time information about traffic condition on road networks** [182–184], as data are generated and recorded dynamically by the travelling vehicles in a fully automated procedure.

FCD are considered relevant for numerous mobility domain applications [185], including the extraction of **travel times** [186], fine-grained **traffic characterisation** and travel speed on a street level [176, 185, 186], **vehicular origin-destination matrices** [176, 187, 188], **frequent mobility pattern identification** (frequent traffic paths) [187, 189], **hotspot detection** (attractive areas) [190–192], **outlier detection** (any kind of atypical phenomena, for instance congestion at unexpected locations due to an accident, extreme weather events, social events, etc.) [188, 193, 194], **traffic light operation optimisation** [194, 195] and **weather effects on vehicle speeds** [196]. Several authors have also utilized FCD for predictive analytics, mainly based on machine learning models or statistical methods for traffic forecasting [196–201]. Neural network models trained on historical FCD seem to be the most prominent and accurate predictive algorithm for short term traffic forecasting [201]. FCD are able to **tackle limitations posed by fixed location sensors** [176] with costly installation and maintenance, bounded geographical coverage, inadequate coverage of minor roads and inhomogeneous measurements. Further, FCD are highly sensitive and can detect atypical traffic events like jams and accidents.

Among the shortcomings of FCD, it must be highlighted that **FCD are privately owned**, commonly by fleet operators and managers, who are the only agents with real time access to the raw data. Third-party entities are typically granted access to subsets of aggregated metadata or historical data for offline analysis and research. In the cases when the FCD can be traced back and linked to the vehicles and/or individuals, the process of **anonymisation** is obligatory before opening the data to third parties. The **volume of FCD can potentially become exceedingly large** when numerous devices contribute to data logging with high frequency. In such cases, the traditional data processing techniques might prove inadequate, demanding algorithms that utilize scalable frameworks and technologies for efficient and distributed **big data processing**. The records inherently include some **positioning error**, typically ranging from centimetres up to a few meters, especially in certain places with reduced GNSS accuracy due to obstacles, for example tall buildings (multipath events), or signal outage. However, those limitations can be countered by accuracy correction and map-matching algorithms [27], [28]. Modern technologies incorporate advanced hardware and software with improved tracking accuracy in the order of a few centimetres [29].

4.3 Sensor personal data

4.3.1 What is sensor personal data?

Sensor personal data category includes datasets recorded from static devices that capture some sort of human activity. The most common examples are **pedestrian flow counters**, such as **cameras, Wi-Fi or Bluetooth sensors**. While cameras identify pedestrians through image recognition techniques, sensors detect nearby personal devices equipped with these connecting technologies and log the relevant data. For instance, a Wi-Fi hotspot records the number of connected devices and a Bluetooth sensor can periodically scan the area for devices with enabled Bluetooth connectivity. Typically, each detected device is paired to a unique identifier (for instance the MAC ID of any Bluetooth device), and subsequent detection of a device by different sensors unveils mobility patterns and unlocks great potential for transport research. Apart from devices that are purposely installed for counting people, many public transport systems include similar elements, since they record the amount of people using a certain service. This is the case of **public transport ticketing** data when no information about the individual user is recorded since it is unrelated to a transport card holder, unlike public transport smart card data (see Section 4.4).

Sensor personal datasets are structured and have a transactional format, i.e. they have a time dimension and describe some kind of event, referring to one or more individuals. In some cases, however, data are recorded after the aggregation of measurements in time segments, for instance when a **camera** reports pedestrian flows aggregated for five-minute periods. Besides the event timestamp, the transaction location is also captured (directly or indirectly), frequently in the form of a unique identifier, for instance the identification number of Wi-Fi sensor. The data spatial accuracy is extremely high given it is a punctual measure and the coverage area of Wi-Fi and Bluetooth sensors is low, however, the temporal granularity is not as remarkable as the spatial granularity.

Some sensor personal datasets are **linked to a certain individual**. This is the case of Wi-Fi or Bluetooth counters, which as it happens in the application to vehicles, can serve to generate local origin-destination matrices. In these cases, anonymisation technics should be adopted before FSP data is open to third parties. In addition, they are proprietary, owned by the public or private entities which control the sensors and/or the recorded event. Organisations are generally reluctant to opening those data as they contain, amongst others, confidential operational information.

4.3.2 What are the opportunities and shortcomings of sensor personal data?

Sensor personal data have great value and applicability in investigating the dynamics of human behaviour and mobility. Sensor personal data acquisition is preferred among other mobility data sources because it monitors certain human activities pervasively, yet the **data collection method is strictly passive**, fully automated and continuous. This allows for collecting data for huge samples compared to other active methods. These data sources are a key element for analysing **pedestrian flows**, which are difficult to assess through floating personal data sources such as mobile phone data.

The main issues with sensor personal data are related to **data openness**. Their proprietary nature poses serious accessibility barriers and private agents are reluctant in sharing them. **Penetration levels** can be an issue for FSP datasets recorded by Wi-Fi or Bluetooth sensors, since not all users keep these technologies enabled while carrying their personal devices on streets. Another consideration in the utilisation of FSP for studying mobility in urban areas is that in certain datasets, for example Wi-Fi or Bluetooth sensor detection, the important detail of **travel mode across street users** is unknown. In this direction, studies have attempted to identify the travel mode utilizing machine learning algorithms with higher than 83% accuracy for three modes, walking, biking and driving [202]. The **volume and high dimensionality** of sensor personal datasets may pose certain limitations and difficulties in processing and extracting knowledge. To this end, the authors of [203] proposed a methodology to reduce dimensionality with two orders of magnitude by applying principal component analysis. The original dataset can be reconstructed with the top eigenvectors with more than 90% accuracy.

4.4 Floating personal data

4.4.1 What is floating personal data?

Floating personal data is composed by the geolocated registers left by devices that can be considered to be attached to a single individual, and therefore moves next to it. The combination of ICT and IoT has multiplied the number of emitting devices that we carry on with us in our daily life and left location registers in databases. The most common sources of floating population data are the following:

- **Mobile phone records**. This refers to the registers recorded by mobile network operators (MNOs) when mobile phones interact with their network of antennas. Each register contains a user identifier, a timestamp and an antenna or cell identifier. It can include information about the event that has triggered the register (e.g. call, SMS, Internet connection...). The database has to be complemented with the antenna network map, and can be enriched with sociodemographic data about each user identifier. In order to comply with privacy requirements, MNOs run anonymisation algorithms to the original database. The spatial scope of these data is usually large, since MNOs usually work at a national level. The spatial granularity depends on the density and distribution of antennas across the territory. Urban areas and infrastructure corridors tend to have more density, in order to meet service requirements. This implies a spatial resolution of tens or hundreds of meters, while in rural areas this can fall to several kilometers [204]. The temporal granularity depends on the events registered by the mobile phone records [205]. Active events are those that require an action from clients, such as performing calls or sending messages, so imply lower granularity. Passive events are those triggered by the MNO in order to locate mobile phones independently of the usage of the device. The access to the data depends on each MNO policy. Some of them have internal departments that commercialise solutions that analyse the data, while other reach agreements with third parties that buy the data to perform analyses for transport-related clients.
- **Mobile GPS data**. This refers to the registers recorded by smartphone applications when they interact with the GPS satellites. Each register contains a user identifier, a timestamp and a position represented by the longitude and the latitude. The register may contain also information about the use of the application or the status of the device. Depending on the personal data that the application owner request from the user, this can be complemented with some sociodemographic features. Exactly as it happens with mobile phone records, most data privacy laws require anonymisation procedures before any exploitation of the data. The spatial scope of GPS data is usually unlimited, since it does not depend on a specific network. The spatial resolution of GPS is the highest possible among current data sources, since it provides a longitude and a latitude, although it has a precision range of a few meters. The temporal granularity depends on the use patterns of each mobile application and the number of location requests made by the application, so it can be very variable. The access to the data is managed by the owners of the mobile applications or the Operating System (OS) of the smartphones. Some of these agents directly commercialize these solutions and others reach agreements with application aggregators, that collect the data from several applications in order not to be limited to a certain user profile. As this document demonstrates, **almost all emerging mobility services have to accessed through mobile applications**, so these transport operators have the ability of collecting GPS data from their users.
- **Public transport smart card data**. This refers to the registers recorded by the public transport ticketing systems when users pay or validate their trips in the network. Each register contains a user identifier, a timestamp and a location identifier where the interaction took place. This data requires a complementary database with all the locations where these events may take place, which implies usually a detailed map of the transport network and a comprehensive list of public transport services [206]. The spatial scope is restricted to the transport network itself, while the spatial granularity is very high, since it is possible to certify where the user exactly performed the interaction with the transport system. Instead of temporal granularity, the critical aspect in this case is in which interactions with the public transport the user is

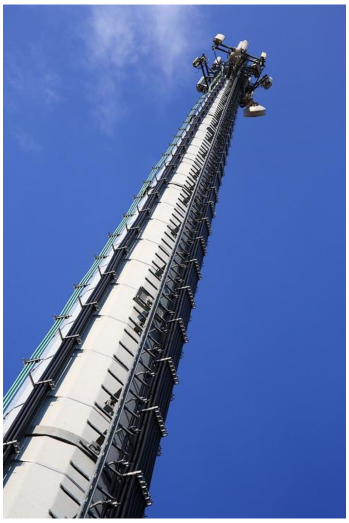
required to use the card. This will determine the actions that leave traces in the database. For instance, in the majority of bus networks it is not needed to use the card at the end of the trip, so the database only contains registers related to the origin of the trip. The access of the data is managed by the transport operators or the transport authorities. This implies that it is often available for performing mobility analyses, especially in those cases where the study is promoted by the operator or the authority itself.

- **Card transaction data**. This refers to the registers recorded by banks when credit and debit cards interact with a Point of Sale (PoS) to perform a transaction. Each register contains a user identifier, a timestamp, a PoS identifier and the transaction details. Accordingly, the data has to be accompanied by the location of each PoS, and may be complemented with the sociodemographic data that the data owner has about the card user [207]. The spatial scope of the data is very large, usually similar to GPS location data, since it is not limited by frontiers. Regarding spatial and temporal resolution, this will depend very much on the use patterns of each sampled person. The access to the data is limited to financial agents and banks that process the transactions. They set up sharing policies similar to those of MNOs and applications owners.

4.4.2 What are the opportunities and shortcomings of floating personal data?

In terms of mobility patterns analysis, the goal of data analysts that work with these sources is generally to reconstruct the activities and trips performed by each user during a given period of time. The different types of floating personal data share some features in relation to this target. For instance, the fact that the data is continuously collected allows analysts an exceptional **flexibility regarding study periods**, an aspect that particularly limits the potential of mobility surveys [204]. Moreover, the passive collection of the data **eliminates the drawbacks of non-response and false response bias** present in surveys [208]. In any case, it is interesting to review the opportunities and shortcomings of each data source:

- **Mobile phone records**. **Sample size** is usually the most highlighted advantage of this source. The high sample size is achieved thanks to two aspects: (i) mobile phone penetration rates, which are reaching 100% of the population in developed countries [209] and (ii) the concentration of MNO market, with each country being controlled by no more than three operators [210]. This implies that anyone with access to an MNO database usually has data about one third or fourth of the population. This allows an **unprecedented quality for trip generation and distribution** information [211, 212], alleviating the so-called "blank cells" problem in origin-destination matrices, which refers to the fact that survey data is not able to capture trips in many origin-destination relations. **Representativeness** must be carefully analysed [213], but the fact that MNO are becoming less specialized and have products for all market segments improves this feature. The temporal and spatial resolution lies at an intermediate point between the sparse registers of cards data and the potential high temporal and spatial resolution of mobile GPS data [212]. This imposes some limitations, such as the **difficulties to detect trip mode in metropolitan areas**, where different transport networks are served by the same antennas and the short distance of the trips limit the number of intermediate registers that may provide information [214, 215]. Unlike GPS data, is hardly ever possible to identify in which building is the user located, so **trip purpose information have to be inferred from observed recurrence patterns** in large data series [216], e.g. trips to work can be detected by observing a recurrent activity in a given number of days per week at a spot different from home location. In practical terms, databases are usually very large and **raw data needs intensive cleaning and preprocessing** efforts before conducting any mobility-related analysis [205]. This implies that data science skills and **high-performance computing capabilities** are essential to use this source.



- **Mobile GPS data**. Even though smartphones represent a wide proportion of the total amount of mobile phones, sample size is usually much lower than the one achieved by mobile phone records [216]. This is due to the fact that each mobile application produces its own data, so only in few cases the penetration rate of a single app is comparable to market shares of each MNOs. Critically this is not only a matter of size but also of **representativeness**: taking the data from a single application may involve profiling biases, since some of these services are only used by a certain population group [217]. Apart from sample effects, this phenomenon also affects to the **temporal granularity** of the data: registers are only generated while using the specific application that is contributing to the data source. Given this situation, the emergence of **application aggregators** tries to overcome this problem, but it takes time to get a combination of contributing applications that covers the whole day use of a smartphone. In addition, those applications that may increase the sampling frequency of GPS location are very consuming in terms of battery [217], so they are usually avoided by most users. In any case, the spatial resolution of GPS is remarkable, allowing **fine grain analyses about trip mode based on speeds and about trip purpose based on high resolution location**. As it is the case with mobile phone records, the size of the databases can be very large, representing a **computational challenge**.
- **Public transport smart card data**. This source represents a remarkable opportunity for analyzing **public transport demand patterns** [218, 219]. Firstly, it usually includes a very large sample, since most operators tend to include nearly all tickets in their smart contactless cards. Secondly, it denotes all the movements that users make across the network, providing information about **combined use of several public transport** modes. Thirdly, it is **owned by the transport operators** or authorities themselves, so they can design the software behind the data collection in a way that makes easier to use the data for mobility analyses. There are two main shortcomings about this data source: (i) it **does not represent the door-to-door trip**, since it only contains information about the public transport leg [220]; and (ii) it **usually does not include specific registers for the alighting**, especially for those trips performed by bus or tram [219]. The first limitation implies that some hypothesis on the real origin and destination of the trip have to be made, taking into account the accessibility of the stops and stations. The second limitation implies that the algorithms that process this data have to infer the drop-off point by looking at recurrent use patterns and the next origin point of each user.
- **Card transaction data**. These datasets are often valued as a way to analyse economic activity in certain areas. In this sense, the **scarcity of the registers**, which only appear when transactions take place, limit the application of the source for mobility analyses. However, this source collects important information about an aspect that is often difficult to retrieve from the other floating personal data sources, which is the **purchase power of the users** [221].

Above all the specific opportunities, it must be highlighted that floating personal data can act as an enabler of activity-based models, as demonstrated by the existing studies [208], overcoming data availability challenge, which is often regarded as a crucial barrier for adopting this modelling approach [222] that seems essential for assessing the impact of emerging mobility solutions.

4.5 Social media data

4.5.1 What is social media data?

Social media is a data source that has attracted in recent years the interest of the researchers and practitioners in transport and mobility [223]. Platforms such as Facebook, Twitter, Instagram, etc. allow people to share its ideas, emotions, information, pictures, videos, etc. with location-related information in a ubiquitous way thanks to the widespread use of mobile and wearable devices. Social media data provide location information in two ways [223]:

- **Location-based services**, that allow users to share its activity-locations choices (check-in) in their virtual networks when they enter places such as shops, malls, stadiums, restaurants, etc. Hence, this can be interpreted in similar terms to floating personal data.
- **Geo-tagged associated data** available in people's posts in platforms such as Twitter or Instagram. This additional information to the location to the user can provide rich information on the role of the activities performed at such location, making a difference with standard floating personal data.

The information from social media is usually provided in the form of transactional data. Concretely, each transaction, that corresponds to a user's "post", normally has a timestamp, an identification code for the user, a check-in location or GPS coordinates together with the content of the post that could be text, hyperlinks, pictures, videos, etc. or a combination of them, depending on the specific platform. Furthermore, this type of data sources is updated in real-time and provides information about a large population, given its widespread and increasing use rates [224].

Social media data sources are **proprietary** and usually owned by **large private companies**. This implies that the access to these data sources it is not allowed or very limited in some cases (e.g. Facebook) or it requires some paid plan subscription (e.g. Twitter, Instagram) to have an access quality that allows a wide and efficient mobility analysis, especially at large-scale. However, the cost of this subscription is low compared with other data sources for mobility analyses.

Privacy is an important issue when dealing with social media data, given that it can **expose sensitive information** from the users and/or it can be used to identify and track individuals [225]. This issue is particularly relevant in those occasions when the user does not allow to share their individual information publicly, making necessary the user of privacy-preserving and or aggregation techniques. However, in some social media platforms users give their **consent to the distribution of their data amongst third parties**. While this is an important advantage for analyses related to people's mobility patterns [224], it can pose significant threats to privacy, and it is therefore crucial that the analyses adhere to ethical standards.

4.5.2 What are the opportunities and shortcomings of social media data?

The **massive and ubiquitous usage** of social media nowadays, which provides millions of geotagged posts every day, in many occasions with **high geographic accuracy,** by millions of users, make this data source one of the most promising at present [223]. Its use for this type of applications began to be explored in 2011 [226], and since then, the number of works and application areas have experienced a significant increase.

Some examples of these applications are **Travel Demand Modelling** [227, 228] where for example it has been used to complement information obtained in mobility surveys; the study of the **travel behaviour** of people at aggregated level [224, 229, 230]; the inference of the **purpose of activities** carried out by individuals [231, 232]; the evaluation of the **satisfaction of public transport users** [233] or the **involvement of citizens in public transport planning** [234]; and the early **detection of traffic accidents** or the **estimation of the state of traffic** [235], among others. According to a recent survey [223], the most promising applications of social media data are travel demand, long-term transport planning and managing operations (e.g. traffic accidents).

From a general perspective, the main advantages of social media data for mobility analysis [223] are the **low acquisition cost**, as mentioned above; the fact that the users provide the information without surveys or laboratory biases which make it more realistic; and the **growing availability** of geo-located social media data due to the widespread and increasing penetration of mobile and wearable devices and usage of social media.

The main disadvantage of the use of social media data for mobility analyses is the high **cost of the data processing** required to extract useful information. Given that the most relevant information of social media data is usually included in the text of the posts, it is necessary the use of **advanced text mining, natural language** and other data mining techniques [236]. This data processing increases the overall cost of the analyses performed with social media data despite the low acquisition costs mentioned above.

The second main disadvantage of social media data is the **representativeness** and its **bias towards social media users** [224] and also towards discretionary and leisure activities. This bias may decrease in the future since current trends show that the penetration of social media users in the population is increasing, resulting in samples more representative of the actual population. In the meanwhile, the best option is to use sampling bias correction techniques.

Another relevant shortcoming of social media data is access to **individual-specific data** that is not shared publicly at the request of the individual [223]. When the analyses are performed using this protected data, due to privacy issues and data protection, information must be anonymised and/or aggregated, so data cannot be traced back to users.

4.6 Mobility surveys

4.6.1 What are mobility surveys?

Mobility surveys are the most traditional method to collect travel demand data. Surveys are based on questionnaires that contain a set of questions opportunistically selected given their relevance for the objectives of a specific study. Questionnaires are handed out to a chosen part of the population, which constitutes the sample of the survey. This is the main difference with a census, where all individuals of the population are asked [237]. The answers of the sample provide information about how people are travelling and why they are choosing to move in a particular way, in order to monitor or model a transport system [238].

There are several types of mobility surveys which consequently generate very different and complementary data. Not all trips in a study area can be surveyed through a single type of survey [239]. In this line, it is possible to distinguish two main types:

- **Household surveys**, which ask all the members of each household in the sample about the trips made within and to/from the study area in the period analysed. These surveys are often conducted either as a personal interview or by telephone. These are usually the longest type of mobility survey, and therefore collects rich information not only about trips themselves, but also about complementary aspects such as the socioeconomic features of the household that are relevant to their travel behavior (e.g. car ownership, income) or the existence of household members that do not generate trips. The application of classical four-step transport models in metropolitan areas has been based on these surveys (Bates 2000).
- **Intercept surveys**, which ask citizens while performing trips. The questionnaire is handed out in a convenient intermediate point of the trip (e.g. roadside surveys at gas stations for car travelers, on-board surveys for public transport users). These surveys are usually short, since they need to limit the interruption of the trip in order to achieve a sufficient sample size. While they do not provide as much information as household surveys, these are needed to assess the mobility patterns of non-residents in the study area. Indeed, long-distance mobility studies have to rely in these surveys, since study areas are too broad to conduct household surveys.

Most surveys are **cross-sectional**, since they collect answers from a chosen sample about their behaviour at a specific point in time. However, it is possible to conduct **longitudinal surveys**, which turn the sample into a panel of respondents that answers the questionnaire in repeated times. This allows to detect changes in their travel behaviour and explore the motivation of these changes [239].

Mobility surveys can be also classified depending on the nature of the information collected [239]. On the one hand, some surveys ask for **revealed preference (RP) information**, which encompass all the aspects related to the current travel behaviour. On the other hand, it is possible to ask for **stated preference (SP) information**, which explores how the respondent would behave if a certain situation (e.g. the introduction of a new transport mode in the city) took place. Depending on the objectives of the study that motivates the survey, it can address either one or both sides.

4.6.2 What are the opportunities and shortcomings of mobility surveys?

Mobility surveys entail a **trade-off between quality, quantity and cost** [238]. The quality of the survey is determined by the design of the instruments that are used for the survey, i.e. the questionnaire, and the features of the sample selected for performing the survey. The quantity of the survey is very much related to the sample size, but also to the number of questions addressed by the questionnaire. As it can be expected, the costs increase with the size, scope and level of quality of the survey.

The motivation for the increasing interest of transport practitioners in the alternative data sources reviewed in this document (e.g. floating personal data, floating vehicular data…) has a lot to do with this trade-off. Basically, Big Data sources seem to distort the relation between these three factors, mainly because of their impact on the quantity-cost relation. These sources are able to achieve sample sizes which may be several orders of magnitude greater than surveys for some studies, normally at a lower cost [213]. In comparison to these emerging data sources, **sample size** is the main shortcoming of mobility surveys [215]. In addition, even if the quality aspects are reviewed carefully, surveys will always provide statements about travellers' behaviour instead of their actual mobility patterns. The potential differences between the statements and the reality introduces **false response biases**. Moreover, not all members of the selected sample provide answers, leading to potential **non-response biases**. These biases are seen as a disadvantage compared to passively collected data, which reflects the actual behaviour since it does not introduce an observer in the mobility situation [212].

Even if biases may compromise survey quality, up to date there are no alternative data source or combination of sources able to entirely substitute the rich information that surveys provide about **travel behaviour and the motivations that underly mobility patterns**. Apart from some trip features that are difficult to evaluate through floating personal data (e.g. detailed trip purpose) there are a set of **subjective elements of mobility** that can be only accessed by surveys (e.g. modal choice reasons). In addition, since mobility surveys are promoted by transport authorities themselves, they can take the **control over the full process of data collection and analysis** [240]. In this line, transport authorities are already familiar with mobility surveys and their personnel **do not need additional skills** for dealing with this data source, which is not the case for the Big Data sources reviewed in this section [241].

4.7 Challenges and gaps in transport data sources research

If any common conclusion can be extracted from this review of transport data sources, it is the fact that **no single data source is able of capturing all the nuances of mobility patterns** that can be exploited by transport models and decision support tools. As a consequence, the main research challenges and gaps with regard to data sources are about the **development of data fusion techniques** that take the most from each source. There are already valuable examples of successful merging of heterogeneous databases to extract mobility information (e.g. social media with other sources [242, 243]), but this issue will require more attention from researchers. **Machine learning techniques** seem to be a suitable approach for inferring mobility patterns from heterogeneous and sparse data sources with different levels of resolution and representativity. There are different methods that have to be explored, such as stage-based, feature-based and semantic-based data fusion, as well as different algorithms as co-training, multi-kernel learning or matrix factorisation among others.

Research challenges and gaps can be organised through three pillars: data and **emerging mobility solutions**, **collection** of data and **analysis** of data.

4.7.1 Data and emerging mobility solutions

Emerging mobility solutions have an advantage over traditional modes such as public transport. Most services have started from **very high technological standards**, with systems capable of collecting multiple datasets from the service operation.

On the one hand, service providers track their fleets through GPS technology. This implies that operators collect high-quality **floating vehicular data** that describe the dynamics of each system. In many cases this data is enriched by adding to the trip data of each vehicle an identifier that corresponds to a given registered user. This converts these databases in a source of both vehicular and **personal data**. This dual character represents a breakdown with public transport data, since it manages to integrate supply and demand data in a single database.

On the other hand, the fact that these services are accessible through smartphone applications opens the room for the collection of **floating personal data** through GPS **beyond the use of the vehicles**. Private concerns and battery drainage seem to be refraining operators from pushing towards this direction.

Several research challenges emerge from this specific topic, such as the implications of **data aggregation** for the analysis (e.g. which descriptive indicators can be still calculated at certain aggregation level?). The development of **innovative descriptive indicators** is itself a challenge, especially due to the coupling between supply and demand (e.g. how should vehicle rotation be depicted to indicate zonal profitability for shared mobility services?)

4.7.2 Collection of data

There is still ample room from improvement in the **collection of data**, as the following gaps and research lines show:

- The **limited coverage of sensor data** can be alleviated through the selective use of floating data. The installation and maintenance costs of sensors, especially of those dedicated to measuring vehicles, imply that the coverage of the sensors has to be limited to main roads and streets. The inference of traffic and people flow in those network segments with no sensors largely remains as an open issue [153, 244].
- The **robustness of video-based sensors** is still limited. Although there has been a lot of advancement in this area in last years, the performance and robust working of these systems is still affected [155] by environmental factors (e.g. poor light conditions, shadows, etc.); scenario conditions (e.g. type of road, camera location, camera resolution); and vehicle motion (e.g. occlusion, abrupt change in motion).
- There is an opportunity for **optimizing survey sample sizes** through the combination of several data sources. For instance, mobile phone records can be used for analysing trip generation and distribution in urban areas and also for determining the sample size needed for a survey that focuses on modal choice.

4.7.3 Analysis of data

The **analysis of data** is also an aspect that will gather the attention of transport practitioners in the following years, through the following threads among others:

- The **cross-validation of results from different data sources** is not very common. This could help in determining the role of achieving certain sample size or penetration levels of the technologies that are related to some data sources (e.g. smartphones) in the quality of mobility demand estimations. The robustness of desired penetration levels with respect to spatial characteristics (city, region or area of interest) and vehicle (taxi fleet, private cars, truck fleet) is also unclear. Research would benefit from the application, validation and comparison of proposed solutions on different city, vehicle type and penetration level configurations.

- The **richness of passively collected data sources** is usually poor, since it is often the case that Big Data sources such as mobile phone records, GPS data or Wi-Fi sensors do not provide socio-economic attributes. This can be solved through machine learning algorithms that exploit a combination of data sources where these attributes are easier to collect (e.g. surveys).
- The application of **clustering methods for mobility patterns** offers a wide range of opportunities in analytical terms. Machine learning algorithms can classify mobility patterns into different categories and identify possible explanatory variables. Spatial analysis and unsupervised machine learning techniques can be used to automatically extract these categories by grouping people with similar mobility patterns. Interpretable machine learning algorithms (e.g., linear regression, fuzzy rule-based systems, probabilistic graphical models, etc.) can be employed to create analytical models that infer the categories of new mobility patterns. This is particularly interesting for the analysis of emerging mobility options, where adoption and use drivers remain unclear.
- In many situations the **penetration levels of each technology are not known** or have to be inferred or estimated. This is particularly the case for Bluetooth and Wi-Fi based sources. This implies that it is still unclear if and how representative they are. This challenge in the analysis and application of sensor datasets in not sufficiently researched and addressed in the available bibliography.
- The role of social media Data can increase among travel demand data sources if more efficient and accurate **text mining and natural language processing techniques** are developed. Given that the most important information from these data sources is collected from the text included in the posts, which can be noisy, large and dynamic [245], these advances can reduce the cost of the information processing required.
- Most of the data sources reviewed in this section deal with individual data. For instance, some studies show that the data provided by users in social media can be sensitive and may harm not only the privacy of the person that uploads the information but also one of the others [225]. For that reason, the development of **new privacy-preserving techniques** is required in other ensure that the information extracted from the analysis does not expose or harm people.

5. Present and future of transport modelling and decision support tools

Transport problems are becoming more widespread and severe in both developed and developing countries. Transport planning, which comes to solve these problems, usually involves a forecast of travel patterns and demand. Therefore, there is a need for techniques and tools able to simulate or represent how people travel. A transport model is a mathematical tool which helps policy makers to decide on the future development and management of transportation systems in view of changing land use and travel patterns [246]. A typical transport model usually consists of a travel demand model to estimate demand and a network supply model to assess the network performance. Decision support tools integrate and/or complement transport models for guiding policy makers with their tasks.

Transport modelling techniques and tools can be applied with several ways, namely:

- For the provision of demand data for the analysis of scenarios, for the design of new infrastructure, and for operational service responding to real traffic forecasts and functional requirements;
- for understanding the impact of a new mobility scheme on mobility flows, representing how demand responds to the new infrastructure and the resulting conditions;
- for understanding how transport conditions will change in the future in response to changes in population, employment, economy, car ownership and development patterns;
- for specifications of network bottlenecks and necessity for additional capacity.

As it is revealed so far, the current changes in mobility ecosystems pose **high levels of uncertainty and complexity** and lead to important policy dilemmas, taking into consideration all the possible impacts resulting from each one of the transport trends. Transport policy-makers, advisors or relevant stakeholders, should recognize and agree on the best model for relating policy actions and/or strategies to consequences or the likelihood of future scenarios/events. The functionalities of models specified above are based on a series of functions and conceptual relations that transport practitioners introduce to deal with the input data and obtain the desired indicators. Therefore, any major change in mobility landscape, either from supply or from demand side, has a potential impact on transport models.

As a consequence, it is understood that **transport modelling should follow the new developments as well**, to bridge the gap between the new array of demands and the services they offer and provide useful guidance on future mobility. Modelling the complexity and uncertainty of future mobility requires a shift from traditional modelling approaches, which can be achieved by creating a different model architecture or/and methodology approach.

Section 5 reviews the current state-of-the-art of transport modelling techniques and tools. It focuses on reviewing **network supply** modelling and **travel demand** modelling, together with an identification of which aspects are key for the **modelling of emerging mobility options**. This Section also provides a review of **transport planning decision support tools**, which often integrate the aforementioned techniques. Finally, it concludes with a list of the **research challenges and gaps** that the changes in mobility landscape imply for modelling techniques.

5.1 Network supply models

5.1.1 Current concept of Dynamic Traffic Assignment

A Dynamic Traffic Assignment (DTA) estimates the evolution and propagation of traffic congestion through detailed models that capture travel demand, network supply and their complex interactions. Unlike static traffic assignment (STA) models, DTA modelling approaches can describe time-dependent dynamics of traffic and replicate the interactions between travellers' choices (route and departure time) and the state of the traffic network. From a traveller behaviour standpoint, DTA is a technique that allows for modelling of both long-term traveller adaptation to experienced congestion and modelling of traveller behaviour in response to unexpected congestion that occurs within a single day. Figure 24 shows a taxonomy of today's traffic simulation models based on the DTA concept, including both commercial and open source, depending on the network loading models they use.

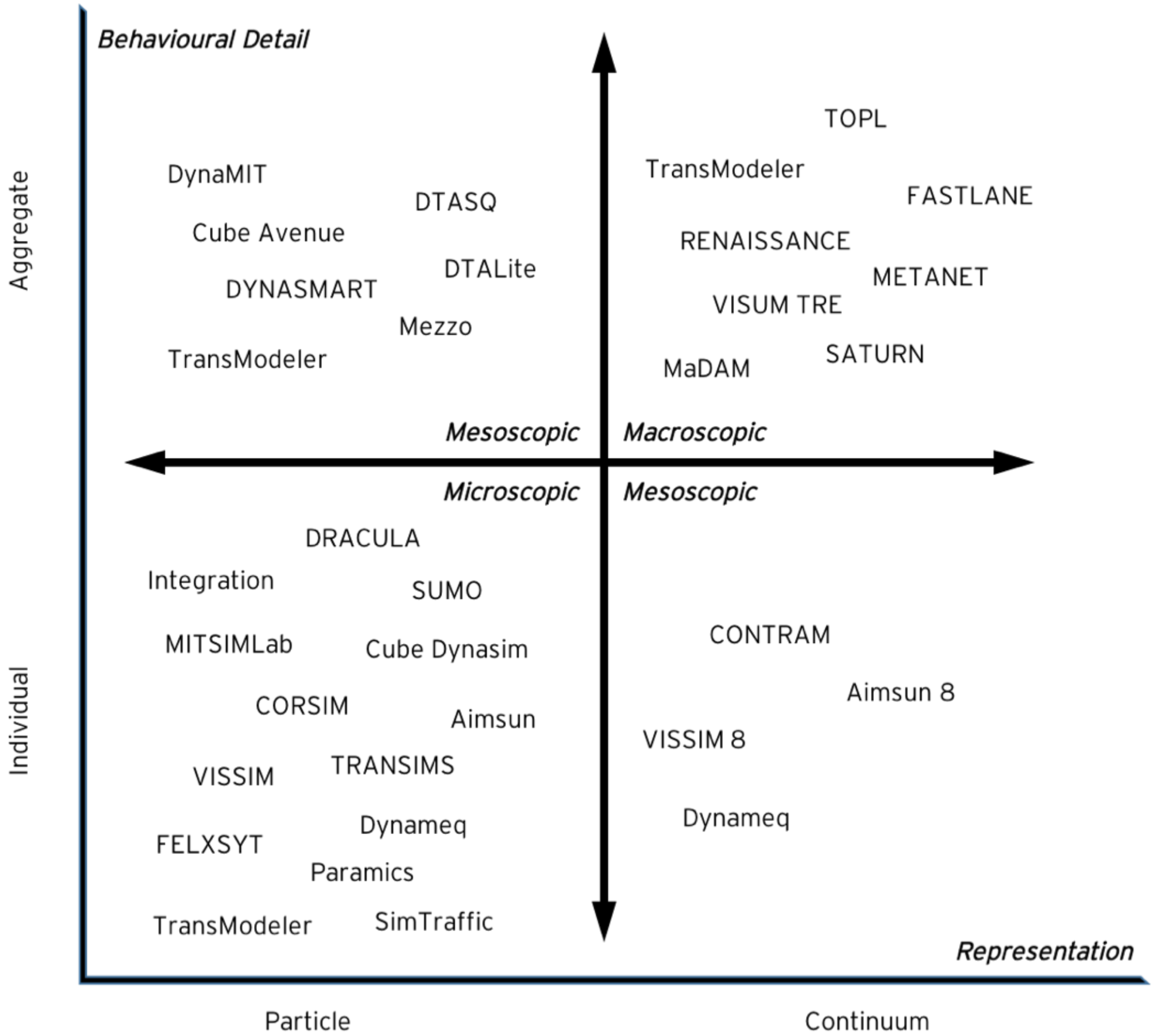


Figure 24 - A taxonomy of traffic simulation models with corresponding network loading models adopted.

All these traditional traffic simulation tools based on DTA modelling approach (route choice analysis and network loading in traffic networks) are not directly applicable in the multimodal context. Currently, most traffic simulation software only considers different vehicle types, referred as multi-class models. In this context a vehicle class indicates a type of vehicle, such as a car, truck, HGV, bus, tram, train, bicycle, other two-wheeler types, etc. In addition, some traffic simulation software, such as Aimsun Next and VISSIM, offer modelling of slow mode traffic, such as pedestrians. However, these properties do not meet all the requirements of the multimodal DTA. To represent a multimodal trip as a path, it is necessary to combine the networks of available modes via transfer, waiting and/or access links into a so-called supernetwork [247]. An additional difficulty is the limited availability of public transport services. The additional service layer needs to be implemented, which implies limited temporal and spatial availability of the public transport network and results with a more complex definition of path alternatives and consequently the sequence of travel decisions.

5.1.2 Multimodal Dynamic Traffic Assignment

Mobility is more than just car movements and therefore an increasing trend shows a movement towards so-called multimodal DTA models. These models consider a trip or path as a chain of the multiple modes of transport (e.g., trip is represented as a ride a bicycle, take a public transport, then walk). It makes sense that if citizens have the ability to consider a combination of different forms of transport for a trip, these should be simultaneously considered. Difficulties in multimodal modelling often stem from a necessity to use different propagation models, a lack of information on the Value of Time (VOT) and behavioural changes, the ability to switch between modes, and the interaction between the modes in the model. However increased urbanisation and mobility in cities demands that all modes be considered as feasible intermodal possibility of travel, especially in urban areas. Examples of the current multiclass models presented in Figure 24 are expected to be further developed and other new multimodal models are expected to be developed and applied to a greater extent in the future.

Some studies have attempted to simplify the network representation or the level of detail, focusing on schematic networks [248]. Notwithstanding, in the absence of complete real-time information concerning passengers' locations and travel plans, a day-to-day dynamic network loading is an essential component of network initialisation in order to estimate passenger departure times as well as waiting and on-board flows (e.g. impact of expected reliability and congestion levels on route choice which their assessment requires an iterative day-to-day assignment). Another challenge is related to the definition of alternatives to the observed path. Not only is it more complex to generate realistic path alternatives in a multimodal network, but there may be a bias in parameter estimates induced by the selection of a restricted choice set [249]. The mechanisms of multimodal traffic assignment rely on sound knowledge of traveller's preferences for attributes of multi-modal trips, such as travel time, waiting time or number of transfers. The recent study of Zimmermann et al. [250] fills a gap in the literature by estimating a multimodal transit route choice model with unrestricted choice sets based on revealed preference data collected in a complex network. The approach has the advantage of yielding consistent estimates and can also be used for prediction in a real network without generating choice sets of paths.

Although still in its early stages, agent-based simulation models emerged recently as an alternative approach to support complex public transport assignment models. A review of the simulation-based approach to public transport assignment models and description of the features of the main models developed in this domain in recent years is available in Cats et al. [251]. The so-called agent-based approach used in a range of sciences is aimed at modelling complex systems by representing the strategies of individual agents and the dynamics between agents and the environment as well as interactions between agents. Agent-based models represent complex systems using a bottom-up modelling approach where each individual entity is represented as an agent. Simulation models can facilitate the dynamic loading of passengers over a dynamic representation of the public transport system. Cats [252] discusses the potential advantages of a multi-agent simulation framework for modelling the public transport assignment problem, in particular in the context of ITS.

5.2 Travel demand models

A travel demand model helps to analyse travel demand changes in response to different input parameter assumptions. Such models provide aggregate or disaggregate demand flows as output by simulating travel choices [253]. Two major approaches for travel demand modelling exist in literature: (i) **trip-based (aggregate)** and (ii) **activity-based (disaggregate)** modelling [222]. While the former approach is being used by the majority, the latter approach is comparatively a recent development. Some of the indicative differences between the two modelling approaches are given in Table 17.

Table 17 - Components of modelling approach and indicative references. Source: Narayanan et al. [254].

Parameter of comparison	Trip-based Four Step Modelling	Activity-based Agent-Based Modelling
Basis	Trip-based	Activity-based
General spatial resolution	Travel Analysis zones (TAZ)	Micro Analysis Zones (MAZ)
Temporal resolution	Peak/off-peak or hour based	Continuous
Realistic constraints for space and time (activity consistency)	No	Yes
Data requirements, modelling complexity & run time	Low	High

Note: Both TAZ and MAZ do not refer to any specific scale. However, while a TAZ is usually defined at the level of region's Census tracts or Census block groups, MAZ is defined at a much finer scale, e.g., a household or a building block.

5.2.1 Trip-based modelling

Under trip-based modelling approaches, individual person trips are used as the fundamental unit of analysis [255]. This is suitable to any sized urban region and is usually used for large scale, strategic transport modelling. Aggregated data at the level of traffic zones are used in this approach. Trip based models are also called as Four Step Models (FSM) and were introduced in the 1960s [239].

As the name implies, FSM usually involve four steps of modelling. The first step in this modelling approach is trip generation, wherein estimation of the numbers of trips produced by and attracted to each zone is calculated using demographic, land use and economic activity data. The second step is called trip distribution, and consists in the assignment of origins and destinations for the generated trips. Usually a gravity model is used for the same. However, growth factor model and entropy-maximising approach can also be used. The third step, mode choice, involves determination of travel mode for the trips using logit models. In the final step, routes utilised for the trips are predicted and the process is known as network assignment. While the first three steps are related to demand estimation, the final step is related to network supply. The travel demand model and network supply model interact with each other and an equilibrium between demand and supply is achieved through several iterations of the modelling steps. A modified four step modelling approach includes time-of-day choice, other than the four steps described above.

5.2.2 Activity-based modelling

Activity-based models are helpful to address many transport policy questions, in particular travel demand management policies, that cannot be adequately answered using trip-based models. The reason for this is the following: activity-based models recognise that the trips are carried out for activity participation and consider the interdependencies and constraints involved in scheduling activities [255]. Further, data at finer and smaller scales are used in this approach [222]. The usual modelling scale used is at the level of an individual and hence, the models are usually developed as Agent-Based Models (ABM) [253]. These models are based on behavioural theories related to how people make decisions about activity participation in the presence of constraints.

Tour-based modelling approach is the basis for the development of Activity-based models [256]. Research on the link between travel and activities started a long ago, with the work of Mitchell & Rapkin [257]. Some seminal works in the field include those of Hägerstrand [258] and Jones [259]. A typical ABM model is linked with a population synthesis model and involve daily activity pattern and tour formulation. Population synthesis involve generation of synthetic population, who are representative for the actual population of the area of interest. Each individual in the synthetic population is associated with a set of socio-demographic attributes, which are then used to construct a daily activity plan, including activity location, start time, duration and the trips connecting two activities. Some of the personal attributes used in the model include gender, age, work status and transit pass ownership and some of the household attributes include number of persons, residential location, household income and number of vehicles owned. From the constructed activity pattern, tours are generated. ABMs usually employ a Monte Carlo process to represent individuals (and vehicles) and their behaviour in a transport system ([239]). Monte Carlo simulations incorporating logit models are used to model choice of activities, tour length, tour characteristics, destination, time of day and mode. Sample enumeration is another technique which can be used for solving ABMs. However, Bradley et al. [260] compared both techniques using the Portland case as a test bed and found that Monte Carlo simulation was faster and more practical.

5.3 Modelling emerging modes of transport

Customers, operators and government (public authorities) are the main stakeholders of the transportation systems, where each stakeholder has several **objectives** (Figure 25). These objectives define the most suitable and therefore most sought-after indicators for the different stakeholders. The **customers** expect minimum waiting time to get picked up and minimum cost and travel time to reach the destination. They also expect maximum comfort while travelling. The main objectives of the **operators** include decreasing the various types of cost incurred (operational, maintenance, fuel/charging cost and parking cost) and the fleet size while increasing the number of requests served and the revenue earned. One way of reducing operational cost is through reduction of total system travel time and this is one of the most common objectives found in the literature. In practical terms, the objectives for customers are integrated in the objectives of the operators through level of service indicators. **Government agencies** aim at reducing accidents, congestion and emission while ensuring adequate spatial coverage and equity. In relation to this, certain Key Performance Indicators (KPIs) such as modal split, car ownership evolution, Vehicle Kilometers Travelled (VKT) or Person Hours Travelled (PHT) are important to assess the contribution of new modes in these terms.

The objectives incorporated in a model depends on the component of the mobility service that is subjected to optimisation.

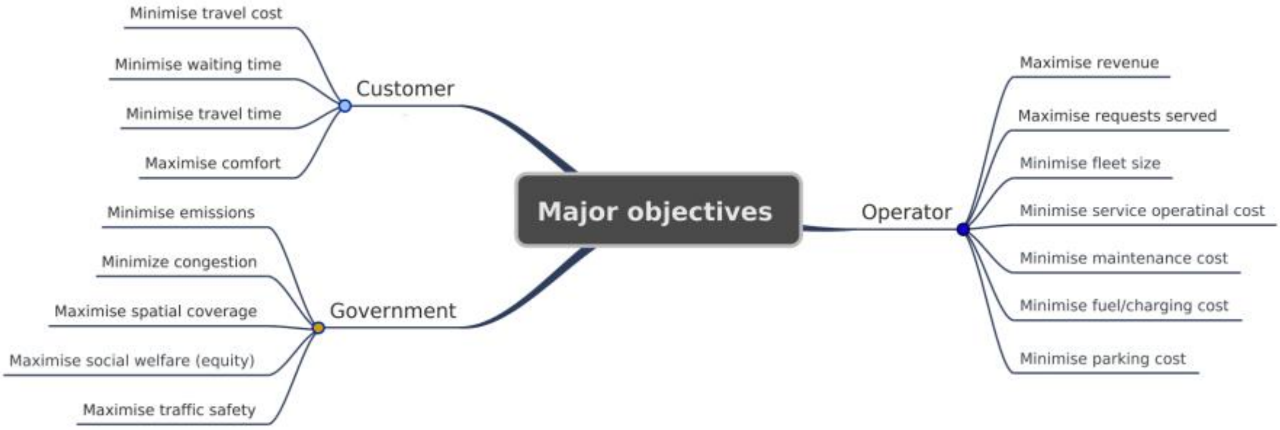


Figure 25 – Commonly observed objectives of different stakeholders of the transportation system. Source: Narayanan [261].

Transport models that simulate emerging modes of transport are inherently complex and a series of components are involved. A review on impact of Shared Autonomous Vehicle (SAV) services, Narayanan et al. (2019), enlists the following eight components required for modelling SAV services; a) Demand; b) Fleet; c) Traffic Assignment; d) Vehicle Assignment; e) Vehicle Redistribution; f) Pricing and g) Charging; h) Parking, as shown in Figure 3. The components listed in the review study can be relevant to modelling of several other emerging modes of transport in the cities, such as carsharing, motosharing, ridehailing, Demand Responsive Transport and Urban Air Mobility. For more info on the components, the readers are referred to Narayanan et al. [254].

The literature and the transport modelling workshop conducted in the MOMENTUM project provide some remarks about the integration of emerging modes in transport modelling tools:

- The inclusion of the emerging modes has to be **flexible** with regard to the configuration of the new services. Current emerging modes are known, but in the future additional new modes might appear. For instance, the growth of micromobility was unexpected until few years ago. It could be helpful to develop standard taxonomies of services in relation to their impacts in modelling, so the emergence of a new mode can be related to the challenges that the taxonomy brings about to models. In other words, this would provide ready-made material to adapt models to incoming services.
- It is suggested that **incremental improvements** are easier to implement than initiatives that intend to add all new services at the same time.
- It is considered that is likely that transport models become **part of larger urban dynamics models** that integrate further elements. Precisely, emerging mobility services imply new factors to consider (e.g. the capacity of urban power grids for electric vehicles). Transport models will need to interact with other models from other fields.
- Given the high uncertainty, **explorative models** are likely more useful than purely predictive models. Models would be a tool for risk assessment under different scenarios, rather than a merely predictive tool.

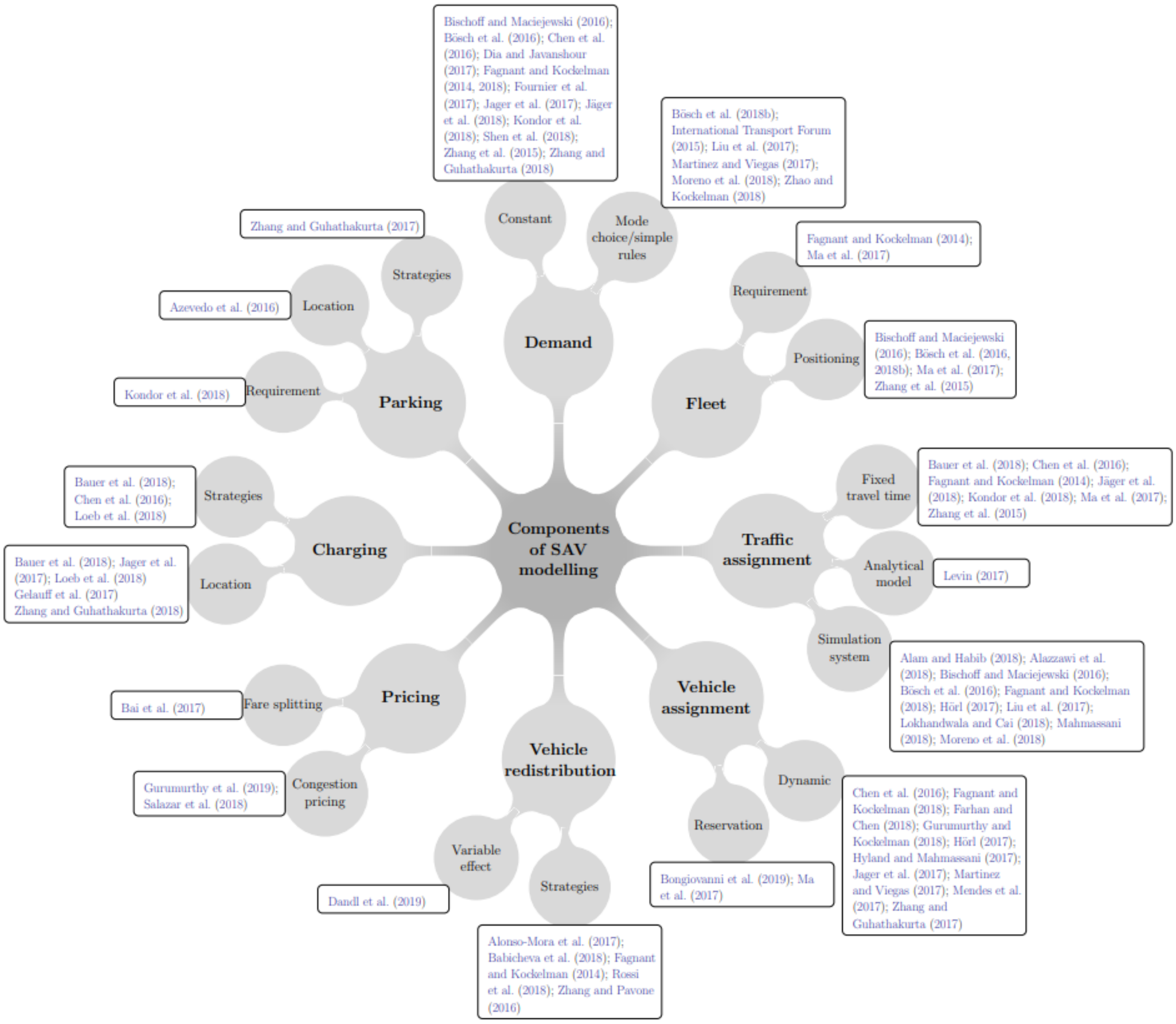


Figure 26 - Components of SAV modelling and indicative references. Source: Narayanan et al. [254].

5.4 Transport models and decision support tools

In many cases, transport models are integrated in wider decision support tools tailored to the needs of each policy maker. This integration intends to facilitate the use of models to take advantage of all the functionalities described in this Section. In this sense, the role of decision support tools is very relevant to the integration of transport models in planning, since they can alleviate one of the barriers for a massive use of modelling techniques, which is the perceived lack of usability [262].

5.4.1 The concept of decision support tools

Decision support tools (DSTs), also known as *decision support systems* (DSSs) are computer-based tools that support the relevant stakeholders in their decision-making processes. According to Sprague [263], a decision support system is defined by its ability to accommodate these features:

- Dedication to less well-structured problems that upper level management faces.

- Combination of a variety of techniques and models.
- Use of interactive environment for non-proficient users to enhance usability.
- Integration in a flexible and adaptable structure.

The scope of decision support systems has been changing through the years. Today, with the rampant advancements in information technologies, DSSs are used in a variety of applications and across many domains. The ultimate goal of a decision support system is to utilize the available data and implement the necessary models to aid the users in their decision making both at strategic and operational levels.

In general, a decision support tool or system consists of the following main components (Figure 27):

- **A Database Management System (DBMS)**: this component holds the available data the DSS acts upon. The large amount of data collected and processed nowadays allows us to talk about Big Data.
- **Models**: includes the techniques, algorithms and processes as well as the type of support provided and area of application.
- **User's interface**: guides and helps the users through the decision-making process by providing a friendly, flexible, simple and interactive interface.

Secondary components include the users themselves and visualisation techniques and tools (e.g. Geographic Information Systems (GIS)).

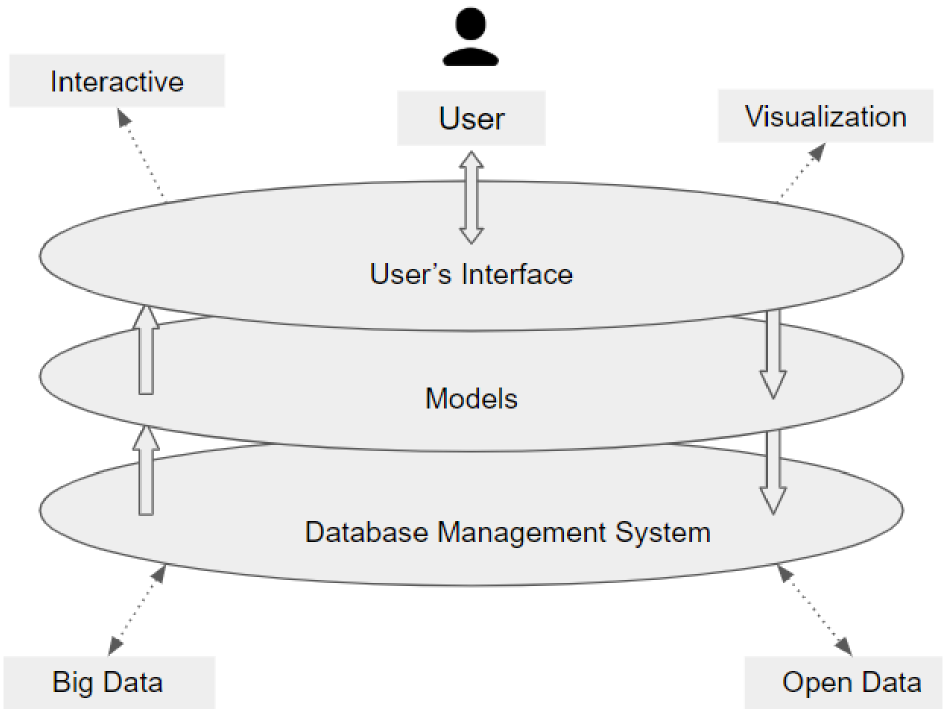


Figure 27 – Main components of a DST

With the decision support tools and their main components defined, the taxonomy of the different types of systems should be mentioned and described. In literature, many researchers have purposed a plethora of characteristics based on which the taxonomy of decision support systems can be produced. The most popular taxonomy is the one that proposes five types of decision support systems [264, 265]:

- **Communication-driven** decision support systems are targeted for internal small teams that work on a shared-task and enable and support their communication and cooperation. Web or client servers are commonly used to execute such task.
- As the name suggests, **data-driven** decision support systems are optimal for data manipulation purposes (e.g. executing queries to a database) that can assist in the discovery of the optimal answer.
- **Document-driven** decision support systems search web pages with specific keywords or phrases and locates relevant documents. Usually implemented with the client-server model.
- **Knowledge-driven** decision support systems utilize artificial intelligence techniques (e.g. neural network, fuzzy logic etc.) in order to provide specialized expertise and information to tackle specific problems.
- In the **model-driven** type belong decision support systems that are based on some specific model (e.g. mathematical) and aid in analyzing and/or choosing between different produced solutions.

5.4.2 Transport decision support tools

Transport-oriented decision support tools or systems are becoming increasingly popular. To this day, many innovative computer-based decision support tools use state of the art techniques and methodology in order to provide better transport services and increase customer satisfaction, safer and reliable services, reduce costs and maximize profits, improve infrastructure and improve the match between supply and demand [266].

Similar to the majority of the decision support tools (Section 5.4.1), transport-oriented decision support tools are composed of the three main components: database management system, models and user's interface. The tools used today tend to be equipped with a wide range of efficient techniques and methods from different scientific fields: operations research, decision sciences, decision aiding and artificial intelligence. The selection of the methods and techniques used in the model base of the decision support tool depends on the transportation problem that the solution or decision making is intended for. Examples of the problems commonly decision support tools in transport are used for are: fleet assignment, vehicle routing and scheduling, fleet composition, crew assignment and scheduling, fleet replacement, fleet maintenance. service portfolio optimisation, infrastructure maintenance and renovation, transportation projects evaluation and others.

5.4.2.1 Classification of transport decision support tools

In the literature, many criteria for classifying transport decision support tools have been proposed by different authors. Zak [266] summarized the main classification characteristics in his work by applying the general rules of generic decision support system's classes in the transport context:

- First, transport-oriented decision support tools can be classified based on their **modal focus** into airborne, waterborne, road, rail and multimodal transportation decision support systems, as well as the specific category of public transportation.
- Another measure of classification is **the size and the scope** of the decision support tool. This refers to the end user of the product and can be distinguished into: single user (residing in normal personal computers), small network or group (team effort) and centralized or enterprise that are used by multiple organisational units in an organisation's hierarchy.
- **Conceptual focus** is an alternative characteristic that stems from the general classification of decision support systems and is described in Section 5.4.1.
- An important metric for differentiation of the decision support tools is their **problem-solving approach** based on which the systems are divided into two categories: passive that do not provide alternative and different solutions and active that allow the user to modify and adjust the solution's metric and parameters in order to generate the most suitable answers.

- **Organisational level** refers to the time frame of the decision-making process. Based on this the decision support tools are classified as: strategic for long-term objectives, tactical for mid-term planning and control and operational for short-term managerial activities.
- As mentioned, the transport sector requires solution to a plethora of distinct problems. In that regard, the decision support systems are classified based on the **subject scope and focus**. This category includes, among others, fleet management and replacement systems, vehicle monitoring systems, vehicle routing and scheduling systems, supply chain management systems, freight forwarding systems, fleet accidents management systems, transportation personnel management systems, crew recruiting systems.
- Another characteristic is the **underlying decision-making methodology** used in the decision support system and distinguishes: optimisation-based (emphasize on the models and algorithms used to achieve optimal solutions for planning and/or scheduling), simulation-based (the real system of interest is modelled and implemented in simulation software), game theory-based (the outcome depends on the decisions of two or more autonomous players [267]), data mining -based (analyzing big data and extracting patterns or predicting future behaviors [268]), hybrid methodology (combination of aforementioned categories).
- One of the main components of a decision support system is the data used. In that manner, the **character of the data** is another characteristic and based on which a system can be defined as deterministic (precisely defined parameters) and non-deterministic (stochastic and fuzzy based systems). Furthermore**, time variability of the data** can be used as measure for classification. Data can either be dynamic (time-dependent) and static. Dynamic data are collected real-time and used for the decision-making processes and are the most popular solution.
- Based on the **internet utilisation**, a decision support system can be either online or offline.
- Lastly, the **way of communication with the user** distinguishes the decision support systems into: passive/ single phase (the solution is presented to the user after the data processing) and interactive (the user can modify and re-evaluate the solutions).

5.4.1.2 Role of transport decision support tools

The transport sector faces various problems that need to be addressed with the utilisation of the technological advancements. The proposed decision support systems for transport attempt to solve some of these issues. They can either focus on a specific problem or can be more complex and sophisticated, tackling a spectrum of issues. As mentioned before, the overall goal of a decision support system is to aid the decision maker in their quest of a short-term or long-term solution of a problem.

Zak [269] is his survey of transport-oriented decision-making system constructed the following list of the most common and important problems:

- Forecasting transportation market situation
- Labor force sizing
- Design/ construction of the most desirable portfolio of transportation services
- Managing transportation order fulfillment
- Assignment of vehicles to transportation jobs / routes
- Fleet composition in a transportation company / system
- Vehicle routing and scheduling
- Fleet replacement and maintenance

Other problems found in literature include the following:

- Analysis and evaluation of different transport policies [270]
- Strategic transportation planning [271, 272]
- Sustainable urban land use planning [273, 274]

It is also important to notice that many of the above problems are varied through the different transportation modes or sectors.

5.4.1.3 Methodologies of transport decision support tools

In this section, the most popular methodologies in the literature are presented. These methodologies are integrated in the model base of the systems and are utilized in the transport-oriented decision support tools with the ultimate purpose of solving or aiding in the problems described in the sections above. It is important to mention that a decision support system may utilize a combination of the following methodologies in order to produce the optimal solution for the corresponding transport problem [266]:

- **Approximate computational procedures – heuristics and metaheuristics** are used more and more frequently due to the complexity of the transport problems, although there is no guarantee of optimal solution but near optimal. Many of the transportation situations require real-time solutions which marks the near optimal solutions as acceptable. In this scope, **specialized heuristics** prove to be efficient algorithms but can be deployed for specific decisions problems only due to their highly customizable nature. In contrast, **metaheuristics** (Local Search, Tabu Search, Simulating Annealing and Genetic Algorithms) can be constructed as abstract computational models that can be customized to different problems transportation problems or a combination of them such as: vehicle routing and scheduling problem, crew scheduling problem, fleet composition problem, fleet replacement problem, fleet maintenance scheduling problem, etc. In this category of methodology belong the **hybrid metaheuristic algorithms** that are more and more popular and are comprised of a combination of usually two metaheuristic algorithms.
- **Multicriteria Analysis (MCA)** addresses the complexity and multidimensionality of the decision problems in transportation. It considers several aspects (economic, social, market orientation, technical, environmental etc.) while being able to cater to the majority of the stakeholders/actors (e.g. service providers, customers) that may have different interests. The above reasons places MCA into one of the preferred methodologies for aiding in decision-making processes in a transport context.
- **Geographic Information Systems (GIS)** provide an ergonomically constructed user's interface that facilitate the operation of the decision support tool. For that reason, GIS capabilities are increasingly adapted and provide visualisation of the solutions produced by the decision support tools.
- **Online communication / real-time** provides a way of real time data analysis for short-term and quick prediction of future and unforeseen events (e.g. traffic jams), aiding in the decision-making processes. The above is made possible with the advancements on Telecommunications that facilitate quick and reliable wireless internet access through the 3G/4G networks with the 5G on the horizon.
- **Web-based Decision Support Systems** are becoming the norm with the rise of the Web 2.0 services. In conjunction with the aforementioned online communication and the standardisation of the data exchange (e.g. XML, EDIFACT).
- **Artificial Intelligence tools** usage in decision support systems created the known Intelligent Decision Support Systems (IDSS). Taking advantage of the 'self-education' capabilities of the artificial intelligence methods, IDSS-s can process complex and unknown problems making them one of the most popular solutions. Furthermore, they can be combines with Expert Systems to produce more accurate and rational

solutions. The most common A.I. techniques used in transport-oriented decision support systems are: Artificial Neural Networks (ANN), Fuzzy Logic, Data Mining, Agent-based Systems and others.

- **Interactive character** is one of the most important features of a decision support system. It enabled the end user to iterate through the alternative solutions, to analyze them and in the end choose the optimal option.
- **Mixed methodologies** are the optimal solution for complex systems and are equipped with a variety of algorithms, methods and models.

5.4.1.4 Advanced applications of transport decision support tools

In this subsection a selection of recent work in the literature on transport decision support systems is presented.

Szimba et al. [275] proposed in their work a high-level strategic assessment tool that is comprised of existing tools and new models and based on the classic transport model for transport demand of passengers and freight. This tool enables the user to define a policy scenario in order to compute policy assessments.

Le Pira et al. [276] combined Discrete Choice Models (DCM) with Agent Based Models in their proposed methodology. The aforementioned combination enabled for taking stakeholder's opinion into account to explore shared policy packages.

In their work, Vasilyeva et al. [277] developed a spatial decision support system that aids medical personnel with their crucial and time-dependent decision-making process while using real-time dynamic and static spatial and non-spatial data.

Tsaridas et al. [278] used artificial intelligence tools in their proposed tool for container transport logistics. Specifically, they equipped their tool with a combination of Artificial Neural Networks and Fuzzy Logic, thus creating Fuzzy Cognitive Maps. FCMs are created based on domain expert knowledge.

Bellini et al. [279] project proposed method based-decision support tool for urban transport system resilience management that "aims at managing critical infrastructure resilience through a more complex and expressive mode". Their model in based on Functional Resonance Analysis Method and exploits smart city data in order to output strategies and recommendations for variability dampening at strategic, tactic and operational stage.

Yazdani et al. [280] designed a comprehensive framework that is comprised of rough number-based decision-making for sustainable freight transport system evaluation. They discovered that rough number-based methodologies have advantages over fuzzy or interval-based models.

Ghorbanzadeh et al. [281] proposed a methodology that is based on the Analytic Hierarchy Process which can be utilized for sustainable urban transport while taking into consideration the inconsistent and uncertain passengers' and stakeholders' results.

Kaewfak et al. [282] proposed a Fuzzy Analytic Hierarchy Process and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution for prioritizing effectively the multimodal transportation routes to improve logistics system performance by constructing the possible routes considering transport cost, time, risk, and quality factors. The proposed methodology produces an accurate, practical, and systematic decision support tool.

Lastly, Fahad et al. [283] proposed a framework for real-time evacuation planning was developed that combines the results obtained from hydrodynamic modelling and traffic microsimulation. They combined the results from both models to generate a time-lapse animation of emergency evacuation and visualized it using a Geographic Information System (GIS).

Table 18 - Key characteristics and methodologies of the recent work review

Reference	Characteristics	Methodology
Szimba et al. [275]	High-level strategic policy assessment, Multimodal, single user, Data-driven, Strategic, Hybrid,	Mixed methodologies (Classic transport model and others)
Le Pira et al. [276]	Dynamic and Static	Discrete Choice Models (DCM) with Agent-Based Models
Vasilyeva et al. [277]	Urban freight transport, Single user, Knowledge-driven, Strategic, Dynamic	Spatial Decision Support System
Tsaridas et al. [278]	Real-time trauma transport, Road, Single user, Data-driven, Operational, Optimisation-based, Deterministic, Dynamic and Static Data	Artificial Neural Networks (ANN) and Fuzzy Logic
Bellini et al. [279]	Container transport logistics, Single user, Data and Knowledge driven, Strategic, Static and Dynamic Data, Interactive	Functional Resonance Analysis Methods
Yazdani et al. [280]	Urban transport, Group-oriented,	Rough number-based
Ghorbanzadeh et al. [281]	Data-Driven, Strategic, Tactical, Operational, Smart City Dynamic and Static Data, Interactive	Analytic Hierarchy Process
Kaewfak et al. [282]	Sustainable freight transport	Fuzzy Analytic Hierarchy Process and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution
Fahad et al. [283]	Sustainable urban transport planning, Single user, Data-driven, Strategic, Static Survey Data	Hydrodynamic modeling and traffic microsimulation

As evident, transport-oriented decision support systems in recent literature aim to solve various problems that rise with the advancement of the transport sector. Numerous methodologies have been proposed to tackle those problems, and the selection of the optimal highly depends on the nature of the problem.

5.5 Challenges and gaps in transport modelling research

Existing models in practice are not capable enough to ascertain the impacts of policies currently being discussed and tested by transport authorities. Following this, there are several challenges and gaps that the transport modelling community is currently exploring to improve existing commercial software packages and to develop new modelling approaches and algorithms:

- **Multimodality in transport modelling**. While it is often the case that private vehicle and public transport are simulated in parallel and not in an integrated artifact, there is a growing demand for models capable of analysing the interactions between both transport options. All traditional traffic simulation tools based on DTA modeling approach (route choice analysis and network loading in traffic networks) are not directly applicable in the multimodal context. Most traffic simulation software currently only considers a set of vehicle types, referred as multi-class models. In this context a vehicle class indicates a type of vehicle, such as a car, truck, HGV, bus, tram, train, bicycle, other two- wheeler types, etc. It is important to develop a multi-modal DTA model to take into account the vehicle dynamics of different public transit modes for more accurate travellers mobility estimations and analysis.
- **Modal choice**. The realistic mode choice of travelers and passenger flow dynamics should be considered in the models.
- **Routing behaviors**. One future direction is to develop a dynamic integrated model with the consideration of various routing behaviors (e.g., taxis cruising for passengers, cars cruising for parking, etc.) and the traffic dynamics of different vehicles in a network for enhancing environmental sustainability.
- **Seamless integration of Big Data transport demand sources**. Transport demand models in planning practice are seldom seen using big data sources such as mobile phone usage records, smart card data and geo-coded social media data.
- **Simulation of future transport options**. Empirical data for inchoate modes such as autonomous vehicles and UAMs are not available and values for the related parameters cannot be validated. Also, the operational characteristics and business models are still uncertain.
- **Simulation of shared mobility services**. As seen in Section 2, shared mobility services are characterized by a high degree of dependency between supply and demand. Modelling of the interaction between supply of and demand for on-demand services are not adequately researched. On the one hand, it has been suggested that specific supply modelling tools could be useful for evaluating the parameters of these services, integrating the outcome of these tools in more traditional travel demand modelling tools. On the other hand, agent-based modelling approaches may be essential to cover the functionalities requested by policy-makers.

Improving **data reliability**, reduction of **computational time** and ability to model **inter-temporal nature of adoption of emerging modes** are some of the other research challenges.

6. Integration of transport planning tools in the policy cycle

The ultimate goal of transport data sources and models is to provide valuable guidance to policy-makers. Therefore, any enhancement of transport planning tools may be ignored if their usability is not ensured. This entails not only advanced visualisation techniques or friendly user interfaces, but also a seamless integration in the tasks that transport planners are expected to perform by urban societies.

Most of policy-makers with urban transport responsibilities adopt Sustainable Urban Mobility Plans (SUMPs) as the standard planning instrument for providing long-term visions of sustainable mobility. Hence, it is crucial that transport models are oriented towards the requirements coming from the processes behind SUMPs creation and implementation.

In an era characterised by the increasing adoption of collaborative approaches to urban mobility planning, transport models and decision support tools can facilitate multi-criteria and multi-stakeholder process in many ways. In this sense, it is essential that transport planning tools and techniques contribute to a more fluent and credible integration of quantitative, evidence-based approaches into participatory planning processes.

In addition, modelling and decision support tools have to be adapted to the paradigm shift in urban mobility planning. The field is moving from traditional static planning to more dynamic planning processes that recognise the intrinsically uncertain and fast-changing environment faced by urban mobility in the years to come. The data collection methods, models, decision support tools and policy recommendations will help cities to adopt this new, much needed vision, empowering them to formulate more flexible and resilient policies that perform well under a range of possible futures.

Once these aspects have been covered, it is also necessary to develop user-friendly and interactive dashboards that facilitate the impact assessment and comparison of different alternative policies, with the aim to achieve a common understanding across all concerned stakeholders. This involves the development of visual interfaces and data representations facilitating the interpretation of the modelling results, the analysis of trade-offs between conflicting objectives, the representation of uncertainty and the multi-criteria evaluation of policy alternatives.

Section 6 discusses the role of transport planning tools in the urban mobility policy cycle from this integrative perspective. It starts by reviewing the **current planning framework created by the SUMP** mechanism. Then, the **current uses of transport models** and decision support tools are identified and discussed, as a previous reflection before the concluding notes about the **future role of these tools** in the urban mobility planning process.

6.1 Overview of the European transport planning context

A **Sustainable Urban Mobility Plan** (SUMP) is a strategic transport policy document, aiming at improving the quality of life in urban agglomerations, meeting mobility and accessibility needs of people and goods. It is based on existing planning practices and considers the principles of integration, participation, and evaluation. The concept of SUMPs, was defined by the Urban Mobility Package of 2013 from the European Commission and since then it has been updated and complemented with guides and briefings on specific aspects. The most recent update of the SUMP guidelines [284] has been published in October 2019. A SUMP is based on the following **8 principles** [284]:

- Plan for sustainable mobility in the 'functional urban area'
- Cooperate across institutional boundaries
- Involve citizens and stakeholders
- Assess current and future performance
- Define a long-term vision and a clear implementation plan
- Develop all transport modes in an integrated manner
- Arrange for monitoring and evaluation
- Assure quality

The process of developing and implementing a SUMP consists of **4 phases**: Preparation and analysis, Strategy development, Measure planning, Implementation and monitoring [284]. Each one of these phases contain particular steps (12 in total) and every step involves specific activities (32 in total). This process is being represented visually through the metaphor of clock phases (see Figure 28).

At the **first phase** of the SUMP cycle, the preoperational steps are the elaboration and diagnosis of the performance of the urban transport system. An overview of the mobility situation and planning framework is formulated, effective working structures are set up considering what is essential for developing the SUMP's vision, objectives, targets, and measures. The analysis of problems and opportunities at the end of the first phase is a crucial milestone of the SUMP. Additionally, it is important to reach an understanding of the main problems and opportunities, together with important stakeholders and citizens, promote the participation levels and create collaborative workgroups and environments among them. The **second phase** of the SUMP policy cycle refers to the creation of the SUMP strategy. The formulation of future scenarios, the future vision, the city's objectives, and the strategic indicators and targets are decided, so the strategic priorities of the SUMP are completed. The results of the second phase provide a stable guiding framework for the **third phase**, which is measure planning. Feedback and participation from citizens and decision makers -if possible- can ensure public support and acceptance. The third phase refers to the adoption of the SUMP. In this phase it is crucial for the SUMP to be legitimized by the elected political representatives of the responsible body for the development, in order to foster acceptance, making it accountable and providing an agreed framework for measure implementation. The **final phase** of the SUMP policy cycle marks the completion of the measure implementation and its evaluation, meaning the end of the whole cycle and at the same time the start of a new SUMP process, reflecting the continuity character of the process.

The Table 19 demonstrates the questions needed to be answered from the involved stakeholder/bodies in every single step of the SUMP process.

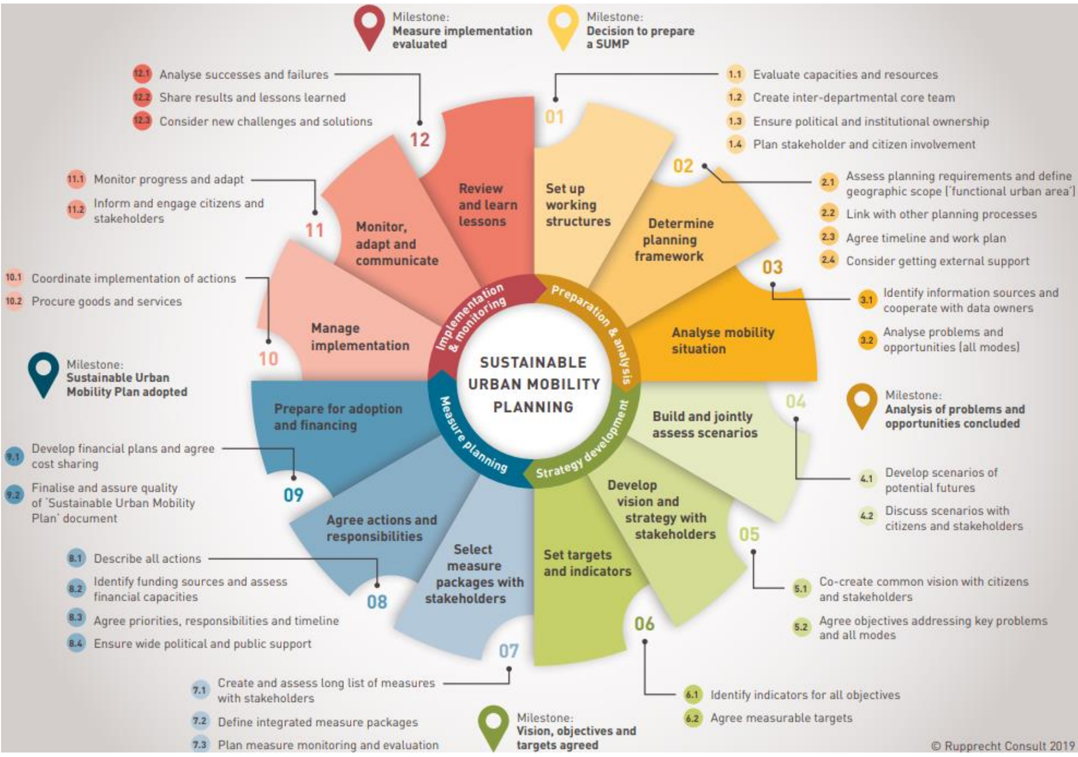


Figure 28 - SUMP policy cycle. Source: [284]

Table 19 - Steps of the SUMP process and questions needed to be answered. Source: [284]

Step	Questions	Step	Questions
1	Set up working structures *What are our resources?*	**7**	Select measure packages with stakeholders *What concretely, will we do?*
2	Determine planning framework *What is our planning context?*	**8**	Agree actions and responsibilities *What will it take and who will do what?*
3	Analyse mobility situation *What are our main problems and opportunities?*	**9**	Prepare for adoption and financing *Are we ready to go?*
4	Build and jointly assess scenarios *What are our options for the future?*	**10**	Manage implementation *How can we manage well?*
5	Develop vision and objectives *What kind of city do we want?*	**11**	Monitor, adapt and communicate *How are we doing?*
6	Set targets and indicators *How will we determine success?*	**12**	Review and learn lesson *What have we learnt?*

The SUMP policy process is usually supported by **transport modelling and forecasting** tools or other **decision-making tools**. The decision on what tools and techniques should be used for assisting the SUMP process is taken from relevant bodies, according to availability of a previous transport model, data or budget. Other factors can influence the choice of planning with or without a decision-making tool, such as the population density or the size of the urban agglomeration.

6.2 Models – current state of practicing in mobility planning

6.2.1 Transport modelling and the SUMP cycle

The SUMP policy cycle, adopted by many cities in Europe and worldwide, proposes the integration of transport modelling to assist the policy-making approach. However, the **use of a full-scale transport model is not always regarded as necessary**. As an alternative, it is possible to used **other types of decision-making tools** (as seen in Section 5.5), depending on the particular planning requirements. The outputs of transport models or decision support tools, complemented with further economic calculations, intend to be the basis for planning tasks.

According to the SUMP Guidelines, these tools and the necessary data needed to feed them should be considered on the budget requirements for a SUMP developed on the first phase. The decision to develop a transport model or to update an existing transport model may have a relevant impact on the overall budget of the SUMP. At the same phase -in case transport modelling is required- it is important to **cooperate with data owners** or check the availability of default values to fill data gaps. At the second phase of the SUMP policy cycle, particularly when **developing scenarios of potential futures**, modelling becomes a very useful technique. Scenario building is a crucial step in the SUMP policy process, because understanding the potential futures by most of the policy makers, relevant stakeholders and citizens, can lead to the development of a common vision, in a collaborative way. After the strategy development of a SUMP, transport models are often used to predict the impacts of measures, which are complex and hard to assess, in order to define integrated measure packages. Well-calibrated models allow policy makers to test several measures, to predict and compare their impacts with the current situation and with the set of already planned initiatives. At this stage, transport models can be complemented with **cost-benefit analyses (CBA),** to appraise the value for money of larger individual measures, usually for infrastructure projects, considering many of the societal, economic and environmental impacts of projects. In order to cover criteria that are not monetized, CBAs are often complemented with **multi-criteria analyses (MCA),** in particular if the monetisation of certain criteria is deemed too complicated. MCAs allow users to combine quantitative and qualitative assessments depending on data availability for different criteria. Standardized CBAs or MCAs are a requirement in many countries to receive funding for larger infrastructure measures, so it is very common to find these techniques among existing SUMP examples. In addition, models and associated tools are often used at this point to conduct a risk assessment of the selected measure packages, for example by running sensitivity tests. This means that the appraisal (or model) is re-run with a range of assumptions. If the preferred package performs well under several assumptions, it can be validated. If its performance is variable, then it is less robust, and less obviously worth pursuing. This may suggest trying to redesign it to improve its performance.

The following chart flow, presents the development of the SUMP policy cycle in parallel with a transport model (Figure 29). The proposed chart flow aims to provide an optimal overlap between the model's capacity and the stages and steps of the SUMP process [285]. The different levels of the model are adapted to the different stages of the SUMP process. The chart flow identifies the following integration steps:

- The **first phase** of the SUMP cycle can be connected with the **development of a macroscopic or a mesoscopic model**. The process of transport modelling at the first stages of SUMP development is recommended, although it is not obligatory. In case there is already a model, it can be updated. Afterwards, it should be clarified if the model's timeline is harmonized with the SUMP timeline.
- At the **second phase** of the SUMP cycle the results of modelling can be used to present the built **scenarios of the potential futures** to the citizens, relevant stakeholders, public bodies and politicians, in order to shape the vision and strategy of the city. As it is shown, tools play a very important role at this phase.
- The **third phase** of the SUMP cycle can be also supported by a forecasting tool, because it is important to **select measure packages collaboratively**, as well as the **final phase** "implementation and monitoring", which involves the **selection of new indicators**, in case the plan was to be modified.

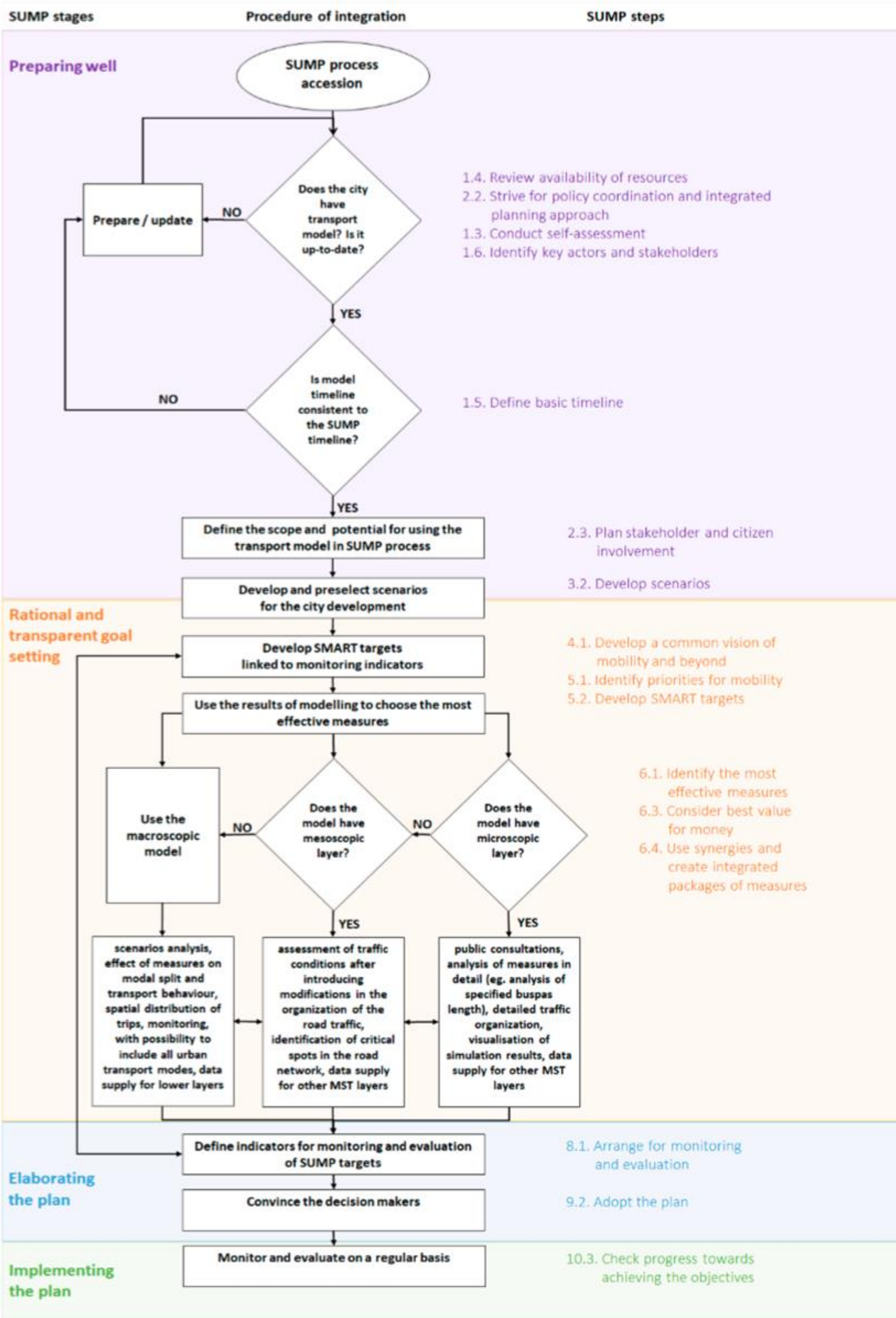


Figure 29 - Chart Flow for the Integration of Multilevel Model of Transport Systems during the SUMP process. Source: [285]

The **second edition of the SUMP guidelines considers a similar integration of the transport models** into the SUMP Policy Cycle (Figure 30). The possible necessity or irrelevance of a transport model should be clearly defined from the first phase of the cycle. This phase will also define the basic requirements of the transport model in terms of level of planning, spatial aggregation and level of data detail. Following this, the questions that need to be addressed at this phase are related to:

- **SUMP cycle step 1.1** "Evaluation of capacities and resources": Does the city already have a transport model and if yes, is it updated? What is the budget we should consider for the creation or update of the transport model?
- **SUMP cycle step 2.1** "Assess planning requirements and define geographical scope": What is the necessary geographical coverage of the transport model?
- **SUMP cycle step 2.3** "Agree timeline and work plan": What model timeline should I define in order to be consistent with the SUMP timeline?
- **SUMP cycle step 2.4** "Consider getting external support": Does the local authority team members have technical skills in transport modelling? What are the skills that need to be externalized?
- **SUMP cycle step 3.1** "Identify information sources and cooperate with data owners": What are the data available that will feed into the transport model? What kind of data collection do I need to externalize (liaison with step 2.4)?

At the end of the **first phase** of the SUMP cycle, an updated transport model can be run for the **evaluation of the current situation**, producing **baseline indicators** (i.e. modal split, private vehicle kilometres, emitted air pollutants, average trip distance, level of congestion, etc.).

For the **second phase** of the SUMP cycle ("Strategy Development"), transport modelling is an appropriate **scenario building technique**, although detailed transport models are usually used for the "development of scenarios of potential futures" (step 4.1) only if they are already available and no high extra costs for their update is required. Results of the model facilitate the "discussion of scenarios with citizens and stakeholders" (step 4.2), although an attentive interpretability of the modelling assumptions and results is required, to facilitate the understanding of the general public. The processes of "identification of indicators for all objectives" (step 6.1) and "agreement of measurable targets" (step 6.2) can also consult the transport model as per what are the SUMP performance indicators the model can monitor and what are the indicated potentialities of the future (indicators' target values).

In the **third phase** of the SUMP cycle ("Measure Planning"), transport models play an important role for the **assessment of long list of measures** (step 7.1) and the **definition of integrated measure packages** (step 7.2), as they are able to predict the impacts of measures on the transport system, but also feed into further economic calculations. Again, transport models can consult the monitoring of the measure packages (step 7.3), as regards the measure performance indicators and their target values.

Reaching the **final phase** of the SUMP ("Implementation and monitoring"), transport models are used for progress monitoring and adaptation (step 11.2), the very least against the strategic-/measure-level indicators that are model-based calculated, for assessing the successes and failures (step 12.1) and, if necessary, for measure/action adaptation (step 12.3) and new indicators' definition (if necessary). The process of discussion with the public at this phase (step 11.2) can be also facilitated by modelling results.

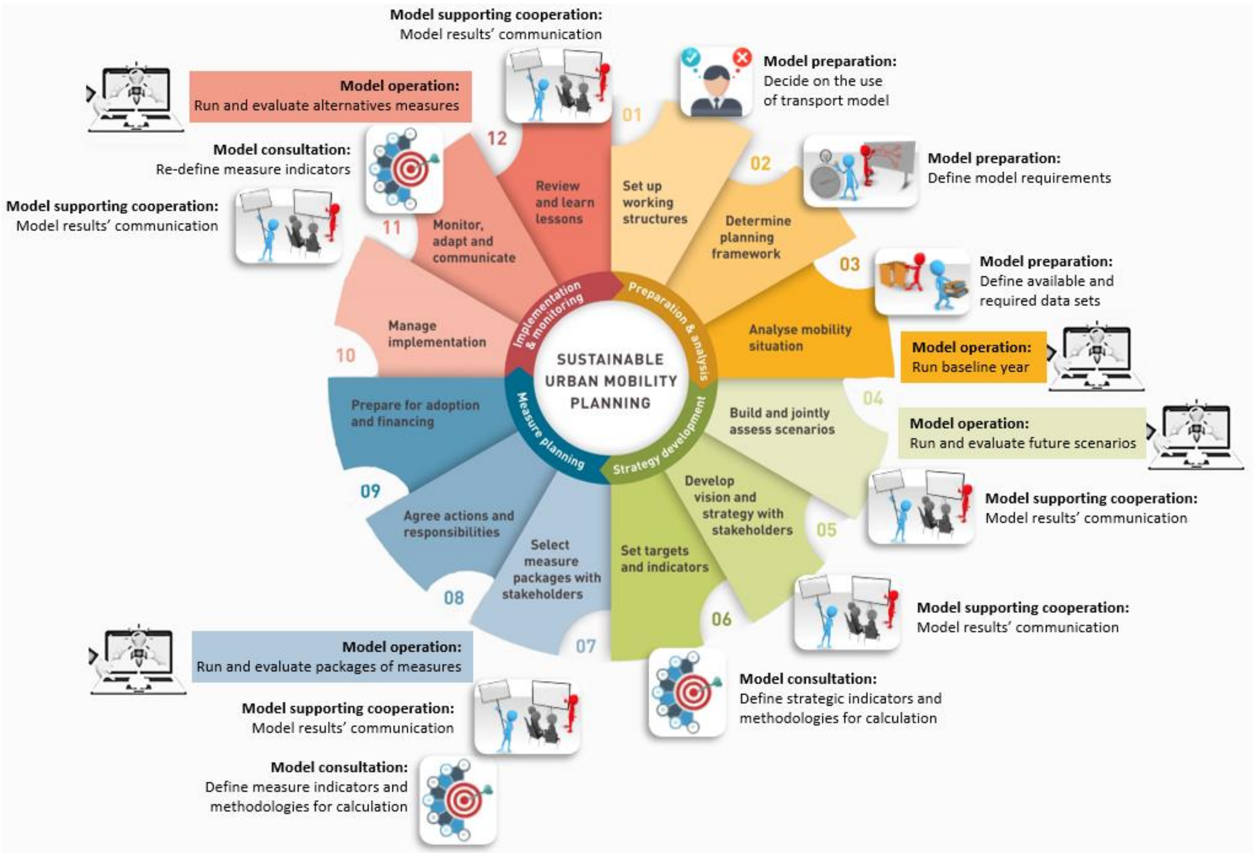


Figure 30 - Integration of transport models in the revised SUMP Cycle

6.2.2 Use of transport models in planning practice

As already demonstrated, a transport model is of great importance during the implementation of a SUMP because it helps understanding how a transport system will behave for different planning scenarios. Although transport models are very useful tools in transport policy making **cities fail to use their full potential**, due to several reasons, from the **lack of cooperation between stakeholders** to the **lack of trust in their outputs** [286]. Hence, the **use of state-of-the-art transport models is limited in transport policy-making processes** [262, 287]. Following this, the participatory modelling approach should be enhanced and built from the early stages and kept running until the end of the SUMP procedure. The participatory approach, one of the key elements of SUMPs process, should be elaborated in parallel with the technical approach. These approaches should be complementary and the tools and quantitative methods should be used to improve SUMP stakeholders' communication.

It is necessary to discuss what are the particular requirements that certain modelling approaches impose on the integration of transport simulation in SUMP cycles. Specifically, **Land Use Transport Interaction Models (LUTI)** are interesting in this context because the assessment of the effects of alternative transport projects on choice of locations has been recently the core concern of the much desired and theoretically discussed interdisciplinary approach in sustainable transport planning [288]. From this point of view, LUTI can be seen as the ideal transport modelling tool to support assessment of SUMPs, as it provides the capability of simulating a wide range of interventions ranging from infrastructural projects, pricing, regulation, co-modality to planning of urban space. They also allow to include within the assessment the effects of "rebound" effects due to re-locations or newly generated demand. A prototype representing the integration of LUTI models into SUMP policy cycle is presented in Figure 31.

However, it is often the case that these models are **too demanding in terms of data and resources** [287]: their setup requires a significant time and effort as well as expertise. The use of four-step models can also be a valuable alternative for the assessment of SUMPs as the capability of handling transport measures is the same. The feedback of transport modification on land use can be assessed by means of more simplified estimations. Aggregated models, also called sketch planning models are an interesting option for initial policy screening within the SUMP process, as they can be built with significantly less resources and allow to explore and identify appropriate sustainable transport policy measures, quantifying their impacts within a consistent framework and setting up the implementation pathway of the future scenarios. Aggregated models cannot however replace the use of more disaggregated models for detailed assessment.

Based on a case study on UK and Israel, Givoni et al. [287] conclude that transport models must be made simpler if their contribution to transport policy and planning wants to be promoted. Other authors have also mentioned **increased complexity** as one of the barriers for increasing the adoption of transport models [262]. However, cities need to deal with all the mobility innovations reviewed in this document, and it seems that **transport models that can simulate evolving transport modes** are inherently complex. In this line, several authors comment that the greatest barrier to increase the use of transport models is the **lack of transparency**, which leads to widespread distrust among practitioners [286]. Interestingly, some of the approaches that seem to be applicable to the simulation of emerging mobility solutions, such as Activity Based Modelling, may seem more natural to practitioners even if they are more complex in their implementation, thus overcoming this mistrust [289].

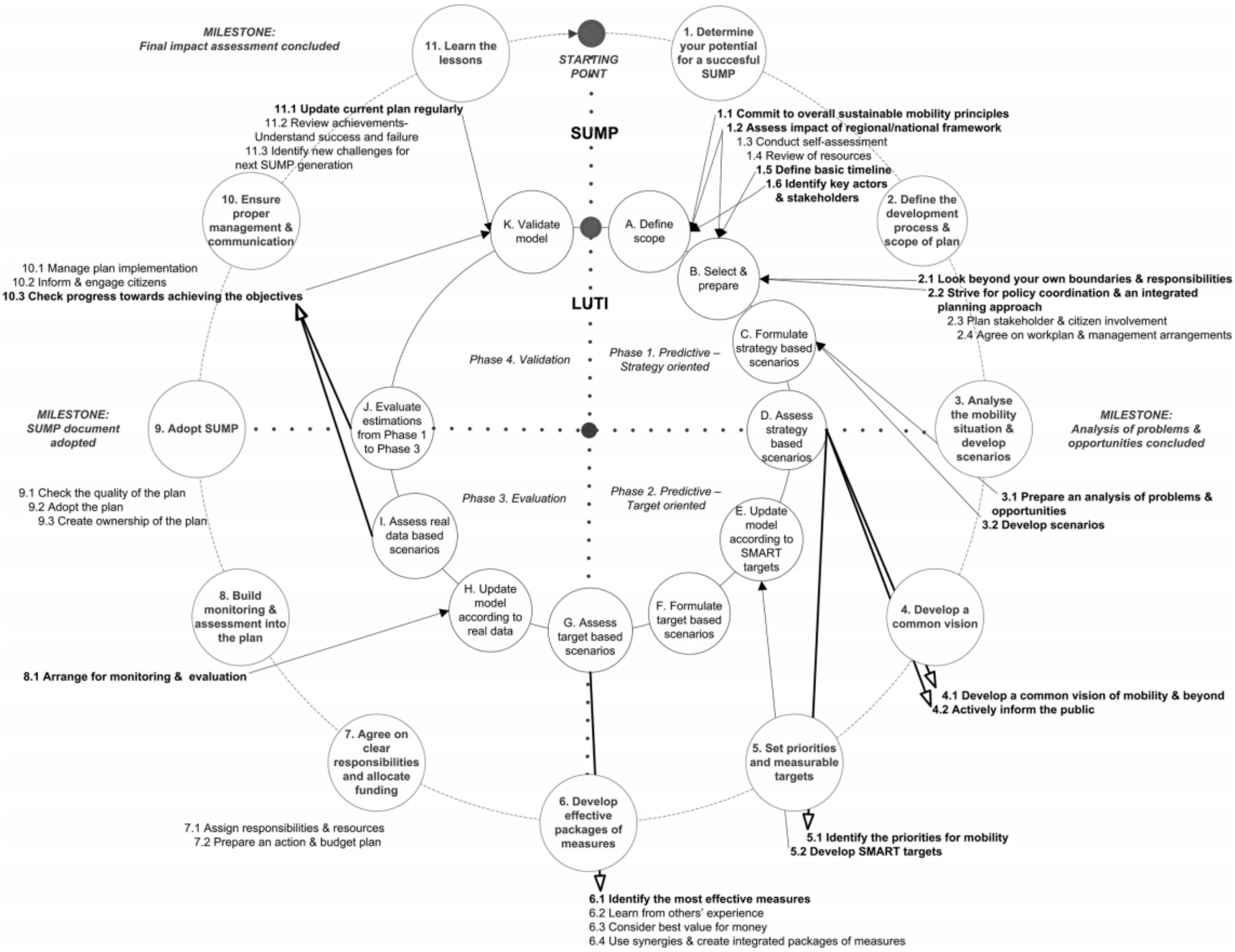


Figure 31 - A prototype representing the integration of LUTI models into SUMP policy cycle [288]

6.3 Future Transport Planning Requirements - Integration of Transport Models into the SUMP policy cycle

As this document shows, the mobility domain is constantly changing, generating both challenges and opportunities to transport authorities. Current mobility trends may lead to very different mobility ecosystems in the future: public and private demand will be affected significantly because they will need to bridge the gap between this new array of demands and the services they offer [290]. Mobility visions and policies encompass new requirements for a comprehensive adoption and coordinated management of mobility supply. Future mobility schemes should be able to maximize the benefits from the upcoming transport trends in mobility, by taking proactive approaches that exploit the opportunities and soothe the unintended consequences of deep changes in the way people travel. Accordingly, transport planning requires to test system design, capacity, flexibility and resilience capabilities. Several cities do not have yet clear visions of what their mobility systems will look like in the future and clear strategies for getting there, with an exception of some cities/countries, that already have prepared long term strategies for transport planning (e.g. UK, Australia, Copenhagen...).

The **interface between transport modelling tools and transport planning processes** is expected to be conditioned by the following aspects:

- **Longer time horizons for transport planning instruments**. Long-term planning is essential in all sustainability spheres. On the one hand, it is relevant for ensuring a productive economy through an efficient transport system. Transport enables businesses to reach new markets, attract new investment, while presenting more job opportunities [291]. On the other hand, long-term planning ensures the maximisation of the socioeconomic benefits of planned investment and the improvement of emission levels and other environmental costs. As a consequence of this trend, modelling tools will be requested to work with longer time horizons.
- **Increased acknowledgment of planning uncertainties**. Many of the important transport planning problems currently faced by transport policy-makers are characterized by high levels of uncertainty, and longer time horizons contribute to this uncertainty. Given the deep uncertainty that concerns transport planning, it is crucial to keep flexible [292]. These uncertainties originate from the potential ignorance of the best model, or the lack of agreement surrounding the selection of future scenarios amongst policy makers, which all together translate into a higher uncertainty concerning the likeliness of any given potential future scenario. Nevertheless, the use of scenarios becomes a must and provides a guidance for the needed flexible thinking. The combined use of predictive, explorative and normative scenarios [133, 293] in planning instruments can be facilitated by adapted simulation tools.
- **More frequent and active participation of citizens and relevant stakeholders**. The participatory approach proposed by the SUMP policy cycle, with the intention of being applied in European cities and/or worldwide, makes an effort to promote the contribution of relevant stakeholders in the process of policy making. Collaborative policy approach, which represents a step forward compared to participatory approaches, will lead towards higher levels of involvement of key stakeholders. A collaborative policy process involves bringing various perspectives to the table in order to consider all problems and opportunities. For a process to be collaboratively rational, all participants need to be well informed, they should be able to express their point of view, and they should be listened to during the SUMP process [294]. A collaborative policy approach can use information and communication technologies to enable the collaboration between people. Achieving increased collaboration is a challenge and organisations have resorted in recent decades to using groupware technologies for collaboration to work for them [295]. Building consensus through a collaborative planning approach means that there is co-design and co-creation [296] in transport planning, early involvement in the design process and continuing collaboration with all relevant stakeholders, customers, transport staff, transport, other government

agencies and the wider community. Transport planning community will demand from modelling tools capabilities that support them in these engagement processes.

These incoming aspects come in addition to the protection of the fundamental principles of planning analysed below [297]:

- The development of the built environment as a way of making people, goods, services accessible to one another. The evolution of transport systems has been driven by the search of improved **accessibility**.
- Land use planning has long been recognized as another determinant of accessibility. Greater **spatial proximity** reduces the need for physical mobility to travel.
- As the digital age advances, a further means has become more prominent – namely **digital connectivity**.

These three elements make up what we refer to as the Triple Axis System [297]. The existence and interconnectedness of these three elements is not new but the degree of maturity of digital connectivity is now such that its contribution to accessibility has become much more pronounced. This has to be also taken into account by modelling tools when used in transport planning initiatives.

Which is the optimum approach to tackle uncertainty imposed by new transport trends? How is it possible to achieve a paradigm shift in urban mobility planning moving away from traditional static planning? Are Sustainable Urban Mobility Plans affected by the new challenges Are current transport modelling approaches able to fulfil SUMP's implementation? Which is the optimum method to advance the state of the art in urban mobility planning, in terms of processes and tools? Are collaborative and participatory policy approaches among model developers, planning practitioners and other stakeholders essential?

We are witnessing profound changes in the way mobility is evolving, enforced by progresses in Information and Communication Technologies, Big Data, technological advancements in transport and new concepts of operation of transport systems. These changes may lead to different mobility ecosystems in the future, accompanied with particular impacts on urban space. In the same context of complexity and uncertainty that characterizes future mobility, it is understood that transport modelling should follow the new developments as well, to bridge the gap between the new array of demands and the services they offer and provide useful guidance on future mobility.

Planning and modelling the complexity and uncertainty of future mobility requires a shift from traditional modelling approaches. The answer to the above questions lies on the investigation and adoption of new transport planning and modelling requirements. Traditional planning methods, current transport modelling and decision support tools cannot fulfil the challenges that municipalities and authorities will face in order to implement a SUMP, under these circumstances. New transport planning requirements include long-term planning, capabilities to tackle future uncertainty and complexity, assistance to collaborative policy approaches among the relevant stakeholders, and tools for co-creating future scenarios, vision and measures. All these advancements have to be cautious enough to fulfil all principles of planning and to ensure the usability of the tools by practitioners, overcoming the barriers suggested in the literature [262, 286, 287].

Multi-sectoral and/or cross-sectoral modelling, implementation of dynamic modelling approaches, methods such as backcasting and the investigation of the potentials of Big Data are examples of on-going research topics that provide answers to these challenges. The knowledge transfer facilitated by incorporating the new transport modelling requirements into SUMP policy cycle is expected to ensure the relevance of the modelled scenarios, increase the confidence in model results and provide useful insights on how to achieve a more fluent and credible integration of quantitative, evidence-based approaches into participatory planning processes. The development of this transport planning procedure from decision-making tools is a key condition in order to make the collaboration approach easier through evidence, e.g. visualisation of the results of future scenarios or impacts.

