OPERATIONAL MODEL AND IMPACTS OF MOBILITY SERVICE BASED ON AUTONOMOUS VEHICLES

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Abstract: Emerging infocommunication and vehicle technologies, especially autonomous vehicles (AVs), imply a significant alteration in urban mobility. Shared, mostly demand-driven mobility services based on small-capacity AVs emerge. The research questions are, how to operate this new transportation system, and what impacts it has. We apply system and process-oriented analytical modeling method. Firstly, the alteration in urban transportation modes is revealed. Then, the mobility service types are identified and characterized. In order to facilitate their integration into the passenger transportation system, the structural model has been developed. The functions and the interrelations between the functions have been revealed to model the operation. Real-time data about current demand, vehicle location, and status significantly affects the operation. Finally, the impacts of this novel mobility service are estimated. The impacts concern the entire transportation system (e.g. shifting in modal share), environmental load, management of traffic and infrastructure as well as passenger habit. The quantitative correspondences are assessed by questionnaire survey applying stated preferences. The calculation method of modal shift has been elaborated. The results can be used as a base to organize and operate the mobility service.

Keywords: alteration in mobility, autonomous vehicle, impacts, operation, functions.

1. Introduction

The technical developments, especially the autonomous road vehicles (AVs) result alteration in mobility services. Shared mobility services based on small capacity AVs emerge, which is called STA - Shared Transportation based on AVs (Földes and Csiszár, 2018). Our aim was to model the operation and impacts of AVs focusing on STA. The research questions were:

- how is the service operated?
- what are the operational functions and how are they interrelated?
- what are the impacts?

The novelty of this work lies in the fact that researches deal primarily with the development of the vehicle and control technology as well as traffic modeling (Szalay *et al.,* 2017), while management of the entire passenger transportation including AVs requires a more complex approach. The results of this paper fill this niche; namely, the technological advancement is placed into a wider context in order to reveal correspondences which are to be tackled in the future. The results can be expeditiously used for development of future mobility systems.
The remainder of the paper is structured as follows. In Section 2, a brief review of the related works is provided. In Section 3, the alteration of the mobility system is described and then the most relevant features of the STA are summarized. The structural and operational model covering the operational functions and their connections are elaborated in Section 4. The impacts are summarized in Section 5; the expectations towards the impacts and the alteration in the modal share are detailed. The paper is completed by the concluding remarks, including further research directions.

2. Literature Review

Several scientific papers study the operational issues and the impacts of AVs. Mobility services based on AVs open new opportunities in terms of demand management. According to Lamotte *et al.,* (2017), implementing demand management strategies into reservation-based services would lead to benefits, such as reduced congestion costs. Kashani *et al.,* (2016) appointed that replacing conventional public transportation with demand responsive services in low demand areas can significantly increase the quality of mobility without any extra operational costs. On the one hand, AVs can be applied in rural areas with low population density as a door-to-door, flexible way of transport. On the other hand, AV-based feeder mobility service can connect high population density areas to public transport (Owczarzak and Zak, 2015). When determining system attributes, it is important to properly assess and forecast future demand towards the mobility system based on AVs. The key to this lies in the investigation of user preferences and expectations. Passenger attitudes were rather positive, especially for services implemented within a major facility (e.g. university) (Christie *et al.,* 2016). Bansal *et al.,* (2016) found that 41% of the respondents would use a shared AV weekly at a competitive price.
Besides survey data collection, novel methods were elaborated to evaluate reliable passenger demand data and to use them for planning purposes. Horváth (2016) developed an OD matrix estimation method to determine the number of departing and arriving passengers between given zones. Atasoy *et al.,* (2015) found, that significant benefit over static allocation of the vehicle can be achieved using dynamic allocation of the vehicles to different service types: taxi,

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shared-taxi, and mini-bus. Schofer *et al.,* (2003) developed a model that estimates the needed number of vehicles in the case of a demand responsive service. The correlation between the size of the service area and trip duration is positive whereas between population density and the size of the fleet is negative.

Benefits of AVs consist of safer roads, travel time reduction, possibilities for older or disabled people and teenagers to use cars, reduction of space required for parking vehicles, increase of efficiency of the transport network (Alessandrini *et al.,* 2015). Chen et al. (2016) found that each 80-mile range shared AV replaces 3.7 privately owned vehicles. However, they highlighted that the efficiency of AVs hinges on automatized recharging. Bischoff et al. (2016) revealed that a fleet of 100 000 AVs could replace the conventionally driven vehicle fleet in Berlin (Germany). Simulation results of Fagnant and Kockelman (2014) indicated that each shared AV replaces 11 private vehicles but generates up to 10% more travel distances. Gruel and Stanford (2016) considered a scenario supposing all vehicles in operation are shared. They found that the number of vehicles in the region reduces, the utilization of cars and thus the trips per AV per day increase. Overall, it can be expected that vehicle kilometers are going to increase.

We conclude from the literature review that all research and development activities should be derived using a system-oriented approach because of the complex and dynamic features of the passenger transportation. Operation of such services requires new information management methods; while several elements of operation of demand-responsive transportation can be adapted.

3. Alteration in Mobility Services

3.1. STA on Mobility 'Palette'

The AVs facilitate the alteration of travel modes. Future transportation modes and the alteration of existing ones are represented according to the number of passengers and flexibility in Fig. 1. The flexibility is a complex indicator depending on, for instance, temporal and spatial availability.

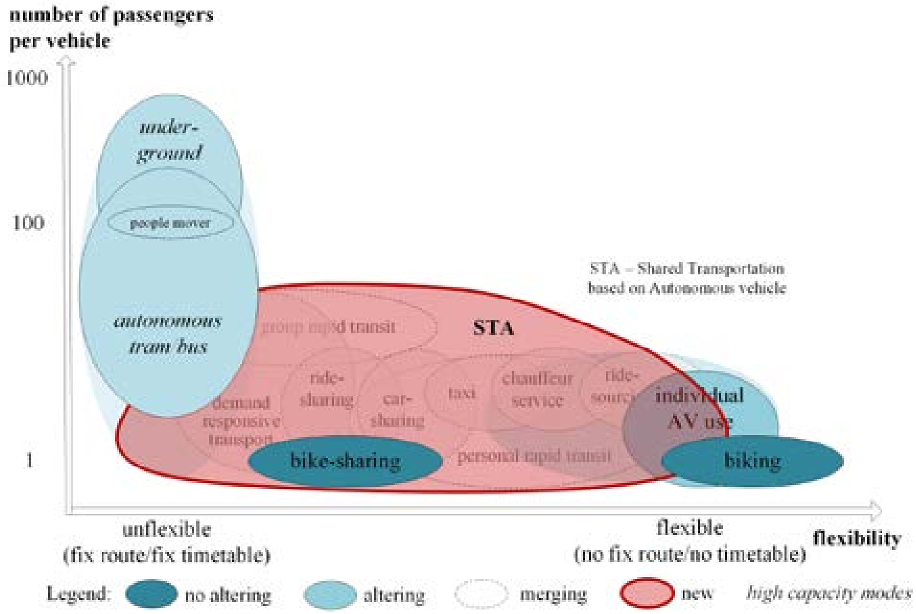

Fig. 1.
Alteration in Mobility Modes

Cycling and bike sharing are mostly unaltered. The individual motorized road transportation modes are used for the most flexible travel purposes. The other transitional modes are merging more-or-less into the new mode. This mode can serve a significant demand which was served by individual car formerly. It provides either direct service or feeder service to the high capacity public transportation lines. Since the large one-directional travel demand cannot be served by any other modes efficiently the arterial lines remain important.

3.2. STA Types

The revealed service types are the following (Földes and Csiszár, 2018):

- s_1 taxi: door-to-door service between any departure and arrival points without capacity sharing.
- s_2 shared taxi: door-to-door service between any departure and arrival points with capacity sharing.
- s_3 feeder pod: feeder service from any departure points in a zone to the stop of a high-capacity line; transfers are guaranteed by the semi-fixed timetable. The operation is symmetric in the opposite direction.
- s_4 fix route pod: mostly feeder service on fix route. The departure and arrival points are fix stops. It is operated according to the fix timetable, but additional departures may be inserted according to the current demand.

The characterization of types is summarized in Fig. 2. Car (max. 4 passengers) and pod (5-15 passengers) are distinguished as a vehicle type. The new mode is highly customized, demand-driven (or demand-responsive), and available via mobile application. Advance ordering is mandatory. A flexible tariff system is to be introduced in order to influence the demand and supply. The rates may depend on the type of service as well as the current demand and capacity. Designated meeting points and so-called smart stops are introduced where the demand is concentrated. Smart stops are equipped with electronic devices which enhance the passenger mental and physical comfort.

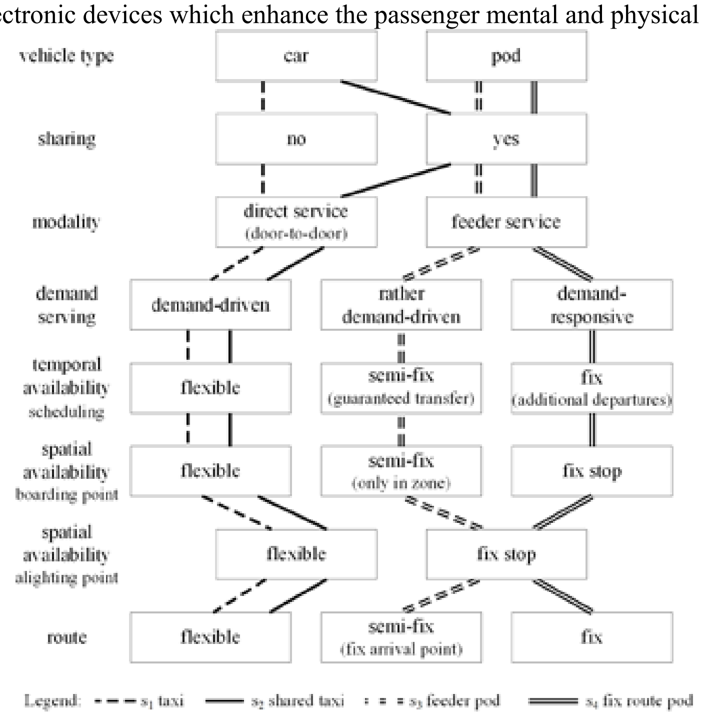

Fig. 2.
Characterization of STA Types

4. Operational Model

During modeling, we applied system engineering principles to envisage the system. Accordingly, both the structure as a framework of processes and the operation were modeled.

4.1. Structural Model

Several methodologies have been developed to address the system engineering issues, but they should be improved as the AVs are to be integrated into the mobility systems. We present the structural model in Fig. 3. The main components are represented by numbers.

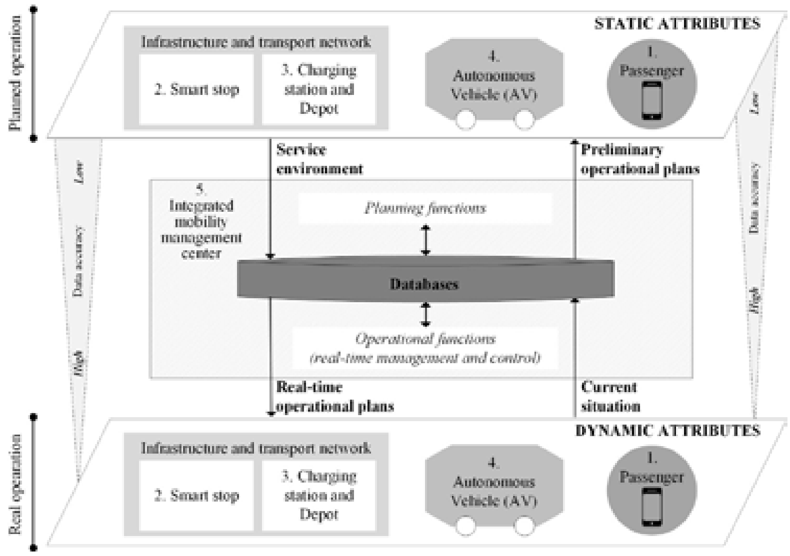

Fig. 3.
Structural Model

The dynamism is one the most significant challenge during the operation. The real-time data should be managed in an integrated manner; they are used not only for operational but for dynamic planning purposes as well. We conclude that the autonomy is a relative concept. Although the AVs are able to make decisions in traffic, the mobility system and services based on them require novel planning, operation, maintenance and traffic control methods.
The model is applicable during data modeling to identify the entities, their attributes, and the connections. The data map both the static and dynamic attributes which correspond to the planned and the real operation. The planned operation is a result of planning functions, whereas the real operation is monitored and influenced by operational functions. As the time of the transport task completion is approaching, the data accuracy is increasing because the current status of the components is getting known due to the monitoring of real-time orders. Accordingly, the dynamism of planning increasingly approximates the dynamism of the operation. The integrated database is primarily managed by the integrated mobility management center.

4.2. Operational Functions

We revealed and categorized the operational functions (Fig. 4.). The categories are represented by different colors. The functions provide data to each other; the output (result) of a function can be an input to another function. The direction of the data flow can be either one- or bi-directional which is represented by the arrows.

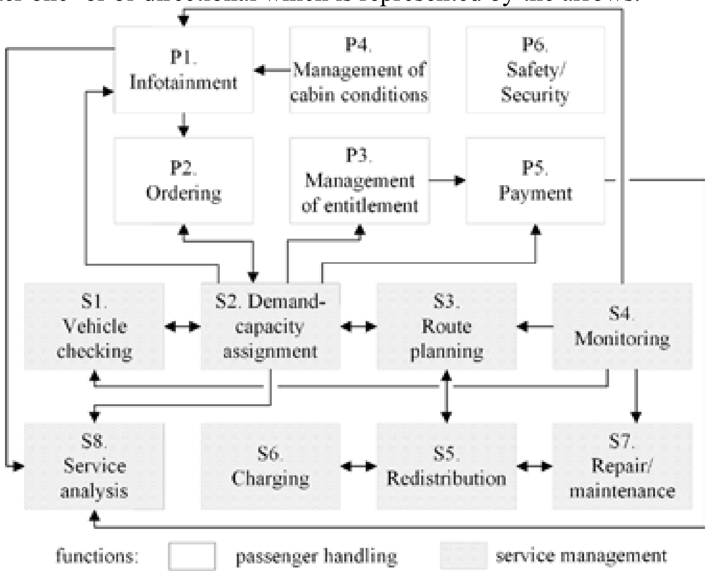

Fig. 4.
Operational Model

<u>Service management functions</u>
S1: the general attributes of the vehicles (e.g. status) are checked to select the serviceable ones. S2: current attributes of travelers and serviceable vehicles are compared (e.g. current direction, number of free seats) and the most appropriate vehicle is assigned to a trip. The ordering and demand-capacity assignment functions are interrelated by an 'iteration', especially in the case of shared services. Finally, information about the planned travel is provided to the passenger. S3: historical, current and forecasted data are used in the route planning function. Furthermore, the dynamic attributes of the route sections are considered. Not only the useful runs (passenger transportation) but the empty runs (approaching charging station or the next passenger) are determined. The demand-capacity assignment and redistribution depend on route planning. S4: the vehicles and the sections of runs are monitored during the travel. The automatic monitoring function provides data for the vehicle checking function (e.g. the failure of a vehicle). S5: completed vehicle runs are followed by redistribution. The vehicle is directed to either a charging point or a parking lot or sent to a zone where the potential demand is high. S6: the charging is automatized and managed by the management center. S7: the repair and maintenance are organized according to diagnostic data. S8: the mobility service is analyzed and evaluated using user feedback, travel or payment data.

<u>Passenger handling functions</u>
P1: the infotainment contains personalized, travel-related real-time information provision (before, during, after the travel) and entertainment functions. The information is mostly provided automatically to the personal or the on-board devices. P2: the ordering with wide-range of customized settings is mandatory, that is executed either in advance or just before the travel (ad-hoc). In this way, the capacity is utilized more efficiently. P3: the vehicles can be opened after an authentication (only the user can use the vehicle who is assigned to it). P4: the cabin condition is monitored and managed automatically or adjusted by the traveler. P5: after arriving at the destination, the price is calculated on the base of current travel, dynamic price factors, passenger discounts, etc. Several payment methods can be applied (e.g.

automatic payment based on location data). P6: the CCTV surveillance and automatized detection (advanced sensor technology) have an important role to prevent and manage safety-critical situations effectively.
Although several functions are automatized, the aid of the personnel is particularly needed in the case of special passenger groups (e.g. technically underdeveloped persons) and situations (e.g. emergency).

5. Impacts

5.1. General Impacts

The impacts of mobility services based on AVs are considerably wide. They concern society, mobility habits, traffic characteristic, management of infrastructure, and the environment of the transportation system. The most relevant qualitative impacts are summarized in Fig. 5.

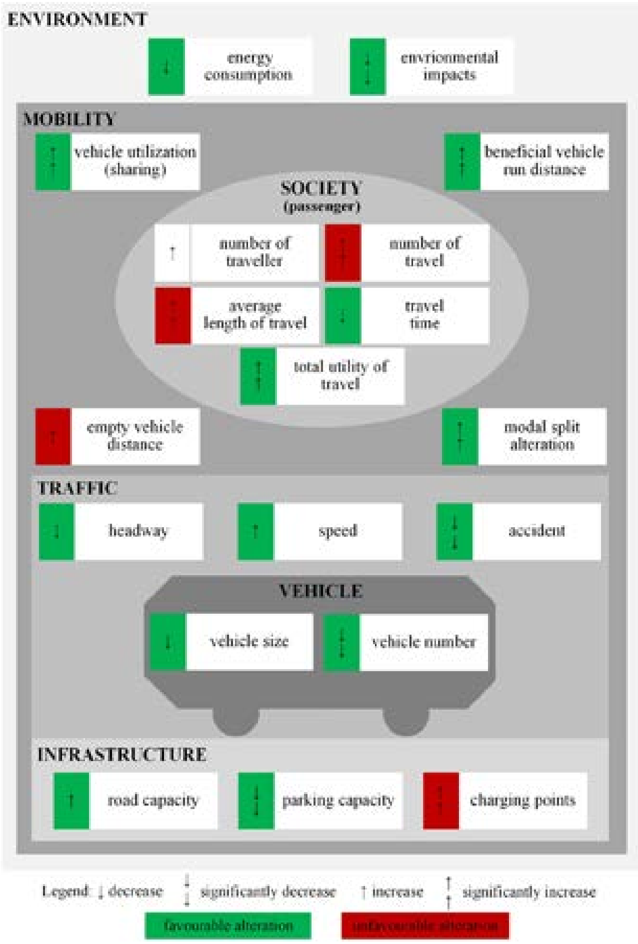

Fig. 5.
Impacts Model

The most striking challenge is to increase the user acceptance toward the AVs. The traffic flow parameters are getting worse at an early stage (Davidson and Spinoulas, 2015). However, with high AV penetration rate, advanced cruise control, and emerging V2V communication technologies, it is expected that traffic flow is getting more fluid. Headway between vehicles certainly falls, because AVs have practically zero reaction time. Significant improvements in traffic parameters (use of limited road capacity) can be achieved with the shared use of AVs as a feeder service. Due to useful (e.g. working during travel) and convenient travel, the travel time is not considered as a wasted time anymore, and thus travelers tend to travel longer distances and more frequently. Moreover, mobility service with more individual features is provided for the population segments who are unable to use private cars. Hence, during the planning STA services, the aim is to service the probably increasing travel demand by fewer vehicle. However, the individual car usage and ownership decrease as the consequence of shared AV service. But, due to vehicle redistribution processes, the length of empty runs rises. Nevertheless, replacement of own cars is rather challenging as people prefer the ownership. Since the required parking capacity corresponds to the number of vehicles and stationary traffic, similar cutdown is expected in this area. These phenomena fairly influence the urban land use. Moreover, energy consumption may be reduced as the consequence of adaptive driving. This also leads to less environmental impact.

5.2. User Expectations

The quantitative system parameters can be determined in several ways (e.g. simulation, analyzing the user expectations). We measured the user expectations by a questionnaire survey. The questions cover the respondents' socio-demographic characteristics, current mode use, willingness to shift to an STA service and expected impacts. The survey was performed via internet in Hungary in February 2018. 510 responses have been received. Most of the respondents were born after 1980, are male, high-educated and live in the capital city (Budapest).
The expectations towards the impacts of AVs are measured by rating questions. The respondents evaluated the impact-related statements using values. For instance: 'Do you agree that the total utility of the travel will increase (without driving the travel time can be spent with useful activities)?'. The 1-3 set of values according to the Likert-scale (Nemoto and Beglar, 2014) was introduced, where the meaning of the values is: 1: I do not agree, 2: I have doubt; 3: I agree. The statements were derived from the Fig. 5. Only the impacts which can be assessed without complex knowledge were considered. The average evaluation values represent the degree of the agreement. The impacts according to these values are presented in Fig. 6. The most agreed impact (energy consumption reduction) can be found on the bottom. The results are to be used to determine the focus areas to be improved. For instance, to make it obvious that the shared use of AVs results in fewer vehicle.

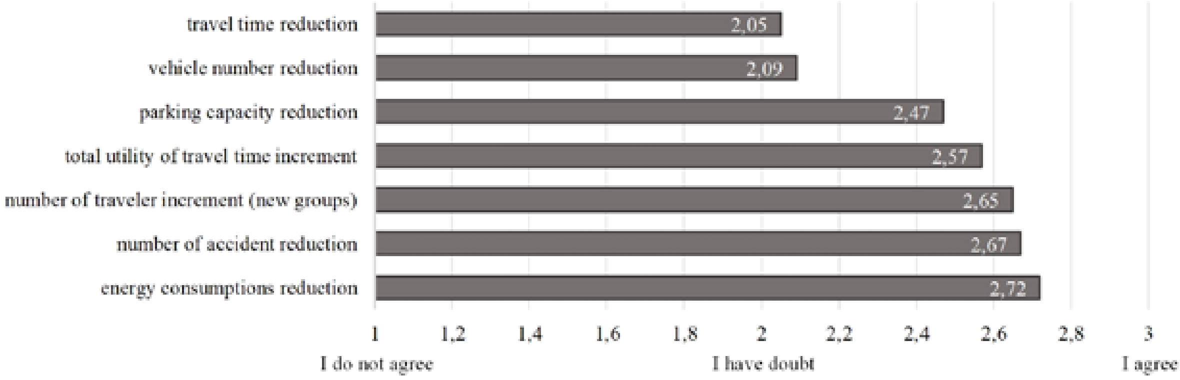

Fig. 6.
Agreement Towards Impacts

5.3. Quantitative Method for Impact Calculation - Alteration in Modal Share

In order to demonstrate the application opportunity of the survey results for determining quantitative impacts, the calculation method of modal share is elaborated and interpreted through an example. The modal share (the percentages of the use of transportation modes) can be calculated in several ways; however, the most appropriate way is to calculate it based on the covered travel distance [passenger-km]. The respondents (r_k) $k = 1..n$, the current transportation modes (m_i) $i = 1..4$ (*1*: walking, *2*: bike, *3*: car, *4*: public transportation) and the STA types (s_j) $j = 1..4$ are considered. The variables are as follows:

- ${}_k^i l$ travel distance of r_k with m_i [km],
- ${}_k^i f$ travel frequency of r_k with m_i in a given time interval (e.g. month) [number of travels/month],
- ${}_k^i a_j$ willingness to shift from m_i to s_j by r_k [%].

The values of the variables come from the survey. The current modal share of m_i is indicated by M_i (1).

$$M_i = \frac{{}^iL}{\sum_i {}^iL} \tag{1}$$

where ${}^iL$ is the current total travel distance with m_i in a given time interval (2). During the total distance calculations, the distances covered by all the respondents are considered.

$${}^iL = \sum_k {}_k^i l \cdot {}_k^i f \tag{2}$$

For the determination of future modal share the future total travel distances are calculated. ${}^iL_j^{'}$ indicates (3) the future total travel distance shifted from m_i mode to s_j type considering the respondent's willingness to shift $({}_k^i a_j)$.

$${}^iL_j^{'} = \sum_k {}_k^i l \cdot {}_k^i f \cdot {}_k^i a_j \cdot {}^ic \tag{3}$$

where ${}^ic$ is a correction factor. It is introduced to consider the proportion of the real (M_i^{real}) and the calculated (M_i) modal shares (4) in order to correct the sample if the survey is not representative. M_i^{real} is available from official data sources.

$$ {}^{i}c = \frac{M_i^{real}}{M_i} \tag{4} $$

${}^{i}L^{'}$ means the future total travel distance with m_i which is calculated by (5). It represents the remaining travel distance with m_i mode after the shifting to all the s_j types.

$$ {}^{i}L^{'} = {}^{i}L - \sum_{j} {}^{i}L_{j}^{'} \tag{5} $$

$L_j^{'}$ means the total future travel distance with s_j after shifting from all the current transportation modes. It is calculated by (6).

$$ L_j^{'} = \sum_{i} {}^{i}L_j^{'} \tag{6} $$

In this way, $M_i^{'}$ and $M_j^{'}$ indicates the future modal share of m_i and s_j according to (7) and (8).

$$ M_i^{'} = \frac{{}^{i}L^{'}}{\sum_{i} {}^{i}L^{'} + \sum_{j} L_j^{'}} \tag{7} $$

$$ M_j^{'} = \frac{L_j^{'}}{\sum_{i} {}^{i}L^{'} + \sum_{j} L_j^{'}} \tag{8} $$

In the case the current m_i mode is shifted to s_3 or s_4 types, the future travel chain contains a feeder distance and a public transportation distance if the length of travel is long enough. This feeder distance is indicated by l_j. The distance covered by the public transportation is calculated as ${}_{k}^{i}l - l_j$. Thus, the additional total travel distance (${}^{i}D^{'}_{j=3,4}$) with public transportation is calculated by (9).

$$ {}^{i}D^{'}_{j=3,4} = \sum_{k} ({}_{k}^{i}l - l_{j=3,4}) \cdot {}_{k}^{i}f \cdot {}_{k}^{i}a_{j=3,4} \cdot {}^{i}c \tag{9} $$

This additional public transportation distance is added to the future total travel distance with public transportation.
We applied the method to determine the expected modal shift in Budapest. As the 2/3 of the respondents are Budapest residents, a valid (but not representative) sample is available. We 'measured' the working, shopping and leisure motivated travels by the survey. The respondents chose the appropriate categories; the categories were transformed into values.

- ${}_{k}^{i}l$ <1 km: ${}_{k}^{i}l = 1$, 1-3 km: ${}_{k}^{i}l = 2$, 3-5 km: ${}_{k}^{i}l = 4$, 5-10 km: ${}_{k}^{i}l = 8$, >10 km: ${}_{k}^{i}l = 12$,
- ${}_{k}^{i}f$ everyday: ${}_{k}^{i}f = 20$, often in a week ${}_{k}^{i}f = 15$, sometimes in a week ${}_{k}^{i}f = 10$, sometimes in a month ${}_{k}^{i}f = 5$,
- ${}_{k}^{i}a_j$ every time ${}_{k}^{i}a_j = 1$, every second time ${}_{k}^{i}a_j = 0.5$, never ${}_{k}^{i}a_j = 0$.

As the public transportation network in Budapest is quite dense, $l_{j=3,4} = 2$ is considered.

The current and future modal shares are presented in Fig. 7. Only the willingness to shift to STA types were considered; other impacts (e.g. promotion of soft mobility modes) were neglected. However, relevant consequences about the tendencies can be drawn. Current car users' willingness to shift is the highest, as bikers' and pedestrians' willingness to shift are the lowest. According to the stated preferences, the individual car use can be significantly reduced by the introduction of flexible shared services (STA type s_1 and s_2). However, the promotion of soft mobility modes and the shared use of AVs as a feeder service are needed in order to avoid the significant increment of motorized road traffic.

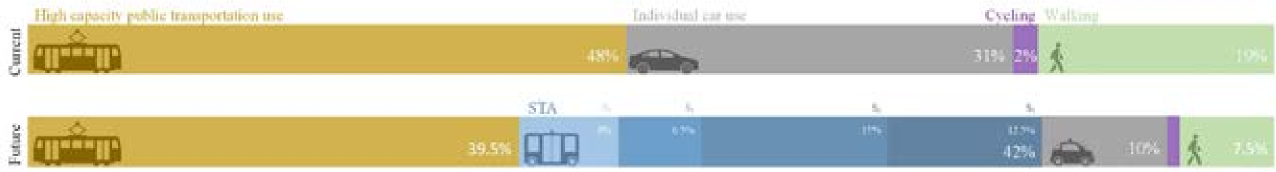

Fig. 7.
Current and Expected Future Modal Share in Budapest
Source: current modal share: Centre for Budapest Transport

6. Conclusion

The AVs and the intensifying passenger expectations require new mobility services. Operation of future passenger transportation system will be rather complex as all constituents have 'intelligence'. The main contributions are the structural, operational and impacts model of a transportation system based on AVs. The user expectations should be considered to enhance the acceptance of AVs.
Key findings include the following:

- although AVs operate in the traffic autonomously, their management requires advanced computer integrated information systems,
- several operational functions (e.g. vehicle-passenger assignment, entitlement checking) alter significantly as the vehicles are unmanned, shared and run according to the current demands,
- energy consumption reduction is expected; whereas travel time and vehicle number reduction are not expected from the spread of AVs by society,
- individual car use decreases with the application of shared AVs as the car users have high willingness to shift.

We faced, as a lesson learned, that only expectations can be measured as the AVs are still barely available. Our further research focuses on the elaboration of the operational functions and the elaboration of additional quantitative methods for impact assessment.

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