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# ALTERATION IN MODAL SHARE DUE TO AUTONOMOUS VEHICLE-BASED MOBILITY SERVICES

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## Abstract

Alteration in road-based mobility services in cities is expected due to introduction of autonomous vehicles (AVs). On-demand and shared services based on small capacity AVs emerge, which influence the modal share. The alteration has been estimated by simulation of scenarios; the travellers' willingness-to-shift to an AV-based mobility service has been considered as a random variable in studies. In our developed modal share estimation method, the travellers' current mobility habits and willingness-to-shift are considered. To determine the value of variables, a questionnaire survey was elaborated. The method was applied to calculate the modal shift in Budapest, Hungary. According to the results, willingness-to-shift is the highest among car users and the lowest among bikers. Based on the stated preferences, individual car use can be reduced by shared, on-demand, AV-based mobility services. Our method is applicable to determine the impacts of AVs.

*Keywords: autonomous vehicle, autonomous vehicle-based mobility service, modal share, modal shift, willingness-to-shift*

## 1 Introduction

The impacts generated by the introduction of autonomous vehicles (AVs) are the increased performance of the transport system, safer transport, individual travel options for people without driving license, increased energy efficiency, improved land use [1], [2]. The impacts can be estimated by qualitative or quantitative methods. In the case of quantitative methods, traffic simulations are used [3], [4], or the travellers' expectations are analysed [5], [6]. Some of the impacts are caused by vehicle characteristics (e.g. shortening head-up distance); moreover, some of the impacts can be influenced by mobility management (e.g. modal-shift).

The modal share (or modal split), i.e. the percentages of the use of transport modes, is expected to be changed. Modal share alteration is analysed by the introduction of scenarios in current studies [3], [7]; the rate of individual car use is compared. However, scenarios are based on estimations; traveller expectations and willingness-to-shift are considered indirectly without measuring them.

The research question is how the alteration in modal share could be estimated based on the travellers' mobility habits and willingness-to-shift. Questionnaire survey-based data collection and analysis methods were elaborated. The AV-based mobility service types were determined according to our previous researches and the literature. The elaborated estimation method could be used for traffic modelling and estimating other impacts (e.g. alteration in land use).

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The paper is structured as follows: the results of the literature are reviewed in Section 2. The alteration in mobility services is summarized in Section 3. The elaboration method is detailed in Section 4. Section 5 presents its application. The paper is completed by the concluding remarks, including future research directions.

## 2 Literature review

The modal share can be calculated in several ways; however, the most proper way is to calculate it based on the covered travel distance. Studies analysing the alteration in modal share can be grouped: based on data estimated by traffic modelling or based on user expectations. The rate of AVs in the whole fleet was expected at 7-60 % in 2050 by transport experts [3]. Scenarios were compered in small-town Brunswick, too [7]. Individual and shared AV use were considered. The shared AVs replace only current car use; however, its modal share is low (2-3 %). The reason for the low value may be that the current modal share of public transport (PT) is low; thus, the modal share of cycling is high. Simulating the alteration in Singapore [8], it was expected that a shared AV-based mobility service could replace 10 % of the current feeder bus services. However, only the alteration in PT fleet was modelled, the willingness-to-shift from car use was neglected.
The willingness-to-shift is influenced by the expected gains. In terms of travel time, travellers consider AV-based mobility services less attractive, which can be characterized as a ride-sharing service, than services which can be characterized as a car-sharing service [9]. Similar to our research objective, the model share alteration was examined in [10]. However, in that research, everybody shifts from individual car use to AV-based taxi or shared taxi service. The willingness-to-shift was estimated for travel groups formed according to census data instead of individuals. It was assumed that AV-based taxi service is used by current car users without PT pass. Walking and high-capacity PT use remain a significant transport mode. The influence of travellers' socio-demographic characteristics on the use of AV-based services in Paris was examined [11]. Only AV-based car-sharing service was considered, the travellers' willingness-to-shift was calculated according to group characteristics. The model share of AV-based mobility service was estimated at 3.8-5.3 %; the shift from individual car use is typical; the modal share of PT increases as feeder AV-based services are used. The willingness-to-shift to shared AV-based service was estimated to Munich, too [12]. Only the shift from individual car use was considered; the modal share of other modes was deemed to be invariable. The result showed that the modal share of shared AVs is 5-13 %.
We conclude that current studies consider the willingness-to-shift at a superficial level. Assumptions are used regarding travel groups instead of revealing the individuals' willingness. Current studies focus mostly on the alteration in car use.

## 3 Alteration in mobility services

The AV-based mobility services could replace individual car use and the use of 'transitional' transport modes, such as car-sharing, taxi. The characteristics of transitional modes take place between the characteristics of the individual car and PT. The new AV-based mobility service provides mostly on-demand, shared, informatics-based service in which pre-ordering via mobile application is mandatory. A small capacity autonomous car (max 4 passengers) and the so-called pod (5-15 passengers) are considered. The service types are the following:

- taxi: door-to-door service between any departure and arrival points without sharing.
- shared taxi: like the taxi service type but with sharing.
- feeder pod: feeder service from any departure points in a zone to the stop of a high capacity line.
- fixed route pod: mostly feeder service on fix route with fix stops.

It is operated according to a timetable, but additional departures may be inserted according to demand. [13]
Since large one-directional travel demands can be served efficiently by high-capacity, arterial PT lines (e.g. subway), their role remains significant. Moreover, the automation of PT vehicles is also expected. The role of soft mobility forms, such as walking, cycling, using micromobility forms, remains essential. Transport modes in the future are as follows (i) individual modes: non-motorized (walking, bicycle), motorized (individual car, motorcycle, micromobility); (ii) PT: small capacity (non-motorized: bike-sharing; motorized: shared AV, shared micromobility), high capacity (autonomous - e.g. bus, automated - e.g. subway).

# 4 Methods: estimation of modal share alteration

## 4.1 Questionnaire survey

The stated preferences about not known or barely known facts can be collected by a questionnaire survey; the respondents' opinions about an imagined situation are measured. The risk of measuring stated preferences is high as the respondent may act in a different way in fact. As AV-based services barely exist, we conducted a survey measuring the stated preferences about the willingness-to-shift. The questions were assigned to the following groups:

- socio-demographic characteristics for filtering, for correlation analyses;
- current mobility habits for the calculation of current modal share;
- using AV-based mobility services for the calculation of future modal share.

The structure of the questionnaire is presented in Fig. 1. One multiple-choice question (signed by box) describes one characteristic of a person or mobility habits. Different values are assigned to one character as a variable according to the answers. Sub-questions are used for different motivations, such as working, shopping, recreational (signed by dark blue). The respondents provide data about mobility habits according to motivations:

II.1 frequently used transport mode. Options: cycling, car use (as a driver or as a passenger), PT use, combined transport use (individual car + PT).
II.2 covered distance. Options: <1 km, 1-3 km, 3-5 km, 5-10 km, >10 km.
II.3 frequency of traveling. Options: daily (5-6 times/week), several times in a week (3-4 times/week), weekly (1-2 times/week), rarely.

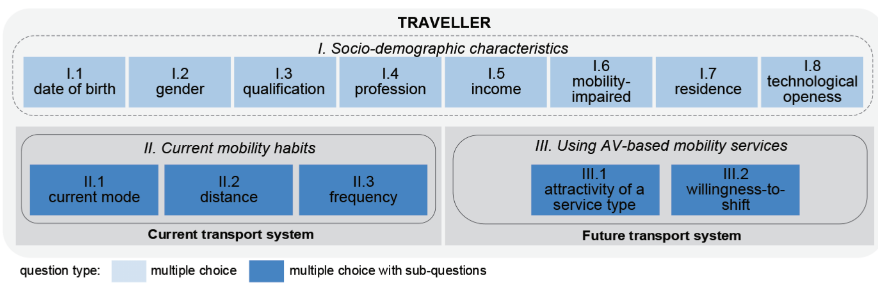


**Figure 1** Structure of the questionnaire

As AV-based mobility services have not been operated in Hungary yet, the survey contains a description of the service types. The respondents provide data regarding the use of AV-based mobility services according to motivations: (III.1) preferred service type instead of current transport mode; (III.2) frequency of willingness-to-shift to AV-based service types - options: never, every second time, every time.

## 4.2 Calculation method

The used indexes are k respondent k∈N, i current transport mode i=1..4 (1: walking, 2: cycling, 3: individual car use, 4: PT use), j AV-based mobility service type: j=1..4 (1: taxi, 2: shared taxi, 3: feeder pod, 4: fixed route pod), m motivation m=1..3 (1: working, 2: shopping, 3: recreational).
The following variables can be determined from the survey. The respondents chose the appropriate options; the options were transformed into values, respectively. The set of values may alter according to the characteristics of the application field. The listed values are typical for Hungarian urban traveling.

${}_k^i l^m$ - travel distance of k respondent with i mode according to m motivation [km]. Options: ‹1 km: 1, 1-3 km: 2, 3-5 km, 5-10 km: 8, › 10 km: 12.
${}_k^i f^m$ - travel frequency of k respondent with i mode according to m motivation [travels/month]. Options: daily: 20, several times: 15, weekly: 10, rarely: 5.
${}_k^i a_j^m$ - willingness-to-shift of k respondent from i mode to j type according to m motivation [%]. Options: every time: 1, every second time: 0.5, never: 0.

Step 1: current modal share: The current modal share is calculated based on the survey. ${}^iM$ signs the current modal share of i transport mode, Eq. (1).

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

${}^iL$ signs the total travel distance with i mode [km], Eq. (2). The distances of each respondent and each motivation are considered. The modal share can be calculated according to motivations (${}^iM^m$); the summarization according to motivation is not needed in Eq. (2).

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

Step 2: future modal share: ${}^iM^*$ signs the future modal share of i mode, Eq. (3), and $M^*_j$ signs the future modal share of j AV-based service type, Eq. (4).

$$ {}^iM^* = \frac{{}^iL^*}{\sum_i {}^iL^* + \sum_j L_j^*} \tag{3} $$

$$ M_j^* = \frac{L_j^*}{\sum_i {}^iL^* + \sum_j L_j^*} \tag{4} $$

${}^iL^*$ signs the total future travel distance with i mode, Eq. (5). It represents the remaining travel distance with i mode after the shifting to all the j types.

$$ {}^iL^* = {}^iL - \sum_j {}^iL_j^* \tag{5} $$

$L^*_j$ signs the total future travel distance with j AV-based service type, Eq. (6).

$$ L_j^* = \sum_i {}^iL_j^* \tag{6} $$

${}^iL^*_j$ summarizes the total future travel distance with j type instead of i current mode according to m motivation, Eq. (7).

$$ {}^{i}L^{*}_{j} = \sum_{m}\sum_{k} {}_{k}^{i}l^{m} \cdot {}_{k}^{i}f^{m} \cdot {}_{k}^{i}a^{m}_{j} \cdot {}^{i}c \tag{7} $$

${}^{i}c$ is a correction factor describing the proportion of the ${}^{i}M_{real}$ real and the ${}^{i}M$ calculated modal shares, Eq. (8). Its application is needed if the survey is not representative for the real modal share to manage the under- or overrepresentation of the modes. If the real modal share is available according to motivations, the ${}^{i}c^{m}$ correction factor according to motivation can be involved in Eq. (7).

$$ {}^{i}c = \frac{{}^{i}M_{real}}{{}^{i}M} \tag{8} $$

If the current i mode is shifted to feeder pod (j = 3) or fixed route pod (j = 4), the travel chain contains a feeder distance with a shared AV and a PT distance with a high capacity vehicle if the length of travel is long enough. The feeder distance is indicated by $l_j$. Its value is constant in the whole study area and depends on the area. The distance covered by PT is calculated as ${}_{k}^{i}l^{m}$ - $l_j$. Thus, the additional total future travel distance with PT (${}^{i}L^{*}_{j=3,4}$) is calculated by Eq. (9). This additional PT distance is added to the future total travel distance with PT (${}^{i}L^{*}$).

$$ {}^{i}L^{*}_{j=3,4} = \sum_{m}\sum_{k} ({}_{k}^{i}l^{m} - l_{j=3,4}) \cdot {}_{k}^{i}f^{m} \cdot {}_{k}^{i}a^{m}_{j=3,4} \cdot {}^{i}c \tag{9} $$

The modal share can be calculated for different m motivations; in these cases, summarization according to m motivation is not needed in Eq. (2), (7) and (9).
The limitation of the method is that only the willingness-to-shift from current mode to AV-based service type is considered. Other impacts (e.g. promotion of cycling) are neglected. In the case of combined transport, the travel distance is divided by car and PT use in a proportion of fifty-fifty. Moreover, the feeder distance $l_j$ is a constant value independently of the real network and the current distance covered by car use. However, even with the limitations, tendencies can be determined.

## 5 Case study

The method was applied to estimate the modal shift, the alteration in the use of modes, in Budapest, Hungary. An online survey was conducted in February 2018. 510 responses have been received. Statistical or random sampling could not have been executed; thus, the sample is not representative. However, relevant consequences can be drawn as the number of respondents is relatively high. The question regarding the residence filtering the citizens of Budapest was used.
The latest reliable official distance-based modal share data from 2017 provided by Centre for Budapest Transport (BKK) were considered. As we conducted the survey at the beginning of 2018, the respondents considered mostly rides travelled in 2017. Official modal share data are 11 % walking, 2 % cycling, 40 % car use, 47 % PT use. As the modal share data according to motivations were not available as reference data, the surveyed data were summarized according to motivations.
Step 1, current modal share: according to 304 responses from Budapest, the total travel distances in km are walking: 2605, cycling: 3850, individual car use: 20 205, PT use: 42 845. Additionally, the calculated current modal share in percentage [ %] are walking: 4, cycling: 5.5, car use: 29, PT use: 61.5.
Step 2, future modal share: as the official and the calculated modal share are not the same, the application of ${}^{i}c$ was needed: walking: 2.93, cycling: 0.36, car use: 1.38, PT use: 0.76. Furthermore, $l_{j=3,4}$ = 2 was considered; we assumed that 2 km feeder distance is adequate considering the dense PT network operating in Budapest. Table 1 presents the alteration in travel distance according to modes. What percentage of traveled kilometers is covered by

the current mode or by the AV-based service types, as well as, what is the increment in the modal share of PT as the consequence of the use of feeder types? (Cells regarding the not considered modal shift between current transport modes are empty.) The future modal share is depicted in Fig. 2 presenting the official modal share as a reference.

**Table 1** Alteration in travel distance according to transport modes [ %]

| | | **Transport mode (i)** | | | | **AV-based service type (j)** | | | | **i** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **walking** | **cycling** | **car use** | **PT use** | **taxi** | **shared taxi** | **feeder pod** | **fixed route pod** | **PT use incre-ment** |
| i | modes | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 4 |
| 1 | walking | 39 | - | - | - | 9 | 19 | 9 | 14 | 10 |
| 2 | cycling | - | 59 | - | - | 7 | 6 | 4 | 6.5 | 17.5 |
| 3 | car use | - | - | 31 | - | 22 | 19 | 4 | 4.5 | 19.5 |
| 4 | PT use | - | - | - | 43 | 7 | 11.5 | 7 | 7.5 | 24 |

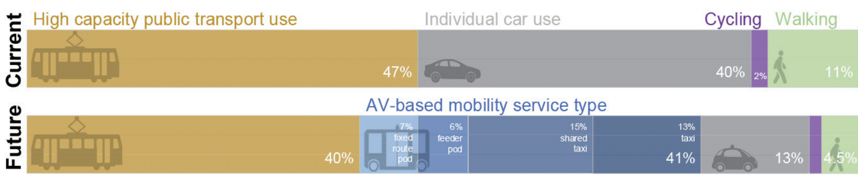


**Figure 2** Alteration in modal share (source of current modal share: BKK, 2017)

The individual car use can be significantly reduced by the introduction of flexible AV-based service types; similar consequences were drawn in [10]. Current car users' willingness to shift is the highest; its modal share is reduced from 40 % to 13 %; only 31 % of the current travel distance covered by car use remains. The travellers‘ willingness-to-shift covering big distances is significant as the increment of PT use is significant in all cases. However, as a constant feeder distance was considered, the percentage of feeder types is low; thus, the increment in PT is high. The willingness-to-shift from walking is popular both in short and long travels as the percentage of shared taxi and the increment of PT use are high. Bikers' willingness-to-shift is the lowest; the willingness to use feeder service types is also high in the case of long travels. The modal share of traditional PT is reduced, but if AV-based feeder service types are considered as PT, as they have similar characteristics as a traditional public bus service, the modal share of PT increases significantly. Small capacity bus lines are expected to be replaced by AV-based feeder services.

## 6 Conclusion

The alteration in modal share is expected after the introduction of AV-based mobility services. The main contribution of our research is the modal share estimation method considering the travellers' current mobility habits and willingness-to-shift. The method was applied in Budapest, Hungary, as a case study. We found that the current individual car users' willingness-to-shift is high. Individual car use can be reduced from 40 % to 13 % with the introduction of flexible AV-based service types, such as taxi or shared taxi. The willingness-to-shift is the lowest among bikers and PT users. However, these travellers are also willing to shift in the case of long travel; furthermore, less flexible AV-based feeder service types, such as feeder pod or fixed route pod, are rather popular. The method could be improved by removing limitations (e.g. use of different feeder distances), or with the application of specific values instead of categories. The research potential in the field examined in this paper is significant; our future research focuses on removing limitations and elaboration of additional estimation methods regarding impacts of AVs considering more user expectations (e.g. alteration in land use).

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