Article

Review of Whole System Simulation Methodologies for Assessing Mobility as a Service (MaaS) as an Enabler for Sustainable Urban Mobility

Mark Muller [1,*] **, Seri Park** [1] **, Ross Lee** [1] **, Brett Fusco** [2] **and Gonçalo Homem de Almeida Correia** [3]

[1] College of Engineering, Villanova University, Villanova, PA 19085, USA; seri.park@villanova.edu (S.P.); ross.lee@villanova.edu (R.L.)
[2] Delaware Valley Regional Planning Commission, Philadelphia, PA 19106-1520, USA; bfusco@dvrpc.org
[3] Department of Transport & Planning, TU Delft, 2628 CN Delft, The Netherlands; G.Correia@tudelft.nl
[*] Correspondence: mmulle02@villanova.edu

Abstract: Mobility as a Service (MaaS) is an emerging concept that is being advanced as an effective approach to improve the sustainability of mobility, especially in densely populated urban areas. MaaS can be defined as the integration of various transport modes into a single service, accessible on demand, via a seamless digital planning and payment application. Recent studies have shown the potential reduction in the size of automobile fleets, with corresponding predicted improvements in congestion and environmental impact, that might be realized by the advent of automated vehicles as part of future MaaS systems. However, the limiting assumptions made by these studies point to the difficult challenge of predicting how the complex interactions of user demographics and mode choice, vehicle automation, and governance models will impact sustainable mobility. The work documented in this paper focused on identifying available methodologies for assessing the sustainability impact of potential MaaS implementations from a whole system (STEEP—social, technical, economic, environmental, and political) perspective. In this research, a review was conducted of current simulation tools and models, relative to their ability to support transportation planners, to assess the MaaS concept, holistically, at a city level. The results presented include: a summary of the literature review, a weighted ranking of relevant transportation simulation tools per the assessment criteria, and identification of key gaps in the current state of the art. The gaps include capturing the interaction of demographic changes, mode choice, induced demand, and land use in a single framework that can rapidly explore the impact of alternative MaaS scenarios, on sustainable mobility, for a given city region. These gaps will guide future assessment methodologies for urban mobility systems, and ultimately assist informed decision-making.

Keywords: sustainability; urban mobility; MaaS; urban regions; STEEP; simulation

1. Introduction

The increasing rate of urbanization, coupled with increasingly urgent global sustainability challenges, are two macro drivers on the future of urban mobility. These significant pressures are addressed as part of the United Nation's global sustainable development goals [1], which have been mapped to four sustainable goals for mobility (accessible, efficient, safe, and green) by the Sustainable Mobility for All (SuM4All) initiative [2]. In response, there is an emerging mobility concept, mobility as a service (MaaS) [3,4], that may mitigate these sustainability challenges. MaaS can be defined as the integration of various transport modes, such as public transit, ride-sharing, and biking into a single service, accessible on demand, via a seamless digital planning and payment application. Historically, modeling and simulation have provided a means for transportation planners to assess such potential changes to a transportation system [5–8].

However, traditional transportation simulation tools may be limited in their ability to assess all of the main aspects of the emerging MaaS concepts for their long-term impacts on an urban mobility system. A mobility system is defined here to include the transport modes (e.g., private automobiles, public transit, taxis, ride-sharing services), the supporting infrastructure (e.g., roads, rail), and associated governance (e.g., policies, pricing) for a given urban area. MaaS concepts leverage potentially impactful, but difficult-to-predict, technological and business model disruptions. Therefore, there is a need to apply a whole system approach, i.e., STEEP (social, technical, economic, environmental, and political) [9,10] to preclude unintended consequences.

System interactions may cause a MaaS implementation to address one challenge but exacerbate another. For example, vehicle automation could reduce the number of vehicles, but increase the number of vehicle miles traveled (VMT), worsening congestion. MaaS policy choices might enhance or degrade equitable access to mobility. System stressors, like the COVID-19 pandemic, can have regionwide impacts on trip generation, distribution, and mode choice. Policy-making responses, such as social distancing, can further contribute to rapid changes in mobility demand patterns. In return, a MaaS implementation should offer adaptability and resilience with offerings that include a range of vehicle types, travel modes, and demand responsiveness. Additionally, smart technology that can reassure travelers that shared vehicles are clean and safe to use could aid MaaS resilience in future pandemic events. These examples show that assessments, at a city or region level of focus, are necessary to drive whole system optimization that accounts for the interdependencies among the multiple elements of an urban mobility ecosystem.

A toolset or methodology is needed to help inform policy, planning, and implementation for future urban mobility aligned with sustainable transportation goals. In particular, stakeholders need a toolset that can rapidly assess a broad range of potential outcomes, defined through scenario planning, to inform their decision-making. This toolset will enable strategic-level assessment of the sustainability impacts of alternative future MaaS implementation scenarios. This paper reviews reported sustainable mobility metrics, MaaS system elements, potential MaaS adoption scenarios, and relevant reported simulation tools and models to identify gaps and support further research into an improved whole system methodology.

2. Sustainable Mobility and MaaS

This section highlights the latest research for defining and measuring sustainable mobility systems, identifying the essential elements of the MaaS concept, and defining potential alternative scenarios for MaaS adoption. The focus is on how these elements can be applied to an improved, holistic modeling and evaluation of MaaS's potential impact on sustainable urban mobility.

2.1. Measuring Sustainable Mobility

When defining a whole system assessment methodology for sustainable urban mobility systems, a set of comprehensive metrics provides a common basis for comparison. Several approaches to sustainable mobility metrics were identified and reviewed. Two of these approaches are defined at the city level: the Urban Mobility Index by Arthur D. Little [11–13] and the City Mobility Index by Deloitte [14]. A third approach, the Mobility Maturity Global Tracking Framework [15], is for comparing sustainable mobility at the national level and is included for relevant insights. The main attributes of these metric approaches are summarized here.

2.1.1. Elements of a Sustainable Mobility Index

The mobility indices that were reviewed all employ high-level categories for grouping the underlying indicators. These categories provide a way of conveying the holistic attributes of the mobility system that are being prioritized for evaluation. For the Urban Mobility Index, the three main categories are "Maturity," "Innovation," and "Performance,"

with nine measures in each category [13]. The City Mobility Index also has three main categories, or "themes," which are "Performance and Resilience," "Vision and Leadership," and "Service and Inclusion" [14]. Finally, for the Mobility Maturity Global Tracking Framework, the measures are grouped into the four categories of safety, universal access, green, and efficiency [15].

The individual indicators used in each of these indices are comprised of several different types. One type is a strictly numerical indicator (e.g., "annual arithmetic average of the daily concentrations of NO_2 recorded at all monitoring stations within the agglomeration area" [13]). Another type is a scaled measure (e.g., "quality of roads, value: 1 = worst to 7 = best") [15]). Finally, some indicators capture the availability of an attribute (e.g., "existence of MaaS-based application (yes/no)" [14]). Each index then uses its own weighting scheme to collect the contribution of these indicators and generate a single index value for comparative purposes.

2.1.2. Sustainable Mobility Index STEEP Assessment

The indicators that comprise these three mobility indices were compared against the five STEEP factors to assess the breadth of coverage. The result of this assessment is illustrated in Figure 1 as a heat map. The relative intensity of the green cells graphically indicates how many of the contributing indicator metrics for each index were determined to be relevant to a given STEEP factor. For example, for the Deloitte City Mobility Index, most of the indicators were assessed to be relevant to technology, such as the efficiency and performance of the mobility system. The STEEP social factor is where equitable, access-related indicators were counted, such as accessibility to public transit, city walkability score, and private car dependency. Overall, all five of the STEEP factors were addressed by all three indices, suggesting a good breadth of coverage. When comparing the three indices, the indicators had overlap in these main areas, suggesting their significance:

- emissions measures of air quality
- accident/mortality measures of safety
- vision/strategy/public sector initiatives
- measures of accessibility
- transport effectiveness and performance

Indices for Sustainable Urban Mobility	Social	Technological	Economic	Environmental	Political
Arthur D Little - Urban Mobility Index	7	11	1	6	2
Innovation	2	7	0	0	0
Maturity	2	3	1	1	2
Performance	3	1	0	5	0
Deloitte - City Mobility Index	12	36	6	5	12
Performance and Resilience	4	13	0	4	0
Service and Inclusion	8	16	5	0	0
Vision and Leadership	0	7	1	1	12
SuM4All - Mobility Maturity Global Tracking Framework	10	19	5	9	2
Efficiency	0	4	5	0	2
Green Mobility	0	0	0	9	0
Safety	8	0	0	0	0
Universal Access	2	15	0	0	0

Figure 1. STEEP Assessment of Sustainable Urban Mobility Indices: Number of Metric Indicators per Category. SuM4All [15], City Mobility Index [14], Urban Mobility Index [11,13].

2.1.3. Summary—Measuring Sustainable Mobility

Several conclusions can be drawn from this examination of sustainable mobility indices, relative to the research objectives.

- Examples of comprehensive, multi-faceted metrics to assess the sustainability of a city's mobility system were identified.
- Though each index has some differences in the categorization and weighting employed, there is significant overlap in the specific indicators/measures that are used.
- A comparison reveals that the three indices that were reviewed do account for the breadth of social, technological, economic, and political elements that comprise STEEP. However, the comparison reveals differences in the relative coverage of the five STEEP categories versus the main categories of the three indices.
- These index examples demonstrate the utility of metric frameworks in comparing the relative state of maturity, best practices, and opportunity for improvement across different urban areas. They also indicate a potential scorecard approach for a holistic MaaS assessment methodology.

2.2. Essential Elements of a MaaS System

In considering a whole system approach to modeling MaaS, it is critical to identify its key elements. Many definitions for the MaaS concept were identified during this literature survey from organizations, such as the European Metropolitan Transport Authorities (EMTA) [16], the MaaS Alliance [17], and the MaaSLab at University College London [18]. These definitions all inform a view of the main elements. The following sections summarize the identified elements that comprise a MaaS system.

2.2.1. Mobility Demand

The mobility demand represents the mobility service users [19]. Underlying this demand are factors that include demographics, economics, and geography. The mobility demand's choices and trends are informed by the entire mobility ecosystem and provides the system with real-time travel data [20].

2.2.2. Mobility Supply

Mobility supply is provided by the multi-modal transportation assets, especially vehicles, with which to address mobility demand [20]. A notable aspect of this part of the MaaS concept is the potentially disruptive variety in the type of transport modes that are being proposed. In addition to traditional modes, such as public transport, private automobiles, taxis, walking, and biking, there are emerging modes, such as ride-sharing, car-sharing, and micro-mobility, to name a few [21]. The migration to electric-powered transport offers the opportunity for reduced emissions. On the horizon is the potential for technologies that enable shared automated electric vehicles (SAEV's). For all of these current and emerging modes, there is a need to provide a level of service that supports customer adoption, captured by the concept of comfortable, affordable, fast, and instantly available (CAFI), as defined by Grush and Niles [22]. As defined by ERTICO [19], infrastructure such as road, rail, electric vehicle (EV) charging stations, parking, tolls, and curbside can be considered as part of mobility supply.

2.2.3. Governance

The overarching element in the MaaS concept, as presented by Corwin, Dinamani, and Pankratz [20], is city management and policy which provides governance, oversight, and a supportive policy environment for the entire system. It can guide system behavior and performance through methods, such as road usage charging and other financial incentives and has overall responsibility for real-time traffic management. A comprehensive set of sustainability metrics can help inform stakeholders whether meeting policy goals is on track. The topic of governance has been examined especially with regard to the uncertainty around such a potentially disruptive capability such as MaaS, and the role

that governance has to steer mobility systems away from unanticipated and undesirable societal consequences [23].

2.2.4. Digital Interface

An element of MaaS common to many of the definitions that have been reviewed is that of a seamless digital interface. This interface, accessible to users via channels such as a smartphone app, provides a unified customer touchpoint that is integrated with supporting digital resources that support booking and payment of multi-modal transport. The notion of a variety of payment systems (e.g., pay-as-you-go, subscription) is also represented [13]. Another view of this central element to the MaaS concept is the mobility operating system, which is envisioned as a foundational digital platform that provides roles that include: stakeholder engagement, mobility market optimization, infrastructure management, and mobility management [20].

2.2.5. Summary—Essential Elements of a MaaS System

This review summarizes the foundational elements that should be considered in a whole system representation of a MaaS system: mobility demand, mobility supply, governance, and a digital interface. The role of governance to incentivize mobility mode choices to align with sustainable policies is one key element. A range of current and emerging transport modes should also be included. These can be generally considered as the high-level essential elements for modeling a MaaS system and its impact on the overall sustainability of an urban mobility system.

3. Alternative MaaS Adoption Scenarios

Scenario planning is primarily used to deal with uncertainty and is a relevant tool for exploring how a MaaS network could emerge out of the current transportation system. Scenario planning can support investigation of future uncertainty and then identify potential challenges and opportunities that could arise as a result. Several studies were identified that define differing scenarios for MaaS adoption and implementation, each from a different perspective. Reviewing these scenarios helps to further define what a whole system, STEEP-based assessment methodology should consider. These different approaches to framing MaaS adoption paths will be examined here.

3.1. MaaS Adoption Scenarios—MaaS Lite

In a paper by Pickford and Chung [24], the authors identify the challenges of developing and deploying a fully integrated MaaS system with multiple modes, including the likelihood that optimal implementation schemes will vary by city or region. They propose a MaaS Lite scheme, which would focus initially on providing services via a peer-to-peer subset of transport modes (e.g., train, taxi) that most meet efficient transport goals in a specific urban region. In this way, the requirements for data sharing, and partnering between mobility providers, is reduced and allows the MaaS service to achieve an initial level of implementation. This can be a transitional step towards more expanded adoption of MaaS mode options as the service gains adoption.

3.2. MaaS Adoption Scenarios—Income vs. Population Density

A study by McKinsey [25] examined potential evolution paths of MaaS adoption. A two-axis framework was defined, examining per capita income versus population density. Along the vertical per capita income axis, there are four levels of MaaS adoption projected as a function of per capita income. These four MaaS adoption levels are:

- **No local acceleration of MaaS adoption**—No adoption of MaaS is assumed.
- **Clean and Shared**—*"characterized by shared multimodal trips centered on human-driven cars, two-wheelers, and mini-buses which are increasingly electrified, as well as expanded provision of public transit. The application of self-driving cars may not be viable in dense,*

developing metropolitan areas, where the state of the infrastructure is poor and the general traffic situation is more complex" [25].

- **Private Autonomy**—*"the private car would maintain its dominance as the central element of mobility. Autonomy and electrification might allow passengers to use time in traffic for business or pleasure. The system as a whole may be stretched by increased demand, as vehicle ownership is expanded even further and empty vehicles are sent on errands or to roam for parking"* [25].
- **Seamless mobility**—*"mobility may increasingly become a door-to-door, on-demand, multimodal service with blurred boundaries between private, shared, and public transport"* [25].

Along the horizontal population density axis, five different categories are defined as rural, developed and suburban areas, developing suburban areas, developed dense areas, and developing dense areas. The study then projects the most likely level of adoption for each type of population region as shown below:

- **"Rural" and "developing suburban areas"** are not expected to experience any acceleration in adopting MaaS.
- **"Developing dense areas"** are expected to adopt MaaS using the "clean and shared" approach.
- **"Developed suburban areas"** are expected to adopt MaaS using the "private autonomy" approach.
- **"Developed dense areas"** are projected to adopt "seamless mobility".

This McKinsey study [25] explores different degrees of evolution from the current automobile-focused mobility systems. These can be thought of as low (clean and shared), middle (private autonomy), and high (seamless mobility). These scenarios try to anticipate how much the level of MaaS adoption extends from current expectations about vehicle ownership and usage, as well as the influence of population density and level of development.

3.3. MaaS Adoption Scenarios—Public vs. Private Platform

A study by Arthur D Little [13] also examined the potential paths of MaaS adoption by defining two main axes. One axis is the dimension between public and private operation of MaaS. The second axis is the dimension between the front-end and back-end of the integrated digital element of the MaaS concept. The front-end permits access and use for customers, while the back-end contains the various functional modules that enable the service. Using these building blocks, they define three possible ways forward with different mixes of these elements:

- **"Scenario A—Aggregated Public MaaS Platform"**—A single public MaaS operator that is a public transit authority (PTS), runs the entire system, with ownership over a single front-back end platform.
- **"Scenario B—Aggregated Liberal MaaS Market"**—The free market results in multiple MaaS operators each with their own complete platform (front- and back-end).
- **"Scenario C—Disaggregated Public MaaS Platform"**—The free market is mitigated by a public operator element so that a mix of public and private operators leverage a common public back-end as an enabler.

The Arthur D Little study [13] identifies several key tradeoffs, depending on the proportion of public versus private control, that include: degree of system simplicity, availability of price competitiveness, the comprehensiveness and competitive evolution of the services provided, and sufficient funding to build-out and keep technology current. As an example, involvement of the public sector is more likely to prioritize the overall social goals of mobility in balance with interests such as the profit motive of the private sector.

3.4. MaaS Adoption Scenarios—Temporal vs. Spatial Efficiency

In a paper by Wong, Hensher, and Mulley [26], the authors define two main axes for considering MaaS adoption. The vertical axis represents the temporal efficiency of mobility,

while the horizontal axis represents spatial efficiency. This scheme results in four quadrants of mobility:

- **active modes**—This upper left quadrant describes modes that are less temporally efficient but more spatially efficient (walking and cycling).
- **private modes**—This lower left quadrant contains modes that are low in spatial and temporal efficiency (ride-sharing/carpooling, private cars both manual and self-driving).
- **shared modes**—This lower right quadrant includes lower spatial efficiency and more temporal efficiency modes (micro-transit, autonomous taxi fleet, private autonomous ride-sourcing, conventional taxis, fleet car sharing, peer-to-peer ride-sourcing)
- **public modes**—The last, upper right quadrant contains high spatial and temporal efficiency mobility (fixed-route minibus, bus, bus rapid transit, light rail, metro/heavy rail).

In this four-quadrant scheme, MaaS is defined to operate in the lower right (shared modes) and upper right quadrants (public modes). Given this conceptualization [26], there are three potential evolution schemes for MaaS. The first is private mode-heavy supported by public modes, with private modes evolving into a shared mode model. The second is public mode-heavy with the private mode evolving into share mode use. Both of these potential evolutions support spatially and temporally efficient, sustainable versions of MaaS. An undesirable outcome would be the continued dominance of private modes, plus public mode users migrating to smaller shared modes. This would potentially result in an increase in congestion and associated negative sustainability outcomes.

3.5. MaaS Adoption Scenarios—Consuming Vehicles vs. Consuming Rides

In a recent book by Grush and Niles [22], the authors present a two-axis scheme looking at consumer choice versus the diffusion, or adoption, of automated vehicle technology. The horizontal axis is defined as the mobility user's choice of consuming vehicles versus consuming rides, which aligns with the MaaS concept. On the vertical axis, the defined alternatives are the diffusion of automated vehicles (AV's) is discouraged versus the encouraged diffusion of AV's. This scheme results in four quadrants of possibilities:

- **household vehicle ownership is encouraged**—Personal vehicle ownership is encouraged by a wide range of factors that include a car-dominant community, status, availability assurance, inadequate transit, cheap parking, privacy, and security.
- **household vehicle ownership is discouraged**—Personal vehicle ownership is discouraged by factors that include the perception of high vehicle cost, expensive parking, urban lifestyle, eco-consciousness, falling disposable income, and land use regulation.
- **shared AV's are discouraged**—Sharing of AV's is discouraged by being more expensive than public transit, regulations delaying deployment, technical challenge, profitability difficult due to peak fleet size.
- **shared AV's are encouraged**—Sharing of AV's is encouraged by factors including 24-h availability, wide vehicle choice, no driver license required, high safety, service personalization, on-demand instant response, and a non-car oriented community. This outcome depicts conditions in which AV's could enable the MaaS concept of shared, on-demand mobility.

This scenario approach focused on automated vehicle adoption, which is valuable because of the highly disruptive nature of this technology if successfully developed. It identifies factors in each quadrant that might be considered in a whole system methodology to predict the interaction of automation technology effects on mobility trends, including MaaS adoption.

3.6. Summary—Alternative MaaS Adoption Scenarios

These are but a few examples of MaaS adoption scenarios that attempt to characterize how MaaS adoption may evolve. These different scenario approaches provide valuable

insights on the holistic, STEEP range of characteristics to consider in projecting the deployment and impact of MaaS in specific urban centers. They also show how a two-axis, scenario-based planning approach can be used to evaluate the complex alternative evolution paths for sustainable urban mobility systems.

4. MaaS Modeling and Simulation

This section presents a review of city-level studies of MaaS impacts, existing transportation simulation tools, and MaaS modeling methodologies. The focus is their potential to support a whole system methodology that considers all of the essential elements of MaaS described above.

4.1. Review of City-Level MaaS Studies

A set of studies were sought to examine how tools or models were currently being used to represent a city-level MaaS implementation and evaluate the resulting impact on the city's mobility system performance. The search criteria were city-level studies of MaaS or future urban mobility. One grouping of studies were distinguished by the stated purpose of informing decision-makers, which aligns with the goal of this research. Representative of these were a set of studies conducted by the International Transport Forum, which used simulation to examine the impact of shared mobility on the cities of Lisbon [27,28], Auckland [29], Dublin [30], and Helsinki [31]. A similar study sponsored by Ruter, the Oslo region's public transport company, focused on the impact of autonomous cars in Oslo [32]. A second grouping of studies were identified that focused on applying new approaches to model shared mobility at the city level, represented by Ann Arbor, Babcock Ranch, Manhattan [33], Zurich [34,35], and Stuttgart [36].

Each study was reviewed for its scope and objectives, simulation models used, key results, and limiting assumptions. The limiting assumptions were used to identify methodology gaps that could provide an opportunity for further research. Each of these studies used a comparable approach by defining a range of scenario-defined conditions that represented different levels of automated vehicle implementation and then applying a transportation modeling tool to simulate the mobility system impact and generate metrics. From the limiting assumptions identified for each of these studies, gaps in modeling MaaS at the city level were identified, and these gaps are summarized in Table 1.

Table 1. Summary of Limiting Assumptions in Representing MaaS in City-Level Future Mobility Studies.

Study/Reference	Limiting Assumptions									
	Changing Population Demographics	Competing Ridesharing Fleets	Pre-Positioning Vehicles	Network Routing of Vehicles	Cruising for Parking	Static Demand Only	Car and Public Transport Modes Only	No Mode Switch From Public Transport	No Travel Behavior Change vs. Time	Travel Behavior Effects on Transport System & Land Use
"Urban Mobility System Upgrade. How Shared Self-Driving Cars Could Change City Traffic" [27]	X	X				X	X			
"The Shared-Use City: Managing the Curb" [28]	X	X	X	X	X	X	X			
"Shared Mobility Simulations for Auckland" [29]	X	X	X	X		X		X		X
"Shared Mobility Simulations for Dublin" [30]	X	X	X	X		X		X	X	X
"Shared Mobility Simulations for Helsinki" [31]		X	X	X		X		X	X	X
"The Oslo Study—How Autonomous Cars May Change Transport in Cities" [32]	X	X				X	X			
"Transforming Personal Mobility" [33]	X	X	X	X		X	X			
"Autonomous Vehicle Fleet Sizes Required to Serve Different Levels of Demand" [34]	X	X	X	X		X	X			
"Assessing the welfare impacts of Shared Mobility and Mobility as a Service (MaaS)" [35]	X	X	X	X		X				
"A Modeling Approach for Matching Ridesharing Trips within Macroscopic Travel Demand Models" [36]	X	X	X	X		X				

Table 1 displays the frequency of the limiting assumptions in the studies reviewed. The limiting assumptions that appeared to be most prevalent were:

- No changes in city population demographics for the future periods that were studied.
- No consideration for competing fleet providers of ride-sharing vehicles, whether human-operated or autonomous.
- Static demand for mode choice, with no induced demand from increases accessibility to mobility or overall reductions in travel costs.
- No mode switching between cars and public transport.

The significance of some of these limiting assumptions, such as induced growth in trip demand and increased urban sprawl, is that they could negate the improved transportation metrics predicted by these studies. These gaps influenced the research roadmap that is presented in a following section.

4.2. Review of Transportation Simulation Tools

For this assessment, the types of tools that were considered were policy evaluation, sketch-planning, and mesoscopic tools, which were deemed most relevant to the research objectives. The tools intended for policy evaluation or sketch planning enable examination of strategic-level trends over large timespans, e.g., decades, while mesoscopic tools can provide a detailed forecast for traffic levels on a specific road network at a particular time of day for a particular scenario of mobility demand and supply. The approach used was to review publicly available documentation for each of the tools, according to the following criteria, which were influenced by those recommended by the Federal Highway Administration (FHWA) [5]:

- **Geographic Scope:** Can the tool model urban or regional transportation systems?
- **Key MaaS Elements:** Can the tool model the key emerging transportation services and technologies to represent "the whole problem" as needed for MaaS at a city or regional level? See the gap analysis results above in Table 1.
- **Sustainability Impact:** Does the tool provide outputs that can be used to compute the sustainability impact to support decision-making by public and private stakeholders?
- **Maturity and Industry Acceptance:** What is the tool's level of acceptance and use (e.g., academic, government, professional)?
- **Ease of Use:** How easily is data in the needed formats obtained, processed, and analyzed to represent urban areas from around the world?

For this review, each tool was qualitatively assigned a score of 1, 3, or 5 for each of these criteria, with 5 being the best score for relevance. This type of scoring approach is used to achieve greater spread in scoring results when performing a qualitative comparison [37]. In addition, each tool's ability to address the city-level MaaS study gaps identified in Table 1 was assessed. The results of the tool comparison and scoring are shown in Table 2. By assigning each tool's relevance score to each of the criteria, a total score was calculated for each tool to enable comparison.

The results of the scoring analysis show that tools developed for policy and sketch-planning scored among the highest when considered for a whole system approach for the identified gaps. It should be noted that the intent of the analysis herein was not to focus on the fidelity of a particular numerical score for a given tool, but to employ a 1-3-5 scoring scheme to get a relative qualitative ranking for this large set of candidate tools. This approach was used to determine tools that would appear best suited to address the modeling gaps identified in the city-level MaaS studies. These tools might then be extended or improved by additional relevant models of the MaaS concept, discussed next.

Table 2. Comparative Assessment of Simulation Tools for MaaS and Whole System Model of Sustainable Urban Mobility.

Tool	Model Approach	Tool Type	MaaS Modeling Gaps				Green Outputs	Industry Accepted	Ease of Use	Total Score
			Network & Geographic Effects	Changing Population Demographics	Induced Demand & Mode Switching	Travel Behavior Effects on Transport System & Land Use				
Choices & Voices (DVRPC) [38]	browser-based policy model	Policy	3	3	3	5	5	3	5	27
Impacts 2050 [39]	system dynamics	Sketch-Planning	1	5	3	5	3	3	5	27
POLARIS—SMART Mobility Analysis Framework [40]	agent-based, MATSIM	Meso-scopic	5	3	5	1	5	3	5	27
BEAM—SMART Mobility Analysis Framework [41]	agent-based, MATSIM	Meso-scopic	5	3	5	1	5	3	5	27
Urban Roadmap 2030 Model [42]	browser-based policy model	Policy	3	3	1	5	5	3	5	25
RVMPO Scenario Viewer [43]	browser-based policy model	Policy	3	3	1	5	5	3	5	25
ITF Shared Mobility Modelling Framework [44]	agent-based	Meso-scopic	5	3	3	1	5	3	3	23
Vision Eval [45]	disaggregate policy model	Sketch-Planning	1	5	3	3	3	3	3	21
MATSim [46]	agent-based	Meso-scopic	5	1	5	1	5	3	1	21
Simulation of Urban Mobility (SUMO) [47]	agent-based	Meso-scopic	5	1	3	1	5	3	1	19

(relevance: 1 = low, 3 = medium, 5 = high).

4.3. Review of MaaS Modeling Methodologies

In addition to a review of existing simulation tools, a literature survey was conducted to identify models or methodologies that might address the gaps identified above in the limiting assumptions. In particular, models that were sought that would complement, or extend, sketch-planning tools which scored well in Table 2 above. These models use approaches such as system dynamics, which is suitable for modeling systems with multiple competing inputs, feedback loops, and large amounts of uncertainty [48].

4.3.1. MaaS Mobility Mode Choice

There is an emerging variety of alternative modes of transport that could comprise MaaS systems, and models that predict their rates of adoption are being developed. Sneider's study defines a utility function that accounts for mode choices, the level of vehicle connectivity, region type/population density, user household income, user age group, and trip parking options [49]. The methodology also accounts for the fixed and variable costs of the different transport modes. This work could help inform a whole system methodology by helping to model mode choice for a large selection of the emerging transport modes being considered for MaaS. Because several of the limiting assumptions identified above were relevant to mode choice (e.g., addressing static demand only, considering car and public transport modes only, per Table 1), such a model could help extend existing tools to model MaaS as part of a whole system toolset for sustainable urban mobility.

4.3.2. Impact of Service Bundling and Pricing on MaaS Mode Choice

With MaaS as an emergent concept, there is uncertainty regarding public acceptance and adoption of the service going forward. One effort [50] used a web-based questionnaire focused on a Netherlands audience, with the resulting data analysis generating two mixed logit models. The first estimates the effects of service attributes, social influence, socio-demographics, and transportation-related characteristics as they impact a potential customer's decision to subscribe to MaaS. The second model estimates the effects of transportation mode pricing schemes, and potential cross effects between transportation modes and individual characteristics on which transportation modes the MaaS provider should include in the subscription. In a systems dynamics approach towards MaaS [51], the model demonstrated how feedback loops can impact the pricing policies and the resulting adoption of MaaS by customers. Another study [52] also used a survey approach with Finnish participants to determine the willingness of customers to pay for MaaS. That study found that 43 percent of respondents would be willing to pay up to 64 percent of their current mobility costs. These studies provide an initial means of quantifying the potential impact of pricing on MaaS adoption that could inform a whole systems model, while acknowledging the need to account for uncertainty.

4.3.3. Diffusion and Adoption of Automated Vehicle Technology

One of the uncertainties of the MaaS evolutionary path is how the technological development and consumer adoption of vehicle automation will unfold. In a paper that develops a system dynamics model of this trend [53], the diffusion of automated vehicles (AVs) is modeled over a timeframe of multiple decades. The model considers a sequence of automobile fleets evolving from SAE automation level 0 to 5 [54], that are adopted by consumers as the technology matures. The model accounts for the impact of vehicle and automation price, vehicle service life, and subsidies for vehicle development. This model could be a candidate for adoption to model the time-based development and adoption of SAEV's as part of a whole system methodology.

5. Gaps and Future Research Roadmap

Based on the reviewed city-level studies, transportation simulation tools, and documented model methodologies, gaps were identified. These gaps included: changing population demographics, competing ride-sharing fleet providers, induced travel demand,

and mode switching between cars and public transport. This gap analysis informed the following research roadmap.

- **Base Tool:** Select an existing base tool that is already accepted for support of transportation planners and other MaaS stakeholders for urban region mobility systems. Table 2 identified candidate tools, e.g., sketch-planning and systems dynamics.
- **Tool Upgrade:** Develop modules to extend the base tool to address the research gaps, identified in Table 1, at the appropriate level of fidelity to reveal interactions and trends over the scale of decades. This timescale supports strategic decision-making. Ensure that the key elements of the MaaS concept (demand, supply, governance, digital interface) can be represented by the upgraded tool. Models that can support this upgrade include mode choice, service bundling and pricing, and diffusion and adoption of automated vehicle technology.
- **STEEP Metrics:** Establish a set of comprehensive STEEP metrics that the extended model will generate to characterize the relative sustainability impacts of different MaaS adoption strategies.
- **MaaS Scenarios:** Define a two-axis MaaS scenario set, informed by those found in this research, and apply it to exercise the extended tool and demonstrate its utility. The scenarios summarized earlier provide reference points for aspects of MaaS adoption that the upgraded toolset should address.

6. Conclusions

This study conducted a review of methods for assessing the sustainability of an urban mobility system, as well as definitions and potential adoption scenarios for the MaaS concept. It also reviewed the suitability of existing transportation simulation tools and study approaches to evaluate the potential impact of MaaS implementations on city-level sustainability, using a whole system, STEEP-based approach.

This review included recent relevant studies, performed at the city level, using existing simulation tools, to predict the benefits of MaaS systems. It revealed limiting assumptions and gaps that provide areas for further research. This effort also identified sustainability metrics that can be applied to measuring the effectiveness of a MaaS implementation at the city level.

To further advance this research, the next phase is to select an analytical methodology, guided by the research roadmap defined above. This methodology will be designed to address the limiting assumptions and gaps that were identified for assessing MaaS that are not currently represented by the city-level study methodologies that were reviewed.

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