Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Transport Technology and Economics

Development of Innovative Transport Systems and Mobility Services

Thesis of Ph.D. dissertation

Author:
Dávid FÖLDES
M.Sc. in Transportation Engineering

Supervisor:
Csaba CSISZÁR Ph.D.
Associate professor

Budapest, 2019

1 Research Field

The developments of infocommunication and vehicle technology have altered the passenger transport system and given way to the emergence of innovative mobility services. The technical innovations have facilitated sustainable mobility developments. The objective of such development is the efficient management of resources as well as complying with user preferences (Monigl and Berki, 2010, Pribyl, 2015). Telematics-based, so-called, transitional transport modes are spreading; these modes blur the borderlines between the individual and public transport, combine the advantages of both. Moreover, the Mobility-as-a-Service (MaaS) concept becomes more relevant facilitating a wide range of mobility services in an integrated way with the travellers in the focal point (Utriainen and Pöllänen, 2018).

Automation can enhance operational efficiency and traveller's comfort. An automated system operates on clearly defined algorithms; an autonomous system is able to make decisions using its cognitive and self-learning abilities. The majority of researches and developments on Autonomous Vehicles (AVs) focus on vehicle control and traffic issues (Szalay et al., 2017). However, passenger handling, operation, and maintenance can also be automatized (Chen et al., 2016). Placing AVs into a wider-approach within the passenger transport system has, moderately, been emphasized yet. Albeit 'mobility palette' is altering as a consequence of spreading AVs, additionally, new methods are required for the planning, the organizing and the operating of the transport. **A new type of mobility service based on small capacity autonomous road vehicles emerges that is shared, demand-driven and accessible only with advance ordering via a mobile application.** (Fagnant and Kockelman, 2014, Bansal et al., 2016, Winter et al., 2016). The mobility becomes more and more a pre-planned activity requiring proactiveness from the travellers. The human skills, the traveller's decision-making processes, and behaviour are also altering. Accordingly, the development of innovative information management methods and services supporting decision-making are required.

As a result of technological developments, a smart mobility system can be introduced based on real-time data, which combines human knowledge, intelligence, and decision-making processes. Data and information become key to decision-making. Consequently, transport systems can be considered as a special information system. The systematic revealing of elements and connections is required. The importance of scientific researches is increasing to further enrich the available knowledge base.

In the light of the above, my research area was how the technological developments, in particular, the autonomous road vehicles, can be integrated into the public transport system and mobility services. My research was done on urban, road, primarily public passenger transport modes and innovative, shared mobility services, as well as customized information services. The focus was placed both on the operation and the traveller. Since the object of the transport is the traveller, revealing the expectations towards the novel mobility services is especially important. If the travellers' expectations are met, the adoption of new technology can be enhanced. The altering transport system, the planning and operational processes of new mobility services, the impacts of mobility services based on AVs, as well as the automation opportunities of planning and operational functions have been examined from the transportation engineering viewpoint. From the traveller side, travellers' expectations and information management processes, as well as the alteration in required human abilities have been studied. The customization of route evaluation has been revealed in order to support the decision-making process. Albeit experience is not available neither from operators nor from travellers as the technology is relatively new, relevant consequences can be drawn from stated preferences and existing mobility services. The research was conducted on a system and process-oriented point of view. My results can contribute to facilitate and prepare the alteration of the transport system.

2 Literature Review

An extensive scientific literature review was conducted to reveal the 'research gaps'. The main pillars of my research were determined according to the identified research areas.

<u>Areas of literature review:</u>

- overview of smart systems in order to model smart mobility (e.g. Mattoni et al., 2015),
- revealing factors influencing decision-making to model the decision-making processes (e.g. Chorus et al., 2013, Ettema and Timmermans, 2006, Tánczos and Török, 2012),
- revealing the impacts of AVs to model them in a system-oriented point of view (e.g. Fagnant and Kockelman, 2015, Gruel and Stanford, 2016, Tettamanti et al., 2016),
- overview of the transport system based on AVs to determine the types and features of future mobility services (e.g. Fagnant és Kockelman, 2014, Bansal et al., 2016, Winter et al., 2016),
- revealing travellers' expectations; considering the expectations in the development of planning and operational methods (e.g. Kockelman et al., 2016, Nordhoff et al., 2016),
- analysing planning and operational methods of existing novel mobility services; considering the results of the analysis in the planning of mobility services based on AVs (e.g. Horváth et al., 2006, Rayle et al., 2016, Wang et al., 2015),
- revealing customization settings of route planning applications and users' expectations to develop a route evaluation method (e.g. Duleba et al., 2012, Katona et al., 2017, Mátrai et al., 2016, Sivilevičius and Maskeliūnaitė, 2010).

The reviewed papers about the transport system based on AVs were categorized according to the main focus areas (Fig. 1). One paper can be assigned to several categories.

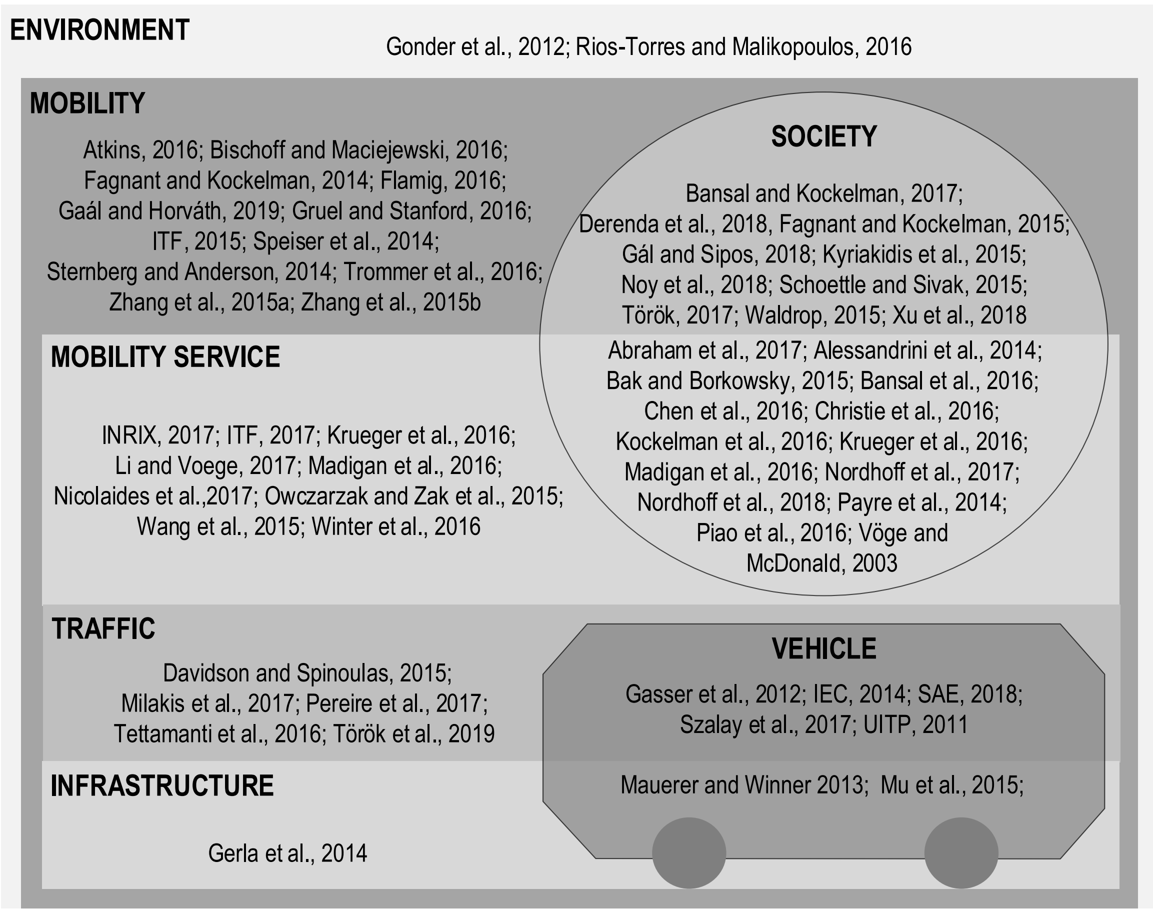


Fig. 1. Categorization of reviewed papers about the transport system based on AVs

Revealed research fields:

- lack of system-oriented research on innovative transport systems and mobility services,
- majority of existing research is technology based; less focus is placed on travellers' expectations and information management processes,
- researches about planning and operating mobility services based on AVs are at an early stage,
- researches deal primarily with the development of the vehicle and control technology; complex automation levels of mobility services have not been determined yet,
- the walking and cycling are neglected or considered in a simplistic way by the route planner application and even the number of customization settings is minor.

3 Research Objectives

The objectives of my research were **to model innovative passenger transport systems, as well as mobility and information services, moreover, to elaborate system planning principles, as well as analysing and evaluation methods**. As technology is developing continuously and rapidly, the elaboration of durable models was endeavoured. The research sub-tasks are linked to one another. The results of a sub-task were used in the elaboration of another sub-task. Tasks are the following:

1. Modelling the smart mobility system; revealing and analysing the characteristics of smart traveller's information management.
2. Integrating autonomous vehicles to the transport system and mobility services; revealing the impact fields considering the relationship between society, environment, and economy.
3. Elaborating the information system model for the planning and operation of the new mobility service based on AVs.
4. Determining complex automation levels for the road-based mobility services; evaluating the alteration in passenger handling functions; analysing the alteration in required human abilities.
5. Elaborating a customizable evaluation method for multimodal routes which provides more accurate results.

The research sub-tasks are summarized in Fig. 2. The arrows represent the main connections. Modelling smart mobility (Task 1) affects other sub-tasks, provides a framework for additional researches. Research tasks related to automation, primarily to mobility services based on AVs (Task 2-4) link to each other. The consequence of new mobility services that the mobility requires more awareness from the traveller, hence the elaboration of methods which assist travel planning is required (Task 5). The five theses were composed based on the results of the five research tasks.

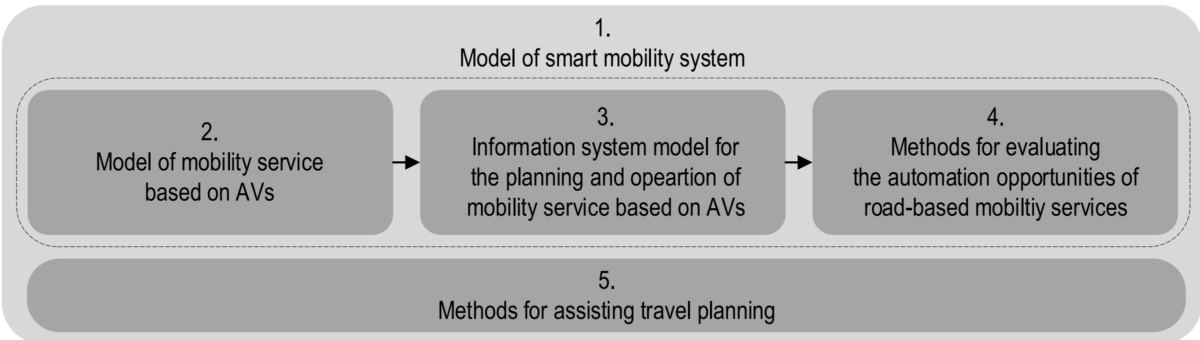


Fig. 2. Connections of research tasks

Hypotheses according to research tasks:

1. Smart traveller's decision-making process is to be supported and even replaced by machine because the information management of a machine is similar to the information management of a human.
2. Integrated mobility management is required for the application of AVs.
3. The expectations towards mobility service based on AVs are influenced by the travellers' personal characteristics. If these characteristics are considered in the planning of a mobility service, personalized service can be provided.
4. Road-based mobility services can be described and evaluated by automation levels. The required human abilities alter as the consequence of automation in mobility services.
5. The route choice preferences are firmly influenced by travellers' socio-demographic characteristics. The perceived and real travel time of a route can be determined by the application of a detailed network model and by the consideration of personal preferences.

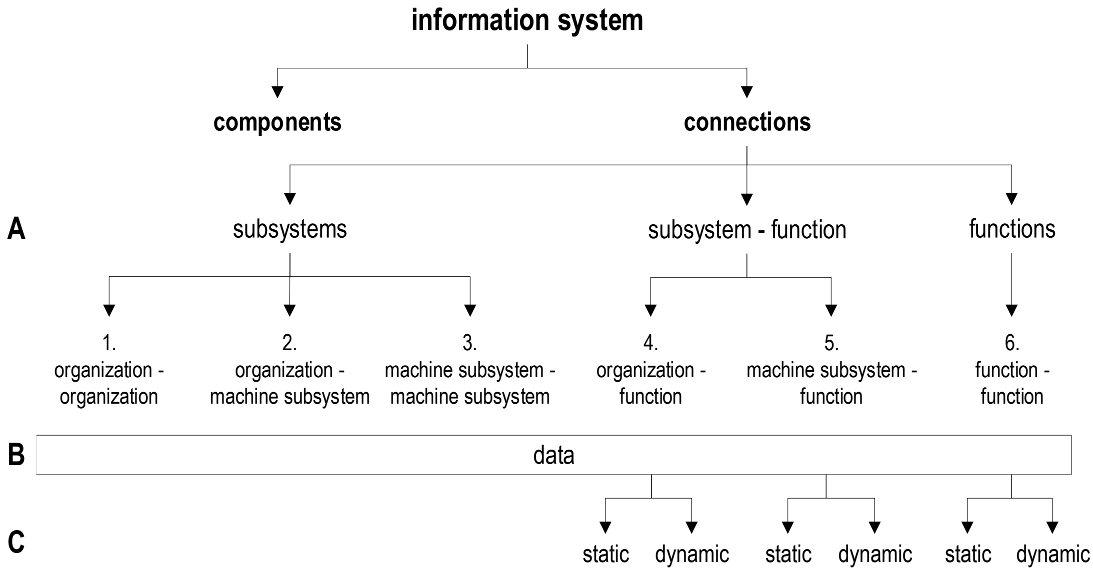
The researches were conducted on urban, road-based public passenger transport and on individual soft mobility forms. In addition, the focus was on innovative, shared, small capacity, AV-based mobility services and related information services. The following limitations were applied according to the research tasks:

1. The smart traveller was put in the focus when modelling the smart mobility
2. The road-based AVs were considered in the highest vehicle control automation level in the case of elaborating the transport system based on these vehicles.
3. The developments in vehicle and communication technologies were considered only to the extent to which they were needed to elaborate planning and operational methods and to reveal the impacts.
4. The functions were analysed by general development principles in the case of determining the automation levels. The technical details of a solution were neglected. The levels were introduced to road-based mobility services.
5. Sustainable transport modes were placed in the focus in the case of route evaluations; i.e. walking, cycling and public transport were considered.

4 Applied Methods

In line with the research objectives and tasks, several classic research methods were applied. I applied a special method for **analysing and modelling information systems** which reveals the structural and operational relationships in different resolutions (break-ups). The aspects and resolutions are summarized in Fig. 3. As subsystems may include humans and/or machines, various connections of organizations and machine subsystems can be investigated (Level A). Machine subsystems are connected in the most cases to human elements (e.g. traveller's smart device). As cooperation is realized by flowing data, the data groups, their properties, and the interrelations are to be revealed (Level B). In the case of the connections between functions, temporal features are also to be studied (Level C). The method was applied to model innovative systems. **Relational data modelling** was used for the elaboration of the database structure for the operation of mobility service based on AVs.

Transport systems and processes are rather complex. Complex systems can be compared using **multicriteria analysis** (Van der Laan et al., 1997). Alternatives are assessed according to several aspects with different weights. **Weighted Sum Model** (WSM) was applied to determine automation levels for road-based mobility service and **Kesselring-method** was applied to compare existing route planning applications.



A: connections B: data structure C: temporal features of operation

Fig. 3. Information systems analysing and modelling aspects

In order to draw the right conclusions on the expectations towards mobility services based on AVs and the route choice, preferences were collected by **questionnaire survey**. Conclusions can be drawn by revealing the connections between data originated from different sources. The data collected by questionnaire survey was processed by database queries. The **connections** between data groups were examined to determine the impact of each data group on each other. Both **deductive** and **inductive logic** were applied to draw the conclusions.

Application of graphs is the most common method to model the transport network (Ortúzar and Willumsen, 2011). I modelled the real passenger transport network and mobility services which can be used for route evaluation. Not only the attributes of a network element but the attributes of a travel were modelled based on the characteristics of the transport modes (e.g. speed). The basics of **graph theory** were used during modelling.

5 New Scientific Results

The new scientific results are summarized in Theses.

Thesis 1

Thesis 1 is based on Section 5 of the Dissertation.

I have defined the structural and operational model of the smart mobility system focusing on the information management of the traveller. I found, that the information management of a machine and a human are similar. The machine system can be developed according to the revealed attributes of human information management. Consequently, information management can be supported and even replaced by a properly adapted info-communication technology.

The smart city can be defined briefly as a system of systems, the aim of which is to integrate information technology with infrastructures, devices, humans, and organizations to solve social, economic and environmental issues. The smart mobility is a decisive sub-system of the smart city; it realizes physical relationships between other sub-systems. Smart mobility includes human knowledge, intelligence, and mechanism of decision-making. It is a cooperative application of advanced information and communication technologies in transport infrastructure, in vehicles, and in travellers. The aims of smart mobility systems are to assist humans (travellers, personnel), and decrease or replace (e.g. mobility based on AVs) human activities.

I have modelled the smart mobility system by revealing the inner structure and processes. The objectives, the system components (subsystems) and their connections were revealed to elaborate the **structural model**. I have elaborated the **functional model** by revealing the information management functions and required data groups**.**

The smart traveller is one of the smart mobility subsystems. I modelled the traveller's information management to reveal the decision-making process. With the knowledge on the decision-making process and required input data, information services can be developed to meet the travellers' needs at a high level. Identification of the data connections between smart traveller and functions enabled me to describe the information management process. The smart traveller term covers pedestrian, biker, passenger, and driver, emphasizing the multimodal travel chains. The information management is different in each role; some differences can be noticed in the information source, and in the movements or data input within the decision-making process. The **information management process** of a smart traveller is presented in Fig. 4.

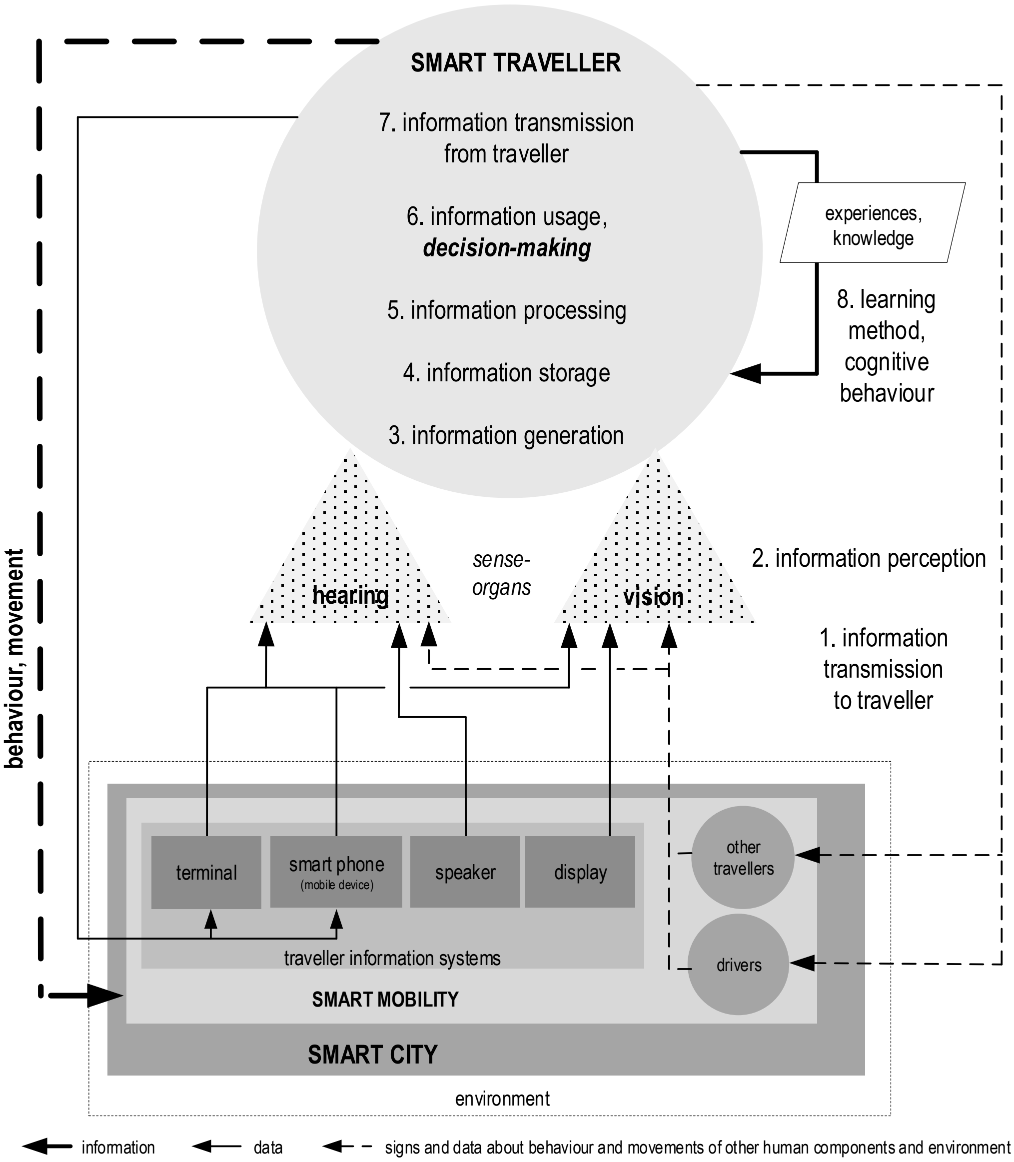


Fig. 4. Information management process of a smart traveller

The use of mobility services becomes more and more complex. However, the traveller's capability to store and process information is limited, and the failure rate is higher during a decision-making process. Consequently, machines are used to assist travellers during decision-making and to expand their cognitive capacity. In addition to 'simple' human and machine components, a new smart human component type appears whose decision-making is assisted by advanced information services.

Own publications related to the thesis: (Csiszár and Földes, 2015a), (Csiszár and Földes, 2015b)

Thesis 2

Thesis 2 is based on Section 6 of the Dissertation.

I have defined the types and the characteristics of the shared mobility service based on AVs. I have elaborated the structural and operational model of this service, as well as, I have revealed the impacts. The conclusion is that autonomy is a relative concept, coordination of several centres with different functions are required to plan, control and operate mobility services based on AVs.

Through the analysis of existing urban motorized transport modes and services, I described the alteration. Based on the literature review and situation analysis, I have identified the alteration in the 'mobility palette' (Fig. 5.). The envisioned future modes were depicted, in terms of the number of passengers per vehicle and flexibility. Flexibility is a complex indicator depending on several aspects (e.g. spatial accessibility, temporal availability).

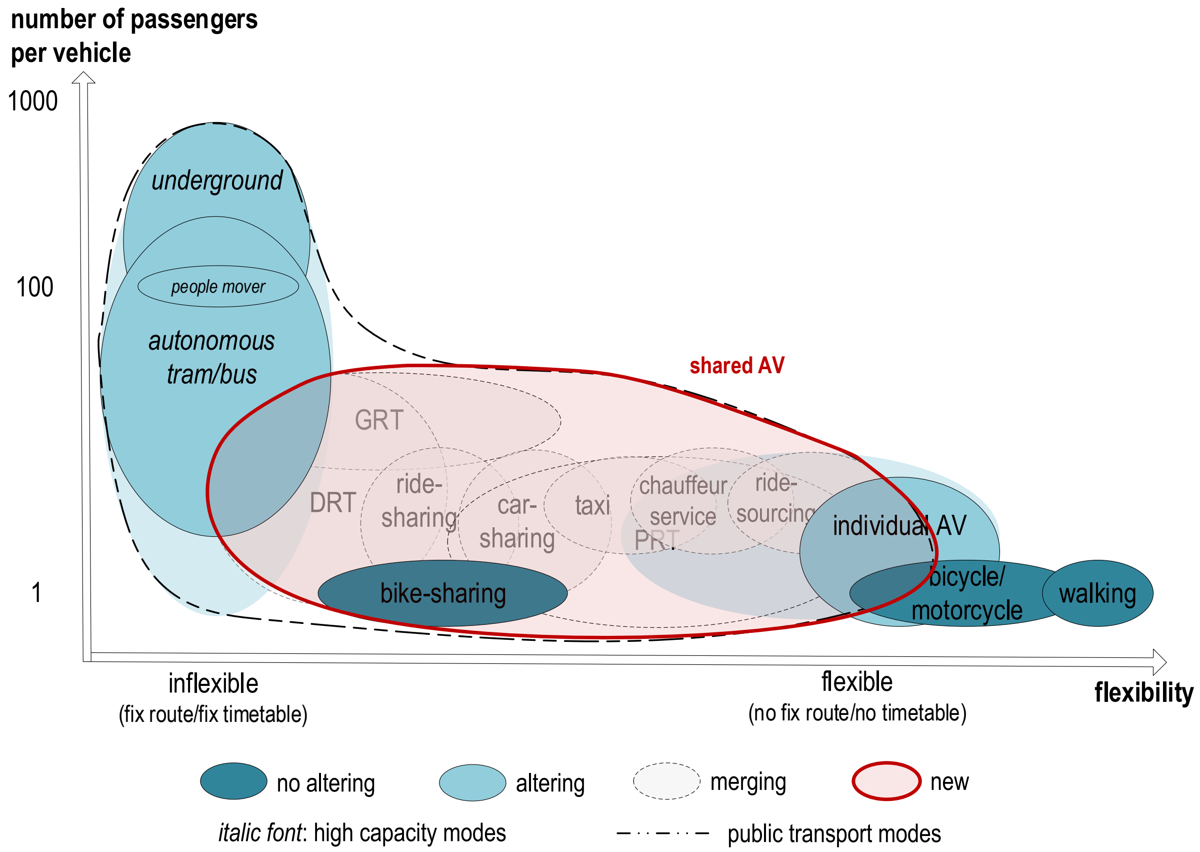


Fig. 5. Alteration in urban 'mobility palette'

The transitional transport modes and, even more, the majority of individual car use can be replaced by the new, shared, demand-driven mobility service based on small capacity autonomous road vehicles accessible only with advance ordering via a mobile application. Among others, a rather flexible door-to-door type and a slightly less flexible feeder type to a high capacity line were also distinguished. The feeder type may run on fix route and/or according to a fix timetable. As the capacity of the built infrastructure is limited, the travel demands can be served efficiently by shared and feeder mobility services.

The **structural model** of the mobility service based on AVs has been developed (Fig. 6). The major system components were thus identified. I introduced the **integrated mobility management centre** organizational unit with its defined tasks (e.g. management of operational data in an integrated database).

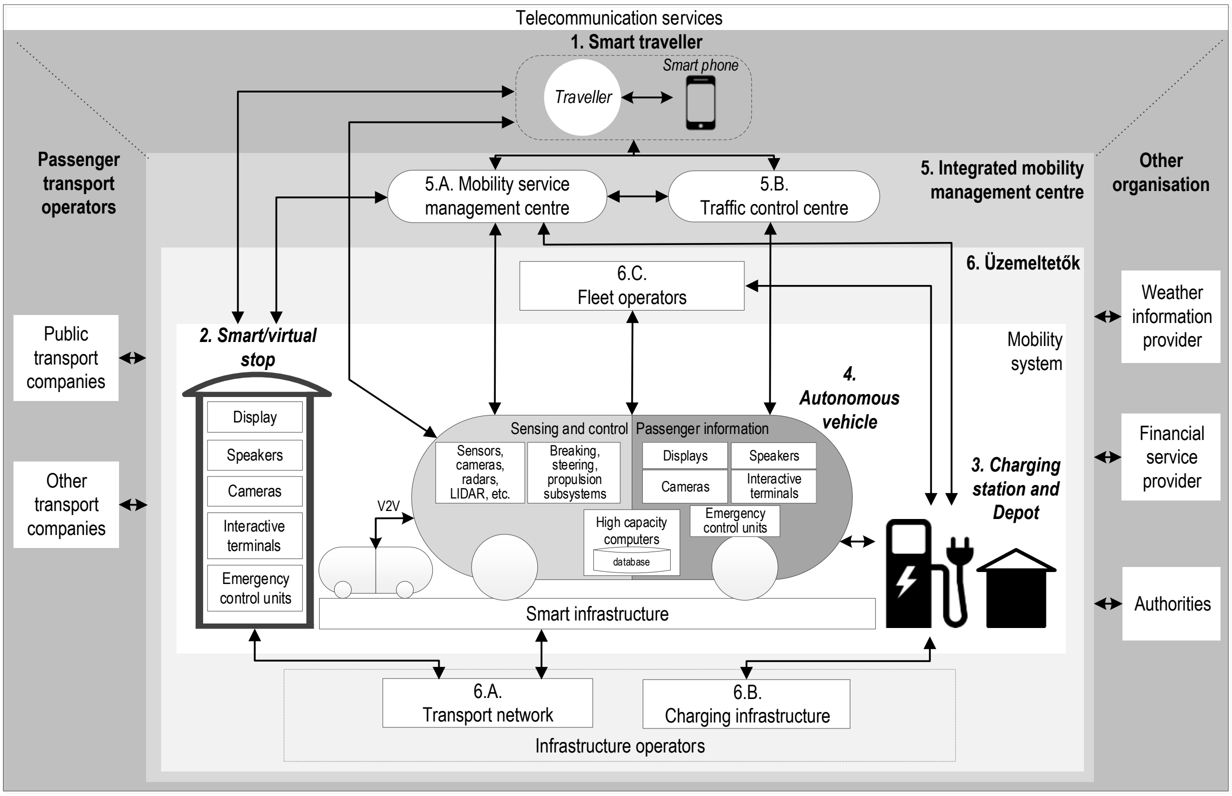


Fig. 6. Structural model of mobility service based on AV

The operational model of the mobility service based on AVs have, also, been defined. A large amount of real-time data is required to control and organize AVs. **The dynamism of planning functions increasingly approximates the dynamism of operational functions.** The time period of information management becomes significantly shorter, almost real-time.

Revealing the **impact fields,** I could estimate the qualitative indicators of the alterations. The impacts concern society (mostly passengers), mobility habits, traffic characteristic, management of infrastructure, and the environment of the transport system. I have developed a model to calculate the alteration in modal share. Stated preferences are used as input data by the model. With the application of the method, I found, that **the individual car use could be significantly reduced by the introduction of a flexible, shared, AV-based mobility service.**

Own publications related to the thesis: (Földes and Csiszár, 2016c), (Földes and Csiszár, 2016e), (Csiszár and Földes, 2017), (Szigeti et al., 2017), (Csiszár and Földes, 2018), (Földes and Csiszár, 2018b), (Földes and Csiszár, 2018c), (Csiszár et al., 2019a), (Csonka and Földes, 2019)

Thesis 3

Thesis 3 is based on Section 7 of the Dissertation.

The information system model has been defined for the traveller-based planning and operation of the new mobility service based on AVs. To define the model, I determined the input data groups resulted from travellers' preferences and I elaborated the data collection method.

The aspects that cause alteration in conventional service planning and operational methods are as follows:

- more complex system structure,
- the new and unknown technology,
- the dynamism of the data and
- the travellers' expectations towards more adaptive, sustainable and flexible service.

Travelers should perform existing tasks in a novel way or should solve new tasks as well (e.g. ordering, boarding/alighting, payment). The role of personnel can be reduced as a result of the introduction of mobility services based on AVs, and the driver's requirement can be ignored. New solutions are to be applied both in the operation (e.g. charging) and in the passenger handling (e.g. information provision). Functions with major alteration are the following:

- real-time demand-capacity assignment,
- vehicle run planning,
- customization of information services,
- travel information,
- vehicle charging.

I have elaborated the **information system model of planning** for such a mobility service. The developments of AVs are in an early stage. Considering the travellers' expectations is particularly important in that stage. Accordingly, I have developed a **data collection and process method** for analysing travellers' stated preferences. The revealed expectations were used as input data to the planning functions. I found that **travellers' socio-demographic and mobility habits influence the expectations towards the mobility service based on AVs.**

With the analysis of planning function, it was revealed that **functions directly affect the passengers depending on the basic service**, external input data from an additional organization are not required. Additionally, I found that **expectations do not influence the planning of supplementary operational activities** (e.g. charging infrastructure, maintenance planning).

The **information system model for the operation** of the mobility service has also been elaborated. I have defined the **relational data model of the integrated database** with the identification of entities, main attributes, and connections.

Own publications related to the thesis: (Csiszár and Földes, 2017), (Földes and Csiszár, 2018b), (Földes and Csiszár, 2018c), (Földes et al., 2018), (Csiszár et al., 2019a), (Földes and Csiszár, 2019)

Thesis 4

Thesis 4 is based on Section 8 of the Dissertation.

I have determined the complex automation levels for road-based mobility services. The control functions, service planning and management, as well as passenger-handling functions were considered. Moreover, I have elaborated assessment methods for the alteration of passenger handling functions and, also, for the alteration of required human abilities. I found that the required human cognitive capability, all in all, decreases significantly as the consequence of automation and machine support, whereas the requirements towards human abilities related to the smart phone use rise.

I have elaborated an **assessment method** for the determination of **complex automation levels** of current road-based mobility services. Sub-functions, functions and mobility services can be assessed. Four levels of automation were distinguished according to functions. Applying the method, the automation (development) level of a mobility service can be described in a general and simplified way using only one value (Table 1).

Table 1. Complex automation levels

no.	name	description	the entity which makes decisions and executes
1	no automation	All processes are executed by human (passenger, driver, and other personnel). The human has full responsibility, there is no direct machine support.	human
2	machine assistance	The human work/decision-making is supported by the machine. However, the role of a human is significant.	human aided by machine
3	partial automation	A significant part of the processes is executed by the machine. The personnel monitors the processes.	mostly machine with human confirmation
4	full automation	Processes are completely operated by machine. The personnel attends only as a supervisor.	machine

I have elaborated a **method for determining the significance of automation development**. Accordingly, the relevancy order of the developments can be determined.

The automation impacts the required human abilities. In order to determine the **aggregated ability alteration**, an **assessment method** has been developed. The method considers every sub-function for the entire travel. With the application of the method, I found, that **less human thinking is required as a consequence of machine support. Moreover, the human can be replaced in certain functions by machine** (e.g. route planning).

Own publications related to the thesis: (Földes and Csiszár, 2016b), (Csiszár and Földes, 2017), (Csiszár et al., 2019a), (Csiszár et al., 2019b), (Csiszár et al., 2019c)

Thesis 5

Thesis 5 is based on Section 9 of the Dissertation.

I have developed an evaluation method for multimodal routes. This method considers the walking phases in detail and evaluates network elements separately. The resistance value of an element provides the perceived travel time considering the physical parameters of the element and travellers' preferences. The method can be used to develop information services providing more accurate results.

The developed **route evaluation method** considers the physical parameters of a route, the characteristics of a mobility service and the travellers' individual preferences (Fig. 7).

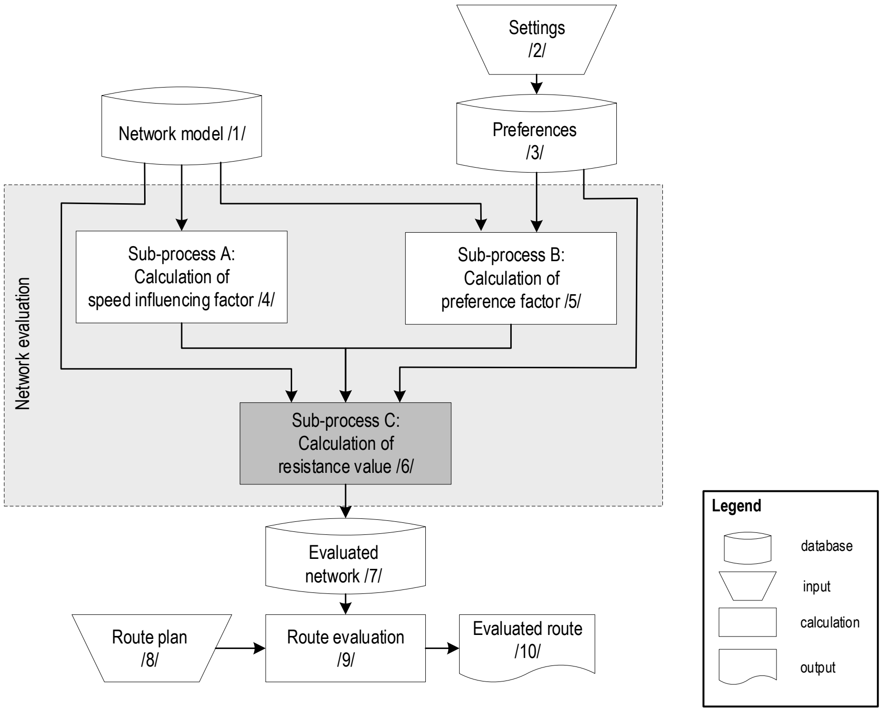


Fig. 7. Flowchart of route evaluation method

The result of the route evaluation is the **resistance value** of network elements which **provide the perceived travel time in the element**. Multimodal routes can be formed with a combination of network elements. If the resistance values of all nodes and edges of a route are known, the total resistance value for the route can be calculated. The method evaluates predefined routes. It provides a more realistic evaluation as considers the realistic parameters of the routes and individual preferences. So, travellers' decision-making can be directly supported.

I examined the current route planner applications in order to reveal customization settings. Accordingly, I have elaborated an **assessment method to determine the customization level of a route planner application**. I found that **customization settings are barely considered in most of the applications**.

A **questionnaire-based data collection and process method was developed to reveal the expectations towards information services and route choice preferences**. The route choice preferences are influenced by socio-demographic characteristics. **Travel groups** can be formed with a combination of socio-demographic characteristics. The information management characteristics and route choice preferences can be assigned to the travel groups. If the traveller's socio-demographic characteristics are known, the traveller can be classified into a group. The socio-demographic characteristics are enough to deduce the route evaluation preferences. Thus, personalized route evaluation can be provided only with a few customization settings. The socio-demographic characteristic should be set only in the first time (profile saving); hence, the route evaluation can be automatized. I applied the method for cycling in detail because the pre-estimation of routes has particular importance in the case of cycling.

I have developed a **multimodal**, graph-based **network model** to consider the physical parameters of a route accurately. The attributes of different transport modes and several mobility services are considered in the model. The required network elements for the mobility service based on AVs were also modelled.

Own publications related to the thesis: (Földes and Csiszár, 2015a), (Földes and Csiszár, 2015b), (Földes and Csiszár, 2016a), (Földes and Csiszár, 2016d), (Földes and Csiszár, 2018a)

6 Applicability of the Scientific Results

Summary of the academic significance, the practical benefits and the educational applicability of the research results are listed as follows.

Academic significance

The previous results of many years of research at the Department in the field of transport systems and information management were extended by me. I conducted researches on automation and innovative transport systems. At the same time, my aim was to contribute to the national and international publishing activity of the Faculty. Due to the increasing complexity of the research area and the constant alteration of technology, I attempted to elaborate durable models.

Practical benefits

The elaborated models on innovative transport systems and mobility services can serve as the basis for creating system specifications and plans. The information management model of smart traveller can be used to develop information services for decision-making support and to reveal traveller behaviour.

The defined mobility service types based on AVs provide a guideline to plan such services in the future. The identified functions and challenges are to be considered as the basis for the planning. The travellers' expectations revealed can be used to provide a traveller-based and personalized mobility service. The identified impact fields of the transport system based on AVs can be used to determine quantitative impact indicators.

The defined complex automation levels can be used to evaluate existing mobility services, to underpin developments and to prepare decisions. The relevancy order of the developments can be determined by the significance of them. The revealed alteration in human abilities can be applied to determine the requirements of software and hardware development and to prepare the traveller to the automation.

Based on the comparison of route planner applications, the customization level of an application can be defined to support and to specify a development. The method used for revealing the expectations towards information services is the base to develop applications to support decision-making. The route evaluation method and the detailed network model can be used to develop a route planner application.

Educational applicability

The success of an innovative system, i.e. the success of a mobility service based on AVs, depends on the users' satisfaction. The traveller has to be taught on the new technology, the use of a new service, the expected consequences and how to make conscious decisions. These require more and more efforts from education and dissemination (raising the awareness). Accordingly, my priority was to utilize the results of the innovative system in academic education. The research results were included in the updated curricula of the subjects taught at the Department both in Hungarian and in English (Transportation Information Systems I-II, Transport Informatics, and Passenger Transportation). The results were included in the lecture notes in Hungarian, titled 'Transportation Information Systems', and in the book in English, titled 'Innovative Transportation Systems'. I have presented my research results about 'future mobility' to a wider audience several times in order to raise public knowledge. E-learning course was developed about autonomous vehicles as well as lectures and vocational training were held for disadvantaged children with the use of my research results in the framework of EFOP projects.

7 Future Research

I am going to continue my research activities with similar commitment and intensity as so far and rely on the results achieved. I have several plans in several sub-areas raised by the literature and identified as research gaps. Basically, multimodal and integrated passenger transport approach is going to be followed.

My objective is to continue the development of evaluation methods for mobility services. The evaluation covers the service quality, flexibility, features of integrity and automation, as well as customization. I will continue the research on developing information services for supporting travellers' decision-making and also on developing mobility services based on AVs. My main objectives in these fields are:

Supporting travellers' decision-making:

- evaluating specific locations and territorial units according to the accessibility of mobility services; i.e. evaluating the accessibility of each service; a mobility service is only an intermediary tool,
- analysing the value of information and its alteration in time (ageing).

Mobility service based on AVs:

- revealing the application fields of AVs and planning mobility services (e.g. demand-driven passenger transport in micro-regions, urban freight transport, combined transport),
- developing planning methods (e.g. determining the required type and the number of the vehicle, locating-method for smart/virtual stop, elaborating tariff-system),
- developing operational methods (e.g. developing passenger-vehicle assignment and redistribution algorithms, elaborating big data methods for the information system, elaborating management methods that primarily increase safety),
- elaborating passenger handling methods (e.g. traveller-vehicle communication),
- determining quantitative impacts (e.g. alteration in vehicle number and length of travel, optimization of land use by the allocation of different transport functions in a differentiated way in space and in time,
- further analysis on travellers' expectations, utility and perceived quality:
    - revealing psychological and sociological effects,
    - analysing revealed-preferences,
    - calculating the individual utility of travel.

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