**Citation:**

**Introducing Autonomous Buses into Street Functional Classification Systems: An Exploratory Spatial Approach**

**Abstract**

The current research focuses on incorporating Autonomous Buses (ABs) in the street functional classification system. Specifically, we propose the creation of a new street type that will be strictly devoted to pedestrians, cyclists, ABs and micromobility modes (i.e. E-scooters), through a data-driven approach. The proposed method consists of five steps and takes into consideration various criteria referring both to urban (e.g. population density, school facilities, public spaces, commercial sites) and transport environment (e.g. roadway width, slopes). It is carried out by using GIS tools. The study area of the research is the city of Kallithea, a densely populated suburb in the southern part of Athens. The suggested planning approach is expected to shape favourable conditions for improving public transport efficiency and visibility by gradually incorporating low-speed, electric, pod-like ABs in a car-dominated system and providing them with a test-bed that will prepare them for their expansion to highway environments, where they would really make a difference in the long term. This is something that adds to the bigger picture of sustainable and socially inclusive transport provision even if route planning implementation is a challenging issue, since ABs should be integrated in the transport network, along with pedestrians and cyclists. The development of a method which introduces ABs in the urban transport system is in line with the emerging Mobility as a Service (MaaS) concept, and it also contributes considerably to the shift from conventional to smart cities.

**Keywords:** Autonomous Bus; Autonomous Public Transport Vehicles (APTVs); Future Public Transport; Street Classification; GIS
1. Introduction

Car-dependent cities suffer from mobility inequalities, increase in average travel distances, inadequate public transport services, inaccessible public spaces, urban sprawl, intense traffic congestion, road accidents and severances to the urban fabric (Dameri, 2017; Knowles et al., 2020; Mendez et al., 2017). In addition, they are considered as places which cannot sustain an acceptable mobility level for all and a sufficient quality of life (Cervero et al., 2017). Addressing these problems requires the adoption of an effective and forward-thinking urban planning vision that embraces multimodality and enhances the role of public transport in the mobility provision paradigm. A new city development model that has first emerged in the late 1990’s (Neirotti et al., 2014) which tries to utilise the potential of technological progress is called the “smart city” (Garau et al., 2016). Smart city, according to Nikitas et al. (2020), is a city with the ability to embrace an integrated brand of autonomous, connected, shared, digital and cloud-based technologies in its strategic decision-making and operations as a means of becoming more sustainable, creative, informed, cost-efficient and people-focused. In other words, a smart city uses AI-enabled innovations to improve the wellbeing and productivity its people (Yigitcanlar et al., 2020).

As transport constitutes a critical function for urban areas, the smart city model highlights the need for transitioning to an integrated, Information and Communications Technology (ICT)-based, clean mobility paradigm (Battarra et al., 2018; Vanolo, 2014). Smart mobility refers to moving people and goods through a personalized ‘service’ available ‘on demand’, with individuals having instant access to a seamless system of clean, green, efficient and flexible transport that maximises among others, and importantly for the present work, the potential of connected and autonomous public transport (Dochezry et al., 2018; Nikitas et al., 2020). One of the genuinely holistic transport interventions that exemplifies this paradigm is the Mobility as a Service (MaaS) notion, which is an innovative transport concept that combines a range of transport modes and services to provide a user-oriented door-to-door travel service via a single interface (Alyavina et al., 2020, Jittrapirom et al., 2018; Kamargianni et al., 2016; Sochor et al., 2018; Wong et al., 2020).

Along with smart mobility, there is the well-known concept of ‘sustainable mobility’ (Banister, 2008) which is gradually gaining traction against conventional mobility approaches. A crucial pillar of this concept is public transport (Vlastos, 2007) since it can play a critical role in reducing traffic congestion, fuel consumption, and carbon emissions in cities by being able to replace longer car trips for which active transport modes would not be applicable (Chong et al., 2011).

Up to now, traditional public transport services have not been capable to orchestrate a major sustainability-focused transition in the complex and dynamic urban landscapes of the 21st century. Hence, conforming to the smart city context, public transport should adopt automated mobility solutions (Smolnicki and Soltys, 2016) which can benefit urban transport systems in several ways (Moorthy et al., 2017). Autonomous Buses (ABs), in the form of low-speed, electric, pod-like shuttles, can be a dynamo in developing multimodal mobility systems (Corwin et al., 2015) by making public transport more modern, attractive, visible and user-centric. Early applications of these ABs have been launched as pilots to fifty-five small monitored areas (Inclodean et al., 2020), for instance Berlin, Germany and Oslo, Norway. They provide a new form of public transport strictly applicable for now to traffic calmed or segregated road environments; the technology has not advanced to a level allowing them to co-exist with high-speeding vehicles. They could co-exist however, as early empirical evidence showcases already, with other low speed and active travel modes and complement them by providing a universally accessible low carbon solution to trips (or part of the trips) that are typically too long for walking or cycling.

In addition, along with new mobility services under the MaaS concept, ABs will increase the freedom of passengers to choose the most suitable mobility mode for each individual trip
(Ainsalu et al., 2018). For these reasons ABs should be taken into consideration by street classification systems which are a fundamental component of transport planning (Huang et al., 2016). As various studies highlight (Liu et al., 2017; Marshall, 2005), the existing classification systems are mainly car-oriented and they also hinder the promotion of sustainable modes. In these adverse conditions, ABs are not taken into account by classification systems, neither in terms of practises (stakeholders’ or planners’ decisions) nor in scientific research, since there is a limited number of related studies in the corpus of literature.

This study’s focus is on integrating ABs in the street functional classification system, as they could enhance public transport operations significantly and become a critical part of the MaaS offering that according to Alyavina et al. (2020) cannot motivate positive travel behaviour change unless it is founded on public transport alternatives. Our study therefore, proposes a method for introducing a new street type in urban road networks which accommodates the movement of ABs. This new street type will be devoted to sustainable mobility, thus facilitating the movement of pedestrians (including wheelchairs), cyclists, micromobility users (e-scooters) and public transport (autonomous mini-buses). It would be a valuable feature in the classification system, missing from the existing schemes.

The main research questions arising are the following: 1) what approach should be adopted? 2) which are the fundamental components of the proposed method? 3) Which are the proper evaluation criteria for selecting the most efficient routes? 4) How can the proposed street type be adequately integrated in the existing classification system? We will attempt to respond to each one in detail in the next sections.

The paper consists of five sections, following this introduction. The second section contains a brief literature review that enabled us to identify research gaps. In the third section, we describe the dataset used in the research analysis and the methodological steps followed. Section 4 contains the various characteristics of the study area and then the formulation of the new street type sustaining shuttle-based ABs. In the last section, we present the conclusions of the research.

2. Literature review

This study used a thematic literature review process underpinned by a keyword-specific Scopus search. Specifically, we identified and examined relevant studies that discuss the key dimensions of Autonomous Vehicles (AVs) and Connected and Autonomous Vehicles (CAVs), in general, and ABs, in particular, followed by an introduction to street functional classification issues. ABs research is still very limited especially when compared to the AVs literature thus why the latter is a generic starting point for this background section. By linking automated mobility with its future street functional classification needs, we formulate a comprehensive background that can support and benchmark the analytical part of this study.

2.1. Autonomous vehicles

The transport sector is changing radically over time. During the last two decades the automotive industries have made momentous leaps in bringing computerisation into what has, for more than a century now, been exclusively a human function: driving (Fagnant and Kockelman, 2015). AVs constitute one of the greatest technological breakthroughs in the field of automation with automated driving getting significant research attention (Shladover, 2017). One typical definition supports that AVs are motorized vehicles which move without any human activity (Howard and Dai, 2014). Complete automation, which this paper negotiates, refers to the fifth level of automation (Fraedrich and Lenz, 2014).

Several studies have been reported on the research and development of AVs (e.g. Milakis et al., 2018; Nikitas et al., 2019; Singh, 2015; Thomopoulos & Givoni, 2015) mentioning that these vehicles are estimated to have a wide range of impacts on urban environment. For instance, the
The introduction of AVs into cities could reduce road accidents eliminating the human driving error factor (Katrakazas et al., 2019) and contribute to energy efficiency levels (Wadud et al., 2016). Furthermore, AVs have the potential to make streets less noisy (Millard-Ball, 2016), improve accessibility for vulnerable social groups (Bagloee et al., 2016) and free valuable road space from curbside parking (Milakis et al., 2017; Okeke, 2020), thus increasing public space useful for active modes and human activities. However, autonomous vehicles are not a panacea for all existing mobility problems in urban areas since they could be potentially linked with cyber security and privacy issues (Liu et al., 2020), liability disputes and moral questions (Gogoll & Muller, 2017; Wu, 2020), mixed traffic problems (Nikitas et al., 2017), loss of situational awareness (Endsley, 1999), high vehicle and infrastructure costs (Fangant & Kockelman, 2015), urban sprawl phenomena (Stead & Vaddadi, 2019), trust concerns (Kyriakidis et al., 2015) and in worse case scenarios with increased traffic congestion and air pollution (Harper et al., 2016; Taiebat et al. 2019).

These complicated conditions imply that AVs would require a substantial amount of time in order to be integrated successfully and in a stable way in the urban environment. Besides, an adequate transition to fully automated road traffic is only possible if AVs are accepted and used by society (Nordhoff et al., 2018). In this context, the complex issue of AVs should be treated with caution and in line with sustainable mobility principles and users’ perception (Fraedrich and Lenz, 2016). AVs might, as a whole, encourage the preservation of the “automobility” culture (Mcbride, 2015) thus the importance of studying ABs in particular and how these, far more sustainable vehicles, can evolve to the main form of automated mobility that will overshadow personal AVs and be the basis for MaaS interventions.

2.2. Autonomous Buses (ABs)

If sustainability and social inclusion are to be the be the pillars of future mobility, AVs should be shared vehicles (Moorthy et al., 2017) which operate in a coordinated manner. Shared use mobility (SUM) is transforming the way people move around cities and is challenging consolidated transport modes such as the private car, taxi and public transport (Santi & Ratti, 2017). The autonomous shuttle bus or self-driving minibus is a flexible solution combining technological advance with public transport principles. This type of buses can cover distances that are either too short to travel by car or are too long on foot (UITP, 2017). They can also serve first- and last-mile trips and operate municipal inbound routes (Shen et al., 2018).

Thus, transportation authorities could introduce ABs in the form of small city-friendly autonomous shuttles (or pods), which can compete with automobiles in terms of price and be more effective and attractive than traditional mass transit, taking for instance 10 instead of 150 passengers, being on-demand instead of on-schedule, and moving on flexible routes instead of fixed routes (Ainsalu, et al., 2018). Public transportation can strongly benefit from the introduction of such ABs. Furthermore, as trunk lines are not directly accessible by the whole population in any area, additional more flexible first- and last-mile solutions (or neighbourhood feeders) are required to feed and complement these trunk lines (Shaheen and Chan, 2016).

As mentioned in the introductory section, these vehicles already operate in pilots with an onboard operator/supervisor and extreme caution in various cities worldwide (Fraszczynk and Mulley, 2017). More specifically, some notable pilots are trialled in the following cities: Michigan, USA (University of Michigan, 2018), Vantaa, Finland (Salonen, 2018), Berlin-Schöneberg, Germany (Nordhoff et al., 2018), La Rochelle, France (Piao et al., 2016), Trikala, Greece (Portouli et al., 2018), Appelscha, the Netherlands (Boersma et al., 2018) and Lyon (Le Boennec et al., 2019). The most significant attempt to integrate autonomous public transport in different cities, was the CityMobil project (Alessandri et al., 2015) that discussed the different categories of automated transport. Due to its success CityMobil was followed by CityMobil2 (Alessandri et al., 2014) a pioneering project that intended to explore the live interaction of pod-based ABs and other traffic participants in shared space. The main focus of this project was to realise a number of demonstrations of ABs in in more realistic traffic condition in
different European cities such as Lausanne (Switzerland), La Rochelle (France), Trikala (Greece), Oristano (Italy) and Vantaa (Finland) (Schieben, 2019).

Perceptions about ABs, have been also highlighted by recent literature. According to Madigan et al. (2017) people that participated in an AB-pilot survey mentioned that automated shuttles are useful, easy to use, and expressed an intention to use them again in the future. More specifically, the evaluation of user acceptance across six demonstrations (Trondheim, Vantaa, La Rochelle, Daventry, Orta San Giulio, Castellon) of the CityMobil1 project, indicated that the most highly rated indicator was ‘ease of use’ with an average of 3.7 on a scale from 1 (completely dissatisfied) to 5 (completely satisfied), followed by usefulness (3.5), reliability, integration with other systems, perception of safety, perceived level of privacy, and perceived cleanliness (3.4), and comfort (3.3) (Gorris et al., 2011). Another research conducted by Wicki et al. (2019) found that the most significant factor affecting the use of autonomous public transport is technology acceptance.

Nonetheless, there are still many concerns regarding the operation characteristics and the utility of these vehicles (Wadud et al., 2016). For instance, Winter et al. (2018), indicated that Americans are not entirely ready for ABs, especially in cases where someone they care about is the one on board, or the bus service operates outside the USA. This effect is explained largely by fear and mistrust (Rice and Winter, 2019). Finally, while potential users are willing to pay for autonomous bus services, this price is rather low compared to services operating with a driver (Axhausen et al., 2008).

Regardless of positive or negative feedback on ABs, it is crucial to note that today’s road network is not yet ready to facilitate their movement (Riggs, 2019). As a result, they need a friendlier road transport infrastructure that provides them with an environment fit for their use (Nikitas et al., 2017). But how, could this be achieved? The primary step is to consider and include these vehicles and their needs within the street functional classification since road infrastructure is the backbone of transport systems (Marshall, 2005).

2.3. Street functional classification

Street functional classification specifies the role of each road or street in the urban transport network (FHWA, 2013), grouping every segment into the appropriate class (Marshall, 2004). Furthermore, it organises the movement of each transport mode in a structured way (Stamatiadis et al., 2017). In other words, street classification introduces a discrete management system, considering the network as a whole (Huang et al., 2016).

According to various researchers (e.g. Marshall, 2005; Jones and Boujenko, 2009), the conventional approach of street classification demonstrates as its basic principle the sustaining of car movement. This condition, though, has caused several negative impacts for modern cities (Marshall, 2004). For instance, it separates road users in a rigid manner, thus leading to the exclusion of pedestrians and cyclists from the streets (Hall, 2006). Furthermore, it neglects the social dimension of streets and undermines the role of other transport modes (Liu et al., 2017). Nevertheless, on the basis that streets are multimodal places (Tumlin, 2012), recent research has focused on alternative ways for street classification (e.g. Jones et al., 2008; Liu et al., 2017; Marshall, 2006; Tsigdinos and Vlastos, 2020; Tsigdinos et al., 2020).

Any future street functional classification should include ABs for the reasons outlined thus far. Until now, there are few attempts to integrate the movement of AVs into street classification. The most significant one is the Blueprints Guidelines (NACTO, 2017) which “outlines a vision for cities in a future where automated transportation is both accepted and widespread as part of the built environment”. Specifically, in the context of a new mobility system that aims to operational safety and efficient use of space, this report suggests the classification of road network into five categories which are the following: Multiway Boulevard, Major Transit Street, Downtown Street, Neighborhood Main Street and Residential Street. In all of the aforementioned types the presence of AVs and especially ABs, that represent microtransit is
quite significant. Nevertheless, this classification addresses a general condition for a street network. If we aim to adjust this street hierarchy to the geometric characteristics of different parts of urban areas (central areas, suburbs, industrial zones, etc.), it would be beneficial to re-specify the proposed categories accordingly and for sustainability reasons limit personal AVs.

The absence of an adequate theoretical background discussing the integration of autonomous public transport, indicates the need for new related research. Therefore, this paper attempts to enrich the body of literature by proposing a new street type that would be considered in the current classification system. For this reason, it is crucial to identify possible criteria to be utilised in a concrete method for formulating this new street type.

2.4. Criteria for creating a new street type for ABs

According to the existing literature, there is a scarcity of studies addressing the issue of formulating routes or new street types for autonomous public transport using spatial methods and techniques. However, a few studies and projects illustrate some criteria that could be utilised for constructing a new method. These criteria are presented in the following table:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road pavement width (minimum 3.5-4.0 m)</td>
<td>Huang, 2010; Ainsalu, 2018</td>
</tr>
<tr>
<td>Speed limit (30-40 km/h)</td>
<td>Thorn et al., 2018; University of Michigan 2018; Ainsalu, 2018</td>
</tr>
<tr>
<td>Roadway edges: Line markers, shoulder, concrete barriers, grating, rails, curb, cones, median barrier</td>
<td>Thorn et al., 2018</td>
</tr>
<tr>
<td>Slope (&lt;10 %)</td>
<td>University of Michigan 2018</td>
</tr>
<tr>
<td>Traffic conditions</td>
<td>University of California PATH Program, 2016</td>
</tr>
<tr>
<td>Street classification</td>
<td>FHWA, 2012</td>
</tr>
<tr>
<td>Single lane direction</td>
<td>Pendleton et al., 2017</td>
</tr>
<tr>
<td>Turns (angles that do not deviate significantly from 90 degrees),</td>
<td>Oliveira et al., 2019</td>
</tr>
<tr>
<td>Roadway users (vehicles, pedestrians, cyclists, micro-mobility)</td>
<td>California Department of Motor Vehicles, 2016</td>
</tr>
<tr>
<td>Land uses</td>
<td>University of Michigan, 2018</td>
</tr>
</tbody>
</table>

3. Developing a method for integrating autonomous shuttle buses

The present work adopts a mixed method approach using a case study as its baseline; this is a research formula analogous or to a degree comparable with other notable works in the field of transport (e.g. Attard and Ison, 2015; Bakogiannis et al., 2014; Shokoohi and Nikitas, 2017; Tsigdinos et al., 2020). Specifically, we conducted a thorough literature review analysis, by exploring relevant studies looking at ABs (key features) and street classification principles and criteria. This procedure provided an informed background for building our main research study.

The main method employed adopts a data-driven approach that focuses on the spatial dimension of urban and transport networks. Various spatial techniques such as Network Analyst and Geoprocessing tools were utilised for our analytical efforts. In addition, our approach required both on-site observations and the use of secondary data in order to identify the exact needs of the study area.

The vast majority of the secondary data was retrieved from the OpenStreetMap platform (open data). This decision aims to ensure that that our method (algorithm) could be applied on a large scale to other study areas as well, without the need for spatial data digitisation, which could
lead to estimates that may contain errors. This analysis included a field observation scheme that added a research element of ethnographic nature in our work. Around eight hours of observations were conducted by each of the authors to become familiar and identify the design specifications and urban transport needs of the street environment of our case study locality. This supporting research mechanism helped us to develop a real-life sense of how ABs could potentially be included in the provided street environment in a sustainable and functional way. The authors visited the key and most representative, as defined by the secondary data, roads in the urban fabric of Kallithea in order to examine how these could be reshaped, rebranded and reclassified to fit ABs.

The analytical framework consists of five distinct steps that are illustrated at the Figure 1.

Figure 1: Steps of the analytical framework

Initially, we examined the operation and the classification of the existing road network of the Municipality of Kallithea, as well as of the wider area. This street classification consists of six possible categories, namely: highways, primary and secondary arterials, collectors, slow or shared streets and pedestrian routes (according to Ministry of Environment, Regional Planning and Public Works, 2001).
In the first step, we examined the most suitable road segments for ABs routes. Such routes are preferred to pass through slow streets (speed up to limit 30km/h), shared streets, and to a lesser degree by pedestrian networks. Each road section which belongs to one of these categories is graded with one (1) bonus point. This choice is based on the assumption that ABs (i.e. pod-like mini-buses) which are going to move with speeds well under 30km/h, even 20km/h, could co-exist with the rest of the existing street users. Besides, there are a lot of examples of conventional buses moving through pedestrianised centres in Europe (see Istiklal street in Istanbul, Turkey; Grand Place, Lile France, Prauge, Czechia; Queen Street Oxford, UK to name a few) without creating notable issues for the other road users; on the contrary this mixed use revitalised further these centres.

In contrast, highways, primary and secondary roads are not suitable for these routes and are therefore removed from the network. This is due to the current operational capacity of ABs; they cannot yet be fully integrated into major roads with high volume and high-speeding motor traffic (Ainsalu, 2018) as already discussed. However, adding ABs to these quieter urban environments can create real-life test-beds for preparing these vehicles to eventually become capable to support major private car-replacing scenarios and be part of motorway and high density road classifications.

Road segments with a pavement width less than 3.5m or with average slope more than 10% are graded with one (1) penalty point. Also, two-way road sections without a median or road segments formulating acute angles with other segments are graded with one (1) penalty point. For example, a narrow road section with slope over 10% is graded with two (2) penalty points.

In the next step, important land uses are mapped using OpenStreetMap and census data from the Hellenic statistical authority. These uses include education and sport facilities, public-green spaces, points of interest, high residential density areas and public transport stops. The aforementioned areas are particularly significant for a city, since they represent places that can nurture vitality and foster pedestrian movement, thus promoting social interaction and communication (Gehl, 2010; Thurstain-Goodwin and Unwin, 2000).

In the fourth step, we create isodistance zones of 250m for school facilities, sport facilities, urban green spaces, and points of interest. Road sections that are within each isodistance zone are graded with one (1) bonus point. For example, a road section which is within the isodistance zone of sport facilities and the urban green spaces is graded with two (2) bonus points. Correspondingly, if a road section of a slow street is within the isodistance zone of sport facilities and urban green spaces, then it is graded with three (3) bonus points.

After the elaboration of the fourth step, we could calculate both the suitability indicator (bonus) that is used in our network analysis. Below, we present the formula used to obtain the relevant outcome:

Suitability Indicator (Bonus):

\[
SI = SR + SF + AF + GS + POI (1)
\]

Where SI is the overall suitability score of the road segment, with SI = {0,1,2,3,4,5} 
SR illustrates the sustainable dimension of the segment, 
\[
SR = \begin{cases} 
1, & \text{if the road segment belongs to pedestrians, slow or shared streets} \\
0, & \text{otherwise}
\end{cases}
\]
SF refers to school facilities, 
\[
SF = \begin{cases} 
1, & \text{if the road segment belongs to the school facilities' buffer} \\
0, & \text{otherwise}
\end{cases}
\]
AF represents sport facilities,
\[ AF = \begin{cases} 1, & \text{if the road segment belongs to the sport facilities' buffer} \\ 0, & \text{otherwise} \end{cases} \]

GS represents green spaces,
\[ GS = \begin{cases} 1, & \text{if the road segment belongs to the green spaces' buffer} \\ 0, & \text{otherwise} \end{cases} \]

POI concerns the points of interest,
\[ POI = \begin{cases} 1, & \text{if the road segment belongs to the points of interest buffer} \\ 0, & \text{otherwise} \end{cases} \]

Therefore, Suitability Indicator results in six potential values, which are the following:
*Inappropriate*: 0; *Very low*: 1; *Low*: 2; *Medium*: 3; *High*: 4; *Very high*: 5

Regarding the significance of criteria, we should note that some criteria may play a greater role in the movement of ABs, and for this reason, these differences should be depicted through weights. However, our research is at a preliminary stage, so we did not include a very sophisticated and tested method to assign weights more accurately (e.g. interviews or multicriteria analysis). Moreover, we did not encounter a similar scientific research portraying these weights. Hence, we have made this assumption.

Exclusion criteria:
- The exclusion criteria are the following: a) Road segment belonging to highways, primary or secondary arterials,
- b) Road segment with slope exceeding 10%.
- c) Road segment encountered in an intersection where the angle deviates intensively from 90 degrees. The intensive deviation from 90 degrees is defined if the intersection angle lies between 0-60 degrees and 120 or greater.
- d) Road segment with width lower than 3.5m and
- e) Road segment with two directions, but without a traffic median.

In the last step, using the Network Analyst Tool, we create the proposed AB route, which will also constitute the new category of the road classification system. Road network sections with at least one (1) penalty point will not participate in the network creation. If no route can be found, then road sections with exactly one (1) penalty point will be included in the network. If there is still no route found, road sections with two (2) penalty points will be included in the network. This process will be repeated until a route is found (see eq. 2). The bonus points of each road section correspond to the scaled cost. Meaningfully, this cost equals the suitability indicator (SI).

Penalty indicator:
- As we mentioned above, in order to formulate a connected network, we also develop a penalty indicator, which measures the already excluded segments of the network
\[ PI = AR + SL + AD + RPW + MD \] (2)
Where PI is overall penalty indicator regarding the road segment, with PI = \{0,1,2,3,4,5\}

AR illustrates the automobile dimension of the segment,
\( AR = \begin{cases} 1, & \text{if the road segment belongs to highways, primary or secondary arterials} \\ 0, & \text{otherwise} \end{cases} \)

SL refers to slope,
\( SL = \begin{cases} 1, & \text{if the road segment's slope exceeds 10\%} \\ 0, & \text{otherwise} \end{cases} \)

AD represents the angular degree of the intersection consisting of the road segment and other segments,
\( AD = \begin{cases} 1, & \text{if the angle of the intersection deviates intensively from 90degrees} \\ 0, & \text{otherwise} \end{cases} \)

RPW represents road pavement width,
\( RPW = \begin{cases} 1, & \text{if the road segment is lower than 3.5m} \\ 0, & \text{otherwise} \end{cases} \)

MD concerns unidirectional roads without median,
\( MD = \begin{cases} 1, & \text{if the road segment does not possess a traffic median} \\ 0, & \text{otherwise} \end{cases} \)

Finally, proposed AB stops are located near the metro or tram stations, within the urban centre and near the points of interest. This decision is based on the fact, that these urban points constitute the most significant centres of the city, and that is the main reason they should be connected.

4. Application and results

4.1. Study area

The study area of the research is the Municipality of Kallithea, which constitutes one of the most significant municipalities of Athens’ metropolitan area. We selected a large Greek municipality because of its urban identity that fits our research agenda and its strategic location in the heart of Athens, but also due to data availability; however, the suggested method could potentially be implemented in cities with similar population and characteristics.

Kallithea is a suburban municipality next to the seafront with high population density (255 inhabitants/ha), belonging to the South Sector of Athens. According to the latest Greek census (ELSTAT, 2011), the area has a permanent population of approximately 100,000 inhabitants and 43,395 households. The central core of the municipality is 3km away from the metropolitan centres of Athens and Piraeus.

Kallithea has diverse urban, social and environmental characteristics, as well as notable points of cultural and recreation interest (e.g. Stauros Niarchos Foundation Cultural Centre, part of Ilisos River etc. and several parks). The existing road network classification is mainly car-oriented, thus allowing the penetration of the central area by major arterials (Figure 2). Moreover, it undermines the role of sustainable transport modes (i.e. walking, cycling and public transport). However, Kallithea has in principle at least great potential (high land use mix, high residential density, low car ownership levels, readable road network structure, etc.) for shifting from conventional to alternative transport modes.

4.2. Describing the road network in place and the key origin and destinations

The total length of the road network within the Municipality of Kallithea is 160km. The length of the primary road network is 11.72km (7.33\%), the length of secondary road network is 2.83km (1.77\%) and the length of the tertiary road network is 17.32km (10.83\%). The length
of the cycle network is 2.89km (1.8%), while the length of the pedestrian network is 5.76km (3.6%). However, the pedestrian network is fragmented and to some degree dysfunctional.

<table>
<thead>
<tr>
<th>Table 2: Categories and length of the road network of Kallithea</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Road Network</strong></td>
</tr>
<tr>
<td><strong>Secondary Road Network</strong></td>
</tr>
<tr>
<td><strong>Tertiary Road Network</strong></td>
</tr>
<tr>
<td><strong>Local Road Network</strong></td>
</tr>
<tr>
<td><strong>Cycle Network</strong></td>
</tr>
<tr>
<td><strong>Pedestrian Network</strong></td>
</tr>
</tbody>
</table>

In the north-western part of the municipality there are two metro stations, while in the southern part, near the coastal front, there are two tram stations. Near the north-eastern part of the municipality, but beyond its borders, there is a metro and tram station. Within the boundaries of the municipality, at the south-eastern end, there is one of the most important points of interest of metropolitan Athens, the Stavros Niarchos Foundation Cultural Centre, which attracts many visitors every day (i.e. 5.3 million visitors in 2018). Kallithea has also a university (Harokopio), as well as the Sivitanidios Public School of Trades & Vocations. The municipality also has 51 public schools and 13 sports facilities. Although densely populated, there is a significant number of urban green spaces, evenly distributed throughout the municipality (Figure 3).

4.3. Planning the new street type

We created five maps to depict the spatial dimension of each step of the methodology. Firstly, in Figure 3 we present the buffer zones of the crucial urban places. Next, we display the road segments that are not suitable for accommodating the proposed AB (Figure 4), and in Figure 5, we illustrate the overall evaluation of the study area, namely: the suitability index per segment along with the excluded links. Finally, the proposed road category is portrayed in the last two figures. More specifically, Figure 6 includes the AB route and potential stops and Figure 7, integrates this new street category into the classification system, demonstrating its spatial relation with the main road network of Kallithea.
Figure 2: Current Road Classification

Figure 3: Buffer zones of education, sport facilities, green spaces, and points of interest
Figure 4: Roads that are not suitable for an AB route

Figure 5: Evaluation of road sections - Likert scale evaluation, where Low: the road section should be avoided for ABs and Very High: the road section is ideal for ABs
The length of the proposed AB route will be approximately 9km, representing ~5% of the total road network. It will serve fifteen (15) stops (Figure 6).
5. Discussion

5.1 Key findings and their implications

This paper suggests a method for introducing a new street type in urban road networks which accommodates the movement of ABs in the form of low-speed autonomous shuttles. This new street type is aimed at making streets “shared spaces” that sustain walking, cycling and microtransit (see also Kumar et al., 2020). The current approach is human-centric, as it adopts the basic principles of sustainable mobility and mixes low-carbon and low-speed multimodal solutions (Schiller et al. 2010) to provide complete door-to-door transport for all erasing social exclusion barriers that non-abled bodied travellers may have if public transit is not available in a network (Aldred and Woodcock, 2008). Our method embraces a scenario where pedestrians, cyclists and autonomous shuttles may co-exist peacefully; this co-existence in streets is found in the works of various scholars (e.g. Gehl, 2010; Loukaitou-Sideris, 2002; McAndrews & Marcus, 2014). Furthermore, the method adopts an integrated approach that considers both transport and urban/land-use characteristics of the network (in line with Jones et al., 2008).

Focusing on our study area, the suggested method as applied in the case of Kallithea is expected to bring about significant changes in the mobility conditions of the municipality. In general, it will be a stimulus for sustainable, innovative, and socially inclusive mobility that fits the vision of a smart city. More specifically, the development of a new street type, devoted to pedestrians, cyclists and ABs is estimated to improve the quality of urban environment (taking into consideration studies such as Zawieska and Pieriegud, 2018), thus boosting the vitality of public space. Another notable impact will be the enhancement of (transport) equity, through the creation of mobility opportunities for vulnerable social groups such as children, elderly and disabled people (Bagloee et al., 2016). Not all the people are equipped to be active travellers or make a whole trip via cycling and walking; public transport in the eco-friendly form of pod-like ABs will give them access to environments and networks that now may not be easily accessible to them. The presence of these groups in the urban public space realm should be unquestionably essential for the city of the future. Finally, the integration of this type of vehicles in the street classification system will increase the level of smartness (and operational capacity) in the transport system (Golub, 2019; Cirella, 2019), and it will also in a best-case scenario gradually inspire people to shift from private motor vehicles to shared mobility solutions, and public transport in particular (in line with Madadi, 2019). It is also essential to note that the method proposed follows a data-driven approach, meaning that a new street type did not occur in an arbitrary manner; on the contrary it was an output of certain spatial techniques seconded by a mixed method approach including field observations and secondary data analysis.

Our method ensures that the routes belonging in this street type link significant land uses with each other, thus increasing the possibilities of a use from a critical mass perspective; this will help improving the acceptance level of this change by residents and visitors of the study area. We believe that the structure of the proposed network, offers great possibility for daily trips since it can accommodate movements to/from public services, retail shops, offices, metro and tram stations, schools and sport facilities. This integration into everyday life will be a key feature that will promote these roads use from residents and visitors. It should be highlighted that the suggested routes are circular, meaning that the buses do not pass through a certain node twice (Kuo, 2014) and facilitate movements between neighbourhoods, which otherwise will be carried out by private vehicles. Finally, the proposed method is constructed for an urban municipality with a population of approx. 100.000 residents and a centre of intermunicipal significance, so it could be to a degree generalisable to urban areas with similar size and spatial characteristics.

5.2 Reflections and Future research
Our method is still at an early stage of its development; therefore, it is important to note that there is potential for future improvements. A potential change in the method would be to re-define the entire existing street classification and therefore question the current car-oriented system. Hundreds of European cities are elaborating or implementing Sustainable Urban Mobility Plans, which limit the role of cars and at the same time, promote greatly sustainable modes of transport. Consequently, if a road segment is located at a central area and due to its land uses, has a great urban interest, but it belongs to the main road network, it would be beneficial for sustainability reasons to be re-defined. This redefinition could include the transformation of this segment into an AB route along with the almost complete restriction of conventional private vehicles (some vehicle types would be still permitted, such as emergency vehicles or garbage trucks). Such a policy would enhance public transport establishment as a viable alternative to automobiles. Another potential adjustment in our approach would be to examine the creation of a more detailed AB network consisting of more than one street type; for instance, autonomous routes could be divided according to their role in the whole network in primary and secondary ones.

Future studies should try to change the existing directions of the road segments in order to favour the movement of ABs. Furthermore, the current research, as it was mentioned before, addresses a method for one medium-sized municipality i.e. local level, and not for a whole metropolitan area consisting of many different administrative units i.e. regional level. Thus, it is quite significant to determine a method, through improving the suggested one, which will be suitable for bigger urban conurbations, especially those with population over 1.000.000 people.

Moreover, the developed method, considers that the significance of all the criteria is the same. Nevertheless, some criteria might be more favourable to ABs, thus making weights a necessity. In this context, we suggest this limitation as a subject for future research, utilising qualitative research such as in-depth interviews, multicriteria analysis and AHP. Such an improvement would be very substantial to our work, upgrading the proposed method even more.

Apart from the above, the most critical limitation of the present work is the lack of using a traffic model to assess the impacts of the proposed modifications on street classification and on the traffic conditions in general. This is mainly due to the exploratory and baseline nature of the research that embraced a spatial approach, and not a strict traffic modelling perspective.

Therefore, we did not take into consideration, neither O-D matrices regarding residents and workers within the boundaries of the municipality, nor data about modal share and traffic flows. We believe that the investigation of impacts on modal share, road congestion, delays in major road segments as well as carbon dioxide emissions and other traffic-related pollutants, should be a matter of a detailed and combinatorial (both spatial and transport) future research.

As it can be clear, ABs and their integration into the transport system constitute a complex issue that cannot be fully examined in one single study. This paper focuses on the creation of one new type accommodating autonomous shuttle buses in the study area and does not consider other automated mass transit solutions or even ABs of more conventional size comparable with the current ones. This would ensure an even more holistic planning solution. We also concentrate on more neighbourhood-based, low volume and low-speed roads promoting shared space use with active transport and other micromobility solutions due to the inability of current ABs to function in highways with dense high-speed motor traffic. When ABs will be functional in terms of technology, legislation, infrastructure readiness and public acceptance they will need to be incorporated in these main road environments so that they can have a more significant sustainability impact taking space from private cars.

Another take would be the development of an optimisation algorithm aiming to find the best route alternatives for the autonomous shuttle buses, integrating more features with positive (bonus) or negative (penalty) direction. Through this algorithm, it would be possible to reduce the calculation time and ease the application of our method to other geographical areas. This
algorithm should not be a rigorous process, replacing the role of urban and transport planners, but on the contrary it should only function as a tool providing different perspectives.

Further research, must also formulate an evaluation framework, in order to assess the quality and the impact of the proposed routes (e.g. traffic simulation models). New scientific attempts can also concentrate their interest on design issues such as detailed cross-sections in order to bridge the gap between planning and design. Finally, the deeper connection of the investigated subject with innovative technologies and data sources (e.g. crowdsensing, mobility data and activity data) in general, would be another useful future research direction.

6. Conclusions

As street classification is considered critical for transportation planning, research that incorporates in this framework the use of ABs is of value. The existing literature discussing street classification and autonomous public transport is extremely limited. This is one of the first attempts that tries to put the foundations in formulating a comprehensive and realistic network for ABs within the urban fabric of a municipality at the heart of a very large and dense metropolitan area.

We believe that the proposed method could function as a support tool for the decision-making of stakeholders and policy makers and could be replicated to some degree in other cities with similar socio-economic and geo-spatial characteristics. In this context, the empirical and theoretical applications described in the current paper could influence the formal transport and urban planning procedures. This means that the contribution of the research has more than pure academic interest; we believe it has immediate potential for real-life applications. This is a first exploratory step in the procedure of incorporating actively ABs into the road network of future smart cities; thus, there is a need for more research papers and projects addressing the ABs and inclusive mobility agenda since this can be an apparatus for delivering more vibrant, inclusive, accessible, sustainable and safer cities.

References


University of California PATH Program. (2016). *Peer Review of Behavioral Competencies for AVs*.


