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# Analysis Methods and Models Facilitating Mobility as a Services Based on Autonomous Vehicles

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Doctor of Philosophy

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# Abstract

Transportation is composed and fused by physical traffic flow, energy flow, and information flow. Road transportation is significantly facilitated by infocommunication technology recent years. Cloud computing supports the provision and interaction of real-time information, which enhance the opportunity to further integrate the complex transportation systems.

Mobility as a Service (MaaS) is proposed as one representative concept of digitalized mobility services, which aims to integrate mobility services as a whole, as well as it is accessible via a single mobile application. Travellers are available to 'put' mobility services into their pockets and manage their travel by fingertips' clicks. Accordingly, the service manager-MaaS operator and service 'assistant'-mobile application are the pivots of a MaaS service.

The current MaaS is implemented focusing on public-private service integration and mobile application development. Incorporation of autonomous vehicles (AVs) into MaaS is envisaged as a further development paradigm. From a perspective of industry, several stakeholders have already considered 'autonomous MaaS' in their development plans. AVs are regarded as smart infrastructure to interact with travellers.

The Dissertation is composed by two lines: analysis methods for MaaS, and modelling approaches for MaaS based on AVs. Thesis 1 is to introduce assessment method of service quality, both regarding MaaS, and AV based services. Methods of mobile application interface function analysis for MaaS are presented in Thesis 2, which leads to the Thesis 3: the concept of mobile application for MaaS based on AVs. Results of analyses substantiate modelling activities. As online connection opportunity and mobile application facilitates the integration and service combination, the models of combined services based on MaaS framework are elaborated in Thesis 4.

My main contribution is that, compared with the existing, mainly policy-oriented research, I analyse and model MaaS services from the perspective of transport informatics, focusing on travellers and mobile applications. Feasible assessment criteria have been proposed and applied to evaluate the MaaS services. The concept of mobile application and combined services are elaborated and modelled based on system engineering approaches. My research results aim to facilitate MaaS service planning and mobile application development based on AVs.

**Key words:** Mobility as a Service (MaaS), autonomous vehicles (AVs), Mobility as a Service based on autonomous vehicles (MaaS based on AVs), analysis, models, service quality, interface functions, mobile application, combined mobility service

# 1. Research Field

The Mobility as a Service (MaaS) is proposed as one of the representative digital mobility services aiding Smart City, which is provided by a typical cyber-physical mobility system [1]-[3]. The physical movement from A to B of passengers and goods remain same as previous processes, however the efficiency of management processes is highly enhanced by digitalization and intelligence. The base functions of travel planning, booking, ticketing, payment, and navigation are available via mobile applications on smartphones [4]. Especially, involving autonomous vehicles (AVs) into mobility system will bring more interaction opportunities. The research topics of four Thesis are identified and summarized in Figure 1 first.

I have summarized topics of 'main streams' in MaaS research field after extensive paper reading and continuously research works. According to topics of 'main streams', I have identified my research niches, then I fill niches with my research results.

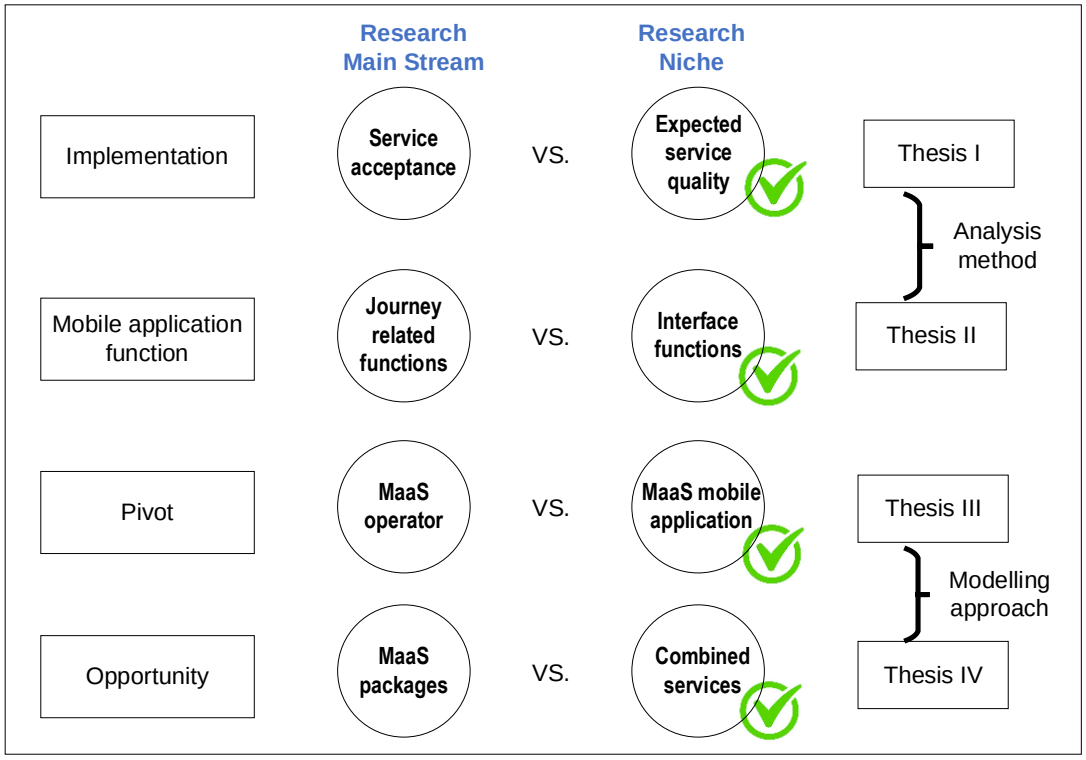


**Figure 1: Identified research niches and topics of Theses**

The acceptance and quality of the introduced new mobility services have been the key questions of service implementation. The acceptance of AVs and mobility services based on AVs have been widely researched, either by applying questionnaire survey-based methods or simulation and modelling approaches. Thus, I have identified the expected service quality analysis for MaaS and MaaS based on AVs as the topic of Thesis 1.

The MaaS business models and the role of MaaS operator have been deeply studied by policy-leading researchers [5]-[8]. The journey related functions, such as route planning and optimization, have been widely studied as well. The detailed analysis and assessment of mobile applications of MaaS are limited [9], [10]. Thus, I focus on the analysis of

frontend interface functions and backend information system models of mobile application. The relatively deep analysis results regarding customization and personalization of mobile application are summarized in Thesis 2, which supports to envisage the concept of a mobile application for MaaS based on AVs in Thesis 3.

Towards the service combination opportunities, the types of MaaS monthly package have been discussed in several works [3], [8]. Various concepts of combined services have been proposed as well [11], however rarely few papers further incorporate concepts based on AVs into MaaS framework. From one aspect, MaaS as an integrated information platform is available to provide further new emerging opportunities. Thus, such a combined service – the embedded crowdsourced parcel delivery based on AVs, incorporated in MaaS framework is elaborated in Thesis 4.

# 2. Literature Review

An extensive scientific literature review had been conducted to identify research gaps. The literatures are systematized reviewed and summarized in Figure 2.

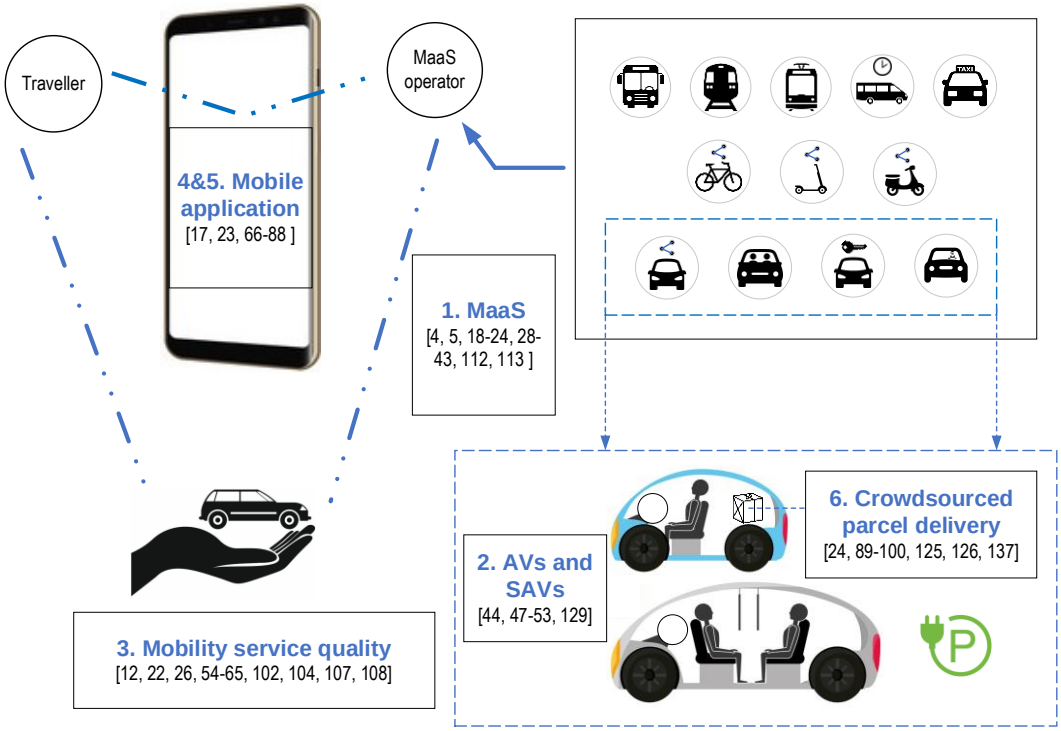


**Figure 2: Systematized literature review**

In topics of Dissertation, I have summarized most relevant reviewed literatures in six mainstreams as follows. First two streams are summarized and used as the base of overall research topic. Then, the following each stream is summarized according to Theses. (*Remark*: figure is from Dissertation, the reference numbers on figure are different from the booklet. Only several papers are referred in the booklet.)

- **MaaS and its implementation**, [5]-[7], [12], [13]
- **(mobility services based on) AVs and SAVs,** [14]-[16]
- **mobility service quality**, [17]

- **mobile application interface function**: *integration-customization-personalization*, [9], [10]
- **mobile application and information system for mobility services**, [4], [9], [10]
- **new types of service combination**: *crowdsourced parcel delivery* [11], [18]

The overall findings have been concluded as follows:

- MaaS is proposed as a 'mobility for all' service, mobility service for people with special needs should be considered.
- shared services based on AVs are major types of future mobility service. In this Dissertation, the AV based carsharing and ride sharing are identified as 'individual vehicle sharing' service and 'small group seat sharing' service.
- MaaS based on AVs could be a blueprint of mobility services.
- new assessment criteria are to be established to assess new mobility services.
- As functions of ticketing and payment have already involved in most MaaS mobile applications due to fast development, fewer highlights are expected on these two functions.
- Terms of customization and personalization are mixed used in publications.
- MaaS is implemented on the base of information systems, and it provides an open information system to further 'integrate' various mobility services.

# 3. Research Objectives

The overall objective of my research is to elaborate the service concepts of MaaS based on AVs by assessment of current MaaS development, focusing on mobile application and information management. The objective of analysis line is to assess MaaS (mainly the mobile applications) by applying weighted, multi-criteria methods. The objective of modelling line is to introduce a conceptual model of mobile application for MaaS based on AVs, and to model an emerging, combined service concept within MaaS framework. The research objectives of each thesis are summarized as follows:

1. To investigate the expected service quality of MaaS by applying triangular fuzzy Analytic Hierarchy Process (AHP) method.
2. To analyse MaaS applications from perspectives of customization and personalization by applying statistical assessment methods.
3. To envisage and model a mobile application concept for MaaS based on AVs considering backend information system and frontend functions.
4. To introduce the crowdsourced parcel delivery based on AEVs as a combined service into MaaS framework, by applying system engineering, process-oriented modelling methods.

The mainstreams of MaaS research are as follows: the investigation of service acceptance, policy oriented MaaS operator analysis, and service combination investigation regarding MaaS monthly packages. Overall, my work supplements to the mainstream. I intended and had run a different direction to 'view' MaaS service, which are: the expected service quality, the mobile application, and the emerging, combined service. Furthermore, incorporation AVs into MaaS framework is put in the focus.

# 4. Applied Methods

My theses are grouped by main research methods: multi-criteria analysis (Thesis 1 and 2) and information system modelling (Thesis 3 and 4), which are summarized as follows.

### *Analysis: weighted multi-criteria methods*

Multi-criteria establishment and weighting are major procedure of the analysis method. The steps of method are summarized in Figure 3.

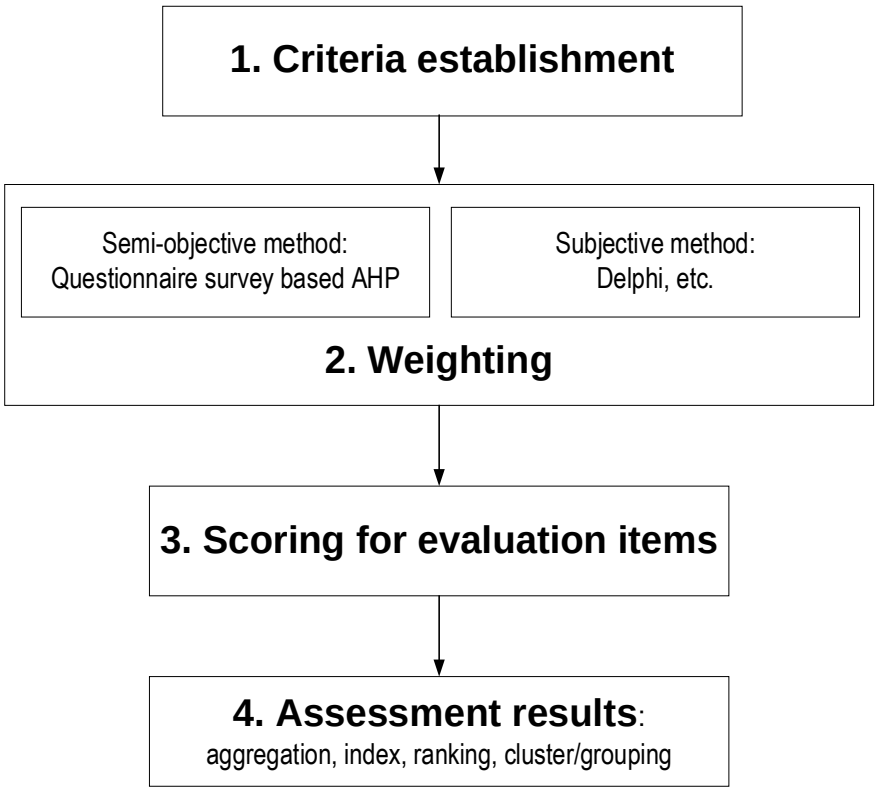


**Figure 3: Steps of weighted multi-criteria method**

As MaaS is a 'new', integrated mobility service, step 1 criteria establishment for MaaS regarding research sub-topics are the focus in my work of Thesis 1 and 2. Typically, the weighting methods are categorized into three types:

1) *Subjective*: Delphi (experts provide weights), etc
2) *Semi-objective*: AHP method (data collection via questionnaire survey)
3) *Objective*: statistical calculation (weights are obtained from evaluation dataset)

**Regarding this Dissertation:**

1) Semi-objective:
    - AHP method, modified triangular fuzzy AHP method [19], [20]
    - Invert phase numbering into weights
2) Objective:
    - Coefficient of variation (descriptive statistics)
    - Correlation coefficient (it is not weight, but it provides similar functionality, it indicates the correlation intensity)

In addition, the correlation analysis, diagram analysis, matching theory, numerical method, etc. have also been applied.

### *Modelling approach: system and process-oriented model*

Mobility services are provided by the mobility systems. The information system is a sub-system of mobility systems, especially in more and more digitalized mobility services [17]. The steps to model an information system are summarized in Figure 4.

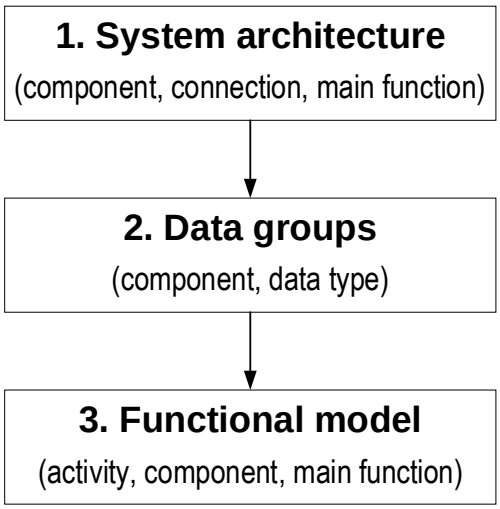


**Figure 4: Steps of information system modelling**

The connections between these models are indicated in Figure 5.

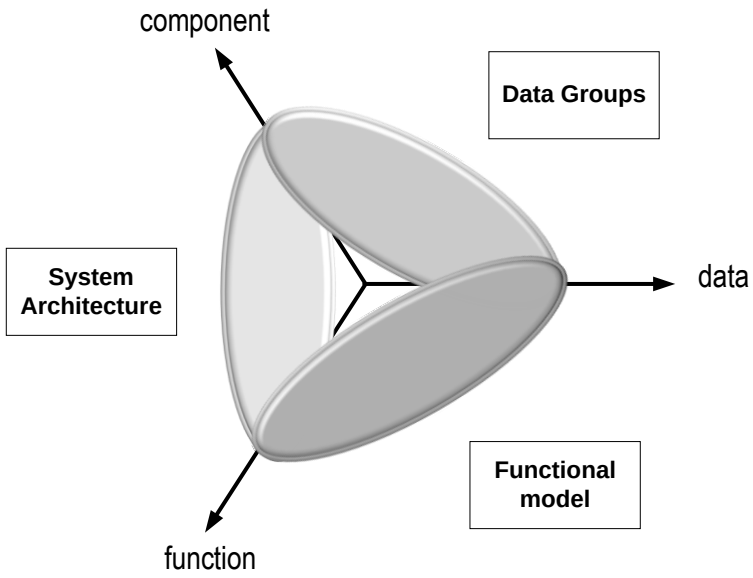


**Figure 5: Connections between models**

Research question of 'what kind of information system is proposed to support providing the mobility services' is answered by system architecture. 'What kind of data groups are needed and produced in the system?' is summarized with data groups table. 'What kind of activities are done by each component regarding main functions?' are answered by functional model.

# 5. New Scientific Results

The new scientific results are summarized in Theses.

## Thesis 1

Thesis 1 is based on Chapter 3 of the Dissertation.

I have determined assessment criteria and elaborated a modified fuzzy Analytic Hierarchy Process method to assess MaaS service quality. Compared with existing methods, my main contribution is that the triangular interval value is used to process the obtained data, in order to decrease the uncertainty of questionnaire data. I have applied this method to assess informatics background of selected MaaS services, and the MaaS services have been grouped according to levels of service quality.

Service quality comprehensively reflects the attributes of the service. The quality of such innovative mobility service is a complex term depending on its subjective and objective attributes. Both attributes are considered to determine the criteria structure, however, only the informatics background are assessed during the method application.

The **(traditional) MaaS** is defined as a semi-public transportation service. Thus, the quality assessment criteria of both public and private transportation are taken into consideration. **I have introduced a weighted multi-criteria evaluation method both considering modified weighting method and criteria structure elaboration. I have elaborated the criteria structure for MaaS service assessment with simplification compared with assessment criteria of conventional public transportation service.**

**I have introduced the modified, triangular fuzzy AHP method to calculate weights of criteria.** The steps of method are summarized in Figure 6.

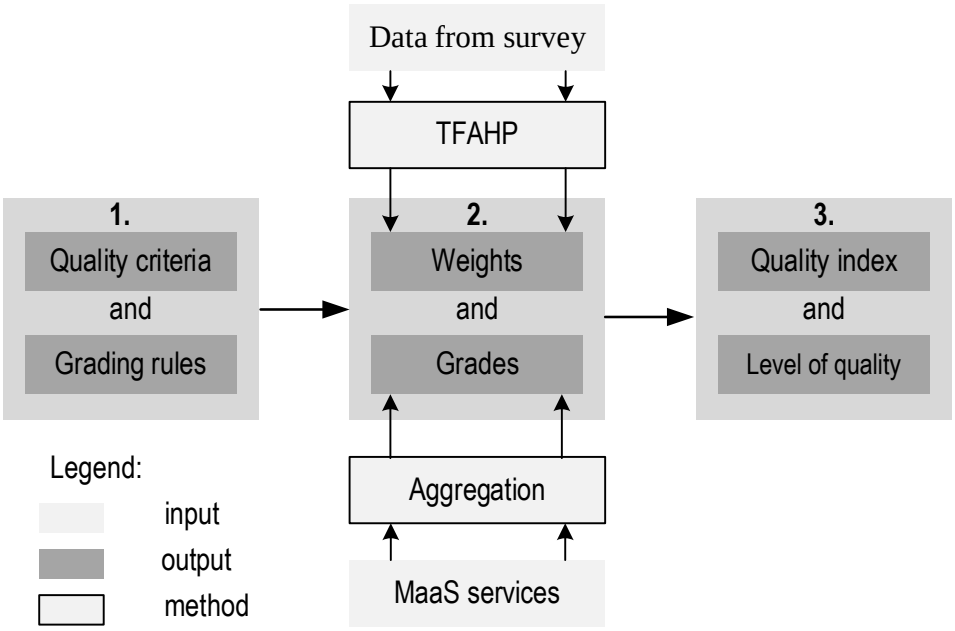


**Figure 6: Steps of the assessment method**

**All the collected data could be used in data process to obtain weights.** A set of values are calculated as a triangular interval value, which is applied as Equation. (1).

$$x_{tk} = \left( l_{tk,\underline{ave}.x_{tk} \le 1}, m_{tk,ave.x_{tk}}, u_{tk,\overline{ave}.x_{tk} \ge 1} \right) \quad (1)$$

The assessment results of MaaS services show results fit the reality, according to ranking of applications from other researchers' results. The weights calculated by the introduced method is applicable. **I have introduced a method to determine the levels of service quality of MaaS**, in order to group MaaS services in similar level development. The results show that only two services are grouped into level 3, the service level of current MaaS is not high, further continuous development is expected.

*Own publications related to the Thesis 1:* (He and Csiszár, 2018b. **5)**, (He and Csiszár, 2020b. **2)**, (Csiszár et al., 2019. **9)**

## Thesis 2

Thesis 2 is based on Chapter 4 of the Dissertation.

I have applied descriptive statistical methods to analyze interface functions of MaaS mobile applications. I have investigated whether the applications are personalized or customized. The base statistical variables are applied as weights, the customization setting options and personalization opportunities are considered as scoring items. The full personalization is not implemented yet, and the correlation between customization and semi personalization is not strong at current stage. I found that existing MaaS mobile applications are setting option-oriented applications.

**I have identified 5 phases of integration for MaaS development** by considering four variables: application function, transport mode, tariff structure, and organization. I have considered the process to determine the phases: how the public transportation service is integrated with private services. The identified phases are presented in Figure 7.

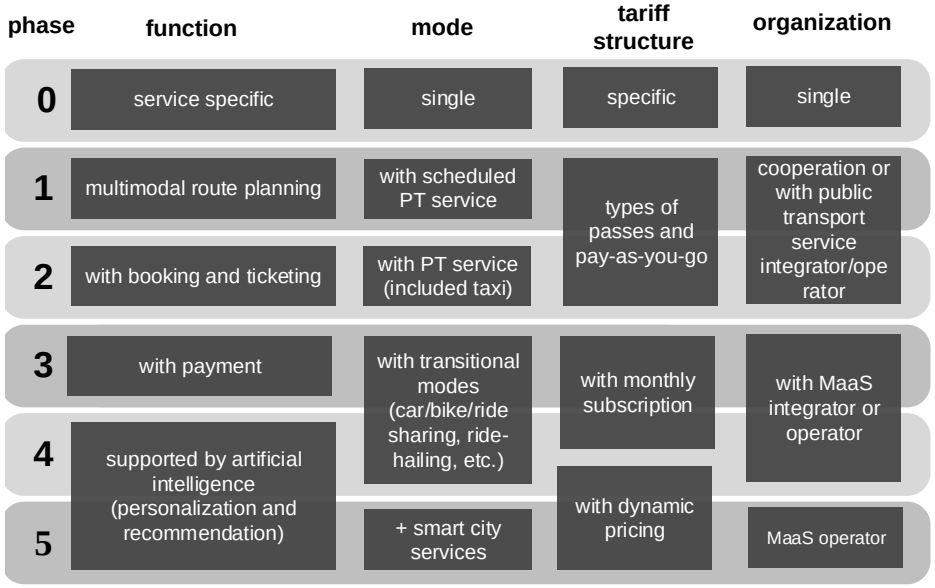


**Figure 7: Phase of integration**

As weights and phases simultaneously indicate the importance of variables, **I invert phases numbering directly into weights to calculate integration index.**

**I have introduced the evaluation criteria to analyse customization setting options. I have applied the statistic weight-the coefficient of variation as Equation. (2) to show evaluation result.** Thus, weights are from evaluation dataset itself.

$$v = \frac{\sigma}{\mu} \tag{2}$$

***Customization*** is achieved by manual selection from lists of options according to travellers' preferences. The traveller provides data. ***Personalization*** is achieved automatically by system cognitive capability and advanced data processes using passively collected, historical personal travel related data. ***Semi personalization*** is achieved by less manual input and more automatic, simple data processes using historical data from other database if needed (e.g. the crowdsourced travellers: waze application). No passively collected personal travel related data is used.

**I have elaborated the evaluation table for correlation analysis between customization settings and semi-personalization opportunities.** The correlation coefficient is calculated as Equation. (3).

$$r_{xy} = \frac{\operatorname{cov}(X, Y)}{\sigma_x \cdot \sigma_y} \tag{3}$$

Typical steps of correlation analysis have been applied. The calculated values of coefficient between customization and semi-personalization are visualized in the chord diagram, which regards to selected MaaS mobile applications.

<u>*Own publications related to the Thesis 2:*</u> (He et al., 2021. **6)**, (He and Csiszár, 2021a. **7)**, (He and Csiszár, 2021c. **8)**

## <u>Thesis 3</u>

Thesis 3 is based on Chapter 5 of the Dissertation.

I have elaborated the concept of mobile application for MaaS including mobility services based on autonomous vehicles. Both backend functions of the information system and frontend interface functions of the mobile application have been determined. Compared with the conventional service processes, the availability and accessibility checking of autonomous vehicles in shared services are highlighted. The system architecture and information management processes have been modelled, as well as the major information flows during each phase of travel have been determined.

The **MaaS based on AVs** is defined as a public transportation service, where highly automated transportation processes are considered. Namely, the AVs are fully incorporated, as well as the real-time task coordination process is managed by machine-to-machine components automatically. The large volume, automated or autonomous

public transit remains. The emerging service types are highly fused, the transitional modes are replaced by the service of shared AVs (e.g., taxi, car/ride sharing, ride-sourcing, chauffer services are fused to small volume, vehicle or seat sharing services).

**As AVs are involved, the previous driver side 'human-machine' interface is eliminated.** It is to simplify service processes and improve efficiency both for service using and operation. The alteration in MaaS and MaaS based on AVs regarding frontend and backend are summarized.

The concept is based on analysis of existing MaaS mobile applications. **I have elaborated the information system architecture of MaaS based on AVs, the formed information flow, and the functional model, as well I have presented a mobile interface function analysis comparing with one benchmarking MaaS application.** The information system architecture indicating backend functions are elaborated in Figure 8.

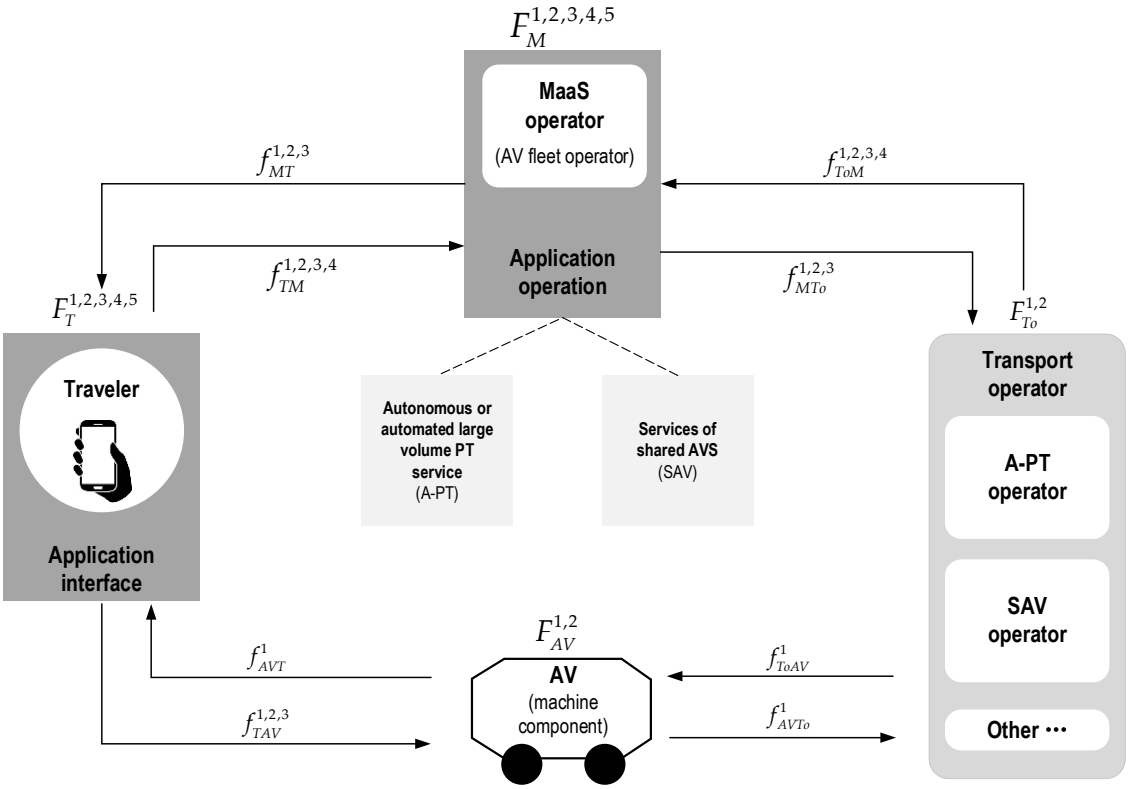


**Figure 8: Information system architecture**

More intensive interactions from 'smart' traveller side are expected. **I have summarized the major alteration of participants' activities in information system when AVs are involved into the matured MaaS. I have elaborated the concept of mobile application for MaaS based on AVs, focusing on information management considering backend and frontend planning together.** I have formed one example of a multimodal travel chain indicated with travel phases. Functions performed by main component are arranged in travel time sequence. The information flow is generated by the involved functions; input and output data keep the information flow in real-time.

*Own publications related to the Thesis 3:* (He and Csiszár, 2018a. **4)**, (He and Csiszár, 2020a. **1)**

## Thesis 4

Thesis 4 is based on Chapter 6 of the Dissertation.

I have elaborated the concept of the crowdsourced parcel delivery embedded into autonomous electric vehicle sharing service within the MaaS framework. The service concept is based on the information system architecture and the functional model. I have determined the service matching conditions of en-route assignment. To highlight the comparison results of scenarios regarding energy consumption, I have applied numerical method and I found that, the embedded delivery based on small electric autonomous vehicles is preferred in short distance multimodal mobility services.

**I have elaborated the mobility system architecture of MaaS based on AVs.** A MaaS system or the so-called MaaS ecosystem, is to be spatially connected by vehicle charging points and 'smart' mobility hubs, especially considering AVs are involved. Inter-city and intra-city mobility hubs are available to deal with partial delivery service. More service combination opportunities are to be provided by the 'smart' infrastructure together with fast technology development of AVs. **I have elaborated the concept of the crowdsourced parcel delivery service embedded into MaaS based on AVs.** The service processes indicating the service concept is presented in Figure 9.

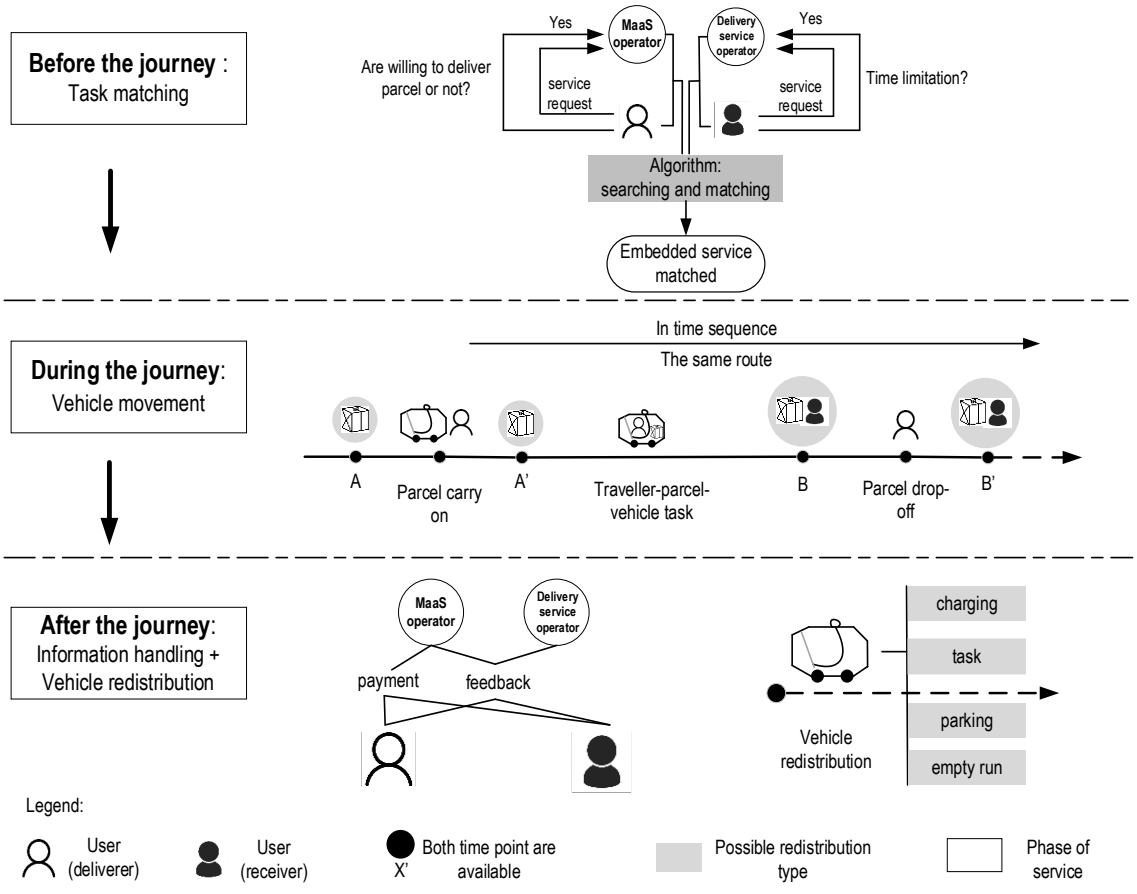


**Figure 9: Service processes**

**I have summarized the most relevant service characteristics of this embedded service by Venn and flowchart diagrams.** The optimal combination is the parcel delivery embedded into individual vehicle sharing service. **I have introduced the information system architecture involving parcel delivery. I have elaborated the three-dimension, functional model to interpretate the service process.** The most important functions are identified and categorized in Figure 10.

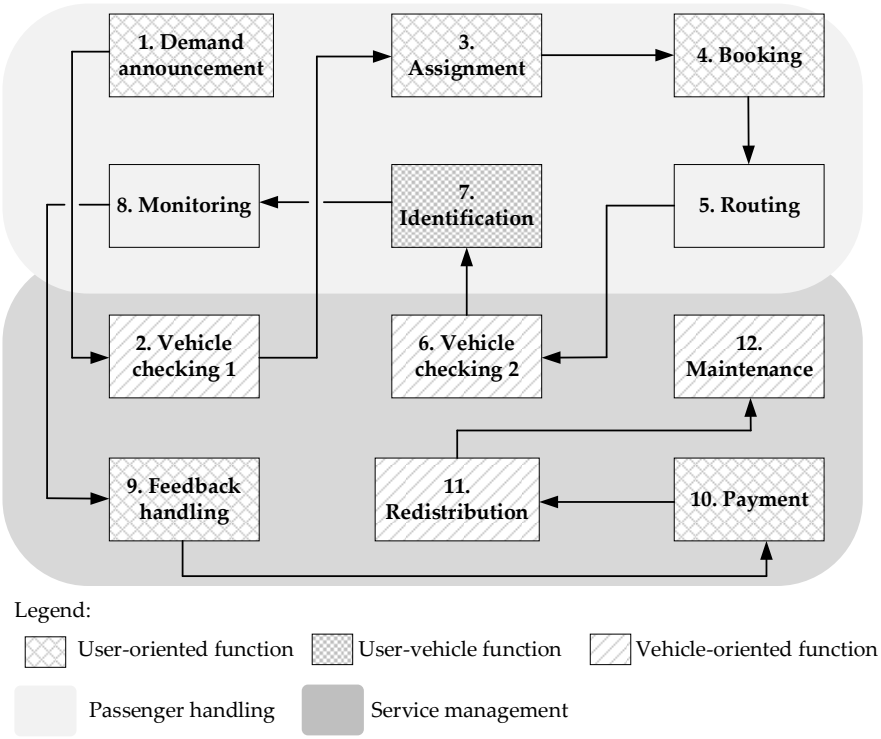


**Figure 10: Functions in embedded delivery service**

User-oriented and vehicle-oriented functions are addressed, as demand and capacity are coordinated with these functions. Two real-time information checking of vehicles are proposed: appropriateness and availability checking. Vehicle checking 1 ($F_2$) is to ensure the vehicle availability: whether the selected AV is available to be used in the estimated time and location. Vehicle checking 2 ($F_6$) is to ensure the appropriateness of selected AV before the movement.

**I have applied the matching theory to summarize the matching conditions of the embedded service. I have applied the numerical methods to demonstrate the energy consumption comparison scenarios for per parcel delivery.** The result shows that the embedded delivery based on small electricity vehicles is environment friendly, from a long period point of view.

*Own publications related to the Thesis 4:* (He and Csiszár, 2021b. **3)**

# 6. Applicability of the Scientific Results

The main theoretical and practical applicability of Theses are summarized as follows:

### *Thesis 1:*

- **Theoretical**: MaaS as a new integrated service has been implemented, accordingly, the service quality assessment of MaaS is expected. I have introduced assessment criteria for MaaS. And in method modification, three average values are used in a triangular interval to present the collected data, it can reflect more information from original dataset. Methods based on fuzzy theory is preferred in assessment, as it can decrease the uncertainty of questionnaire data.
- **Practical**: towards assessment of MaaS, to determine who is the first does not have much meaning in practice, ranking is not the assessment purpose. Thus, a further step 'grouping' or 'cluster' has been developed. MaaS services can be grouped according to the introduced levels. MaaS service operators may identify the weakness of provided services, as well as potential aspects for priority development.

### *Thesis 2:*

- **Theoretical**: the appropriate weights assignment is the key to the assessment method. I have summarized typical MaaS mobile application interface functions. And I have applied descriptive statistics variables as the weights in the evaluation.
- **Practical**: customization setting option development is the current phase for data collection, as well as for analysis purpose of developing 'automated' functions. For service operators, towards further personalized service, fewer manual input is required, and recommendations based on personal travel data are expected.

### *Thesis 3:*

- **Theoretical**: The two alterations in information systems are: the driver interface is eliminated from frontend; the vehicle control module is added into backend. I indicated that two checking of AVs are needed to make sure the vehicle availability and accessibility before vehicle movement. I have elaborated the major information management and information flow among travel phases.
- **Practical**: I have elaborated the information system models for MaaS based on AVs, to support interaction of information flow in entire travel phases. The results of my work support for information system planning and operation of such service, as well as development and improvement of the mobile application interface functions. For service operators or software developers, the results are summarized as the alteration in information system introducing AVs.

### *Thesis 4:*

- **Theoretical**: MaaS is not only proposed for passenger transportation, but also for freight transportation. Thus, integration of logistics system into MaaS is taken into consideration. Crowdsourced parcel delivery is a small part of logistics system. As its operation tightly depend on the mature information system, I combine this service into MaaS based on AVs, to elaborate the embedded service concept with the vehicle solution.
- **Practical**: the results of my work support for information system planning, integration, and operation of such innovative, joint mobility service development. As well as support researchers or service operators to develop business models

for such services. The integrated information system as the essential subsystem is taken into consideration, especially in the digitalized mobility services.

# 7. Future Research

My research results presented in this dissertation are only a very beginning start, for to further investigate the integrated mobility services, as well as the shared, AV based mobility services. MaaS is one of the names of integrated mobility service. According to development history of transportation, whether it is called MaaS, the integration in urban transportation system happens aided by fast technology development.

Although digitalization in road transportation system still remains at a rudimental level, the highly connected, smart, green transportation system as the blueprint is expected. I had already decided to be a university teacher at second year of my BSc study. Thus, at first after my PhD study, I plan to pick up two points of the following as my continuous two years postdoctoral working plans.

- **Regarding Thesis 1:** A method comparison study about AHP methods regarding MaaS service evaluation. To analyse the weight differences resulting from traditional AHP, fuzzy AHP and the modified fuzzy AHP method.
- **Regarding Thesis 2:** A comprehensive review summary about MaaS service: from both point of view - academia and practice are taken into consideration.
- **Regarding Thesis 3:** Pivot factors identification regarding the gamification opportunity aiding mobility services. A relatively wide range questionnaire survey is to be conducted, as the results reflect the using experience of end-users.
- **Regarding Thesis 4:** Information system planning for smart parking and charging service in the framework of MaaS, as well as connecting to the MaaS based on AVs. As the reallocation, assignment performance, charging, and parking are major tasks of shared AVs.

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## Own publications related to the theses

***Journal paper:***

**1)** HE, Y. & CSISZÁR, C. **2020a.** Concept of mobile application for mobility as a service based on autonomous vehicles. Sustainability, 12, 6737. Doi:10.3390/su12176737. **(IF=3.251)**

**2)** HE, Y. & CSISZÁR, C. **2020b.** Quality Assessment Method for Mobility as a Service. Promet-Traffic&Transportation, 32, 611-624. Doi: 10.7307/ptt.v32i5.3374. **(IF=0.898)**

**3)** HE, Y. & CSISZÁR, C. **2021b.** Model for Crowdsourced Parcel Delivery Embedded into Mobility as a Service Based on Autonomous Electric Vehicles. Energies, 14, 3042. Doi: 10.3390/en14113042. **(2020: IF=3.004)**

***Conference paper:***

**4)** HE, Y. & CSISZÁR, C. **2018a**. Information Management for Mobility-as-a-Service Based on Autonomous Vehicles. In: Közlekedéstudományi Konferencia. Széchenyi István Egyetem Közlekedési Tanszék, Győr, pp. 293-303. ISBN 978-615-5776-13-7. Avaiable from: http://real.mtak.hu/id/eprint/78822

**5)** HE, Y. & CSISZÁR, C. **2018b.** Quality Assessment Method For Mobility-As-A-Service Based On Autonomous Vehicles. In: International Conference on Traffic and Transport Engineering. University of Belgrade, Faculty of Transport and Traffic Engineering, Belgrade, pp. 901-910. ISBN 9788691615345. Avaiable from: http://real.mtak.hu/id/eprint/90282 (**involved in WoS**)

**6)** HE, Y., FÖLDES, D. & CSISZÁR, C. **2021.** Integration Index for Mobility as a Service. In: 6th International Conference on Road and Rail Infrastructure, 2021. május 20-21., Zagreb (Croatia). Doi: 10.5592/CO/CETRA.2020.1010

**7)** HE, Y. & CSISZÁR, C. **2021a.** Analysis method of customization settings for Mobility as a Service. 2021 Smart City Symposium Prague (SCSP), IEEE, 1-6. Doi: 10.1109/SCSP52043.2021.9447389

**8)** HE, Y. & CSISZÁR, C. **2021c.** Correlation Analysis Method of Customization and Semi Personalization in Mobility as a Service. European Green Deal Challenges and Solutions for Mobility and Logistics in Cities. 19th European Transport Congress of the EPTS Foundation. Maribor, 7.- 8. October 2021. Slovenia : Andreja Kuzmanič, Zum urbanizem, planiranje, projektiranje d.o.o. (2021) pp. 383-400. 18 p.

***Book chapter:***

**9)** CSISZÁR, C., FÖLDES, D. & HE, Y. **2019**. Reshaped Urban Mobility. Sustainability in Urban Planning and Design. IntechOpen. Doi: 10.5772/intechopen.89211