Investigating Autonomous Vehicle Readiness of Cities: a Structured Text and Content Analysis

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Abstract. The process of urban integration of autonomous vehicles is posing increasing challenges for many cities today. Based on the growing number of autonomous vehicle tests on urban roads, it seems that the urban presence of these vehicles requires only minimal preparation from cities. However, their widespread adoption, integration, and effective and safe operation at the urban level require substantial preparation. Various studies have explored the key factors influencing AV readiness using different methods such as backcasting, online surveys, and expert interviews. However, the added value of our work lies in synthesizing these individual findings through software-supported structured text and content analysis using MaxQDA 2023 software. Based on the results, nine main factors and twenty-seven key elements that could be crucial in supporting the future mass adoption of autonomous vehicles in urban areas are identified. The paper seeks to contribute to a deeper understanding of urban autonomous vehicle readiness and the identification of measures necessary to achieve it[1]. Representing the 27 key determinants with indicators offers a great opportunity for further research, thereby urban autonomous vehicle readiness could be measured based on this synthesized framework.

1. Introduction

The question today is not if autonomous vehicle-driven urban mobility will become a reality, but when (Threlfall, 2018). (Threlfall, 2018). There are various estimations about it, nevertheless, the technological developments related to AVs have accelerated by now (Grindsted et al, 2022). The number of involved cities and companies with road test permit is increasing; In July 2024, California issued road test permits to 7 companies

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without safety drivers, granted deployment permits to 3 companies, and allowed 36 additional companies to test with safety drivers.[2].

One of the companies has already travelled 20 million kilometers with over 600 vehicles accident-free throughout the USA, completing over 2 million paid rider-only trips[3]. There is a major expansion in the urban robotaxi services functioning without a safety driver in developed countries; the number of both the issued permits and the areas covered by the service is dynamically growing (Zou – Xu 2023, Tavor – Raviv 2023).

The potential benefits of the autonomous vehicle revolution have significant potential for well-prepared cities. Some authors highlight the benefits of traffic reduction claiming that sharing-based AV fleets will be able to move the same amount of traffic by using fewer vehicles compared to privately owned vehicles (Liljamo et al., 2021, Kesselring et al., 2020, Spurling – McMeekin, 2014, Fagnant – Kockelman, 2016, Alazzawi et al., 2018, Martinez – Viegas, 2017, Overtoom et al., 2020), thus the new mobility system may substantially reduce the number of vehicles in urban traffic (Alazzawi et al, 2018; Martinez and Viegas, 2017; Overtoom et al, 2020). Autonomous vehicles can represent a new urban mobility paradigm, where private car ownership is replaced by autonomous fleet usage and integrated transport system, active urban mobility, and sustainability play an important role (Medina-Tapia – Robusté, 2018, Kovacic et al 2022, Zardini et al 2022). Based on other scenarios, autonomous vehicles can become counterproductive (especially if they are privately owned), and, contrary to expectations, they may slow down urban mobility (Overtoom et al, 2020; Alam and Habib, 2018).

Other authors emphasize that the mass adoption of autonomous vehicles entails economic and social benefits (Threlfall, 2018, Lipson – Kurman, 2016, Litman, 2017, Bezai et al., 2021): the hours spent driving can be converted to productive time, the number of road accidents caused by human error can be reduced, safety and comfort can increase, environmental pollution and fuel consumption can decrease, and the movement of disabled and elderly people can become easier (Litman, 2017, Bezai et al., 2021).

However, several urban challenges are associated with autonomous technologies (Threlfall, 2018, Bezai et al., 2021), including the potential vulnerability of the transport system (Alfonso et al., 2018, Atzori et al., 2018), traffic management (Straub Schaefer, 2019), and urban budget (Smahó 2021). Narayanan et al. (2020), DuPuis et al. (2015), Chapin et al. (2016) and Fraedrich et al. (2019) found that urban land use is one of the major areas where autonomous technology and lifestyle tendencies collectively give rise to substantial changes.

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[2] Currently available on https://www.dmv.ca.gov/.

[3] www.waymo.com

As a result, the concept of urban autonomous vehicle readiness becomes more significant, which highlights that the success of autonomous vehicle adoption does not only depend on the advancement of the technology but also on the characteristics of the receiving environment; cities must take proactive steps for the safe introduction of AVs (Khan et al., 2019). Autonomous vehicles require special urban development interventions for the safe operation of the technology. AV-specific urban development is key in the realization of benefits and avoidance of drawbacks expected of from autonomous vehicles. Without it, autonomous vehicles may even increase the mobility problems which road authorities currently face (Duarte–Ratti, 2018).

The present research investigates what is required for the mass adoption and effective and safe operation of autonomous vehicles in future cities. The methodology of the research is software-supported structured text and content analysis, in which the factors and key determinants of the autonomous vehicle readiness of cities is determined by coding and analyzing 223 key factors identified in the international literature. The results can provide important assistance for urban policy makers and professionals to understand the logic of the new urban mobility paradigm and the preparation required in their city to support the mass adoption of autonomous vehicles.

To achieve the research goal, we review the literature on the topic and then present the analysis methodology and the database. Following this, we discuss our findings, focusing on the factors and the 27 key determinants, which we introduce individually. Finally, we conclude the study with our conclusions.

2. Literature Review

In terms of capturing AV readiness, the widely referenced AV Readiness Index of KPMG must be highlighted, which defines autonomous vehicle readiness with the help of four pillars (technology, policy and legislation, infrastructure, social acceptance) (Threlfall, 2018). As the critical mass and spatial concentration of autonomous vehicles which represents an issue requiring the most comprehensive planning and preparation will affect cities, the present study focuses on capturing AV readiness on urban level. Nevertheless, the national framework is considered an important cornerstone which the interventions of urban autonomous vehicle readiness must match.

Studies on urban AV readiness generally focus on a few specific areas in many cases (e.g. legislation, infrastructure, land use, governance, and social aspects). Several studies emphasize the prominent role of infrastructure when examining the factors of AV readiness.

Riggs et al. (2020) tested how AVs can appear on city streets to increase urban liveability with a focus group including car manufacturers, engineers, and planning and policy professionals. They emphasize that road infrastructure becoming AV-friendly is key, but it is a long and gradual transformation process. Manivasakan et al. (2021) focused on developing, evaluating, and testing urban infrastructure supporting AVs. They defined three factors to evaluate the readiness of AV-compatible infrastructure: safety, efficiency, and availability. Based on the results of Chajka-Cadin et al. (2020), the first step of the adoption of connected and autonomous vehicle technology is the development of physical and telecommunications infrastructure. Dale-Johnson (2019) studied the issue of urban AV readiness with a focus on legislation and property market, identifying the following related factors: safety of AVs, their integration into the transport ecosystem, land use, infrastructure, and municipal revenues.

Lau and van Ameijde (2021) consider the topic of AV readiness an urban planning task. They ran several simulations with an animation software to explore how the use of AVs can lead to more open urban spaces, dynamically changing flexible zones, and progressive social processes. Aoyama and Leon (2021) examined the urban appearance of AVs in terms of governance, suggesting that cities must implement four complementary functions for successful AV deployment: regulator, mediator, data catalyst, and promoter. In a similar approach, Zhou et al. (2021) highlighted the impact of the transformation of mobility on land use and urban development. Grindsted et al. (2022) also apply the governance aspect of AV readiness, analyzing 39 planning documents of 10 European capitals according to the objectives related to sustainable cities and communities defined by the UN. They found that municipalities must make specific interventions if they would like autonomous technology to contribute to the objectives targeted at sustainable development.

Campisi et al. (2021) approach AV readiness from the aspect of smart cities and identify the criteria of urban mobility optimization, paying special attention to the future development of AVs. Seuwou et al. (2020) also study AV readiness from the aspect of the mobility of future smart cities, identifying six factors: consumer acceptance, cost of vehicles, legislation and issue of responsibility, social and ethical problems, cyber and data security and data protection concerns, and infrastructure. Milakis and Müller (2021) focus on the societal dimension of the deployment of autonomous vehicles in terms of AV readiness, and identify three related key areas: societal acceptance, societal implication, and the governance of autonomous vehicles (Table 1).

Table 1. Studies capturing the key topics of urban autonomous vehicle readiness

Author(s)	Focus	Characteristic
Aoyama and Leon (2021)	Governance	They describe various types of roles of cities on a conceptual level from four aspects: city as regulator, mediator, data catalyst, and promoter. Two examples are presented based on Pittsburgh, Pennsylvania, and Boston, Massachusetts.
Campisi et al. (2021)	Smart city	They review the development of smart cities, defining a methodology which enables identifying the criteria for determining the optimization of urban mobility, paying special attention to the development of future autonomous mobility.
Chajka-Cadin, et al. (2020)	Infrastructure	Autonomous vehicles and connected autonomous vehicles. Their work is based on the experience and opinion of representatives and professionals. Questionnaire survey is conducted.
Dale-Johnson (2019)	Legislation	Interviews with well-informed professionals. Comprehensive description of the pillars of readiness. Questionnaire survey is conducted.
Grindsted et al. (2022)	Governance	Apart from the impacts of shared autonomous vehicles, the impacts of privately owned autonomous vehicles. They compare plans with the objectives of UN related to sustainable cities.
Lau and van Ameijde (2021)	Urban planning	It breaks with car-based planning practice. Wide-ranging applications of autonomous vehicles.
Manivasakan et al (2021)	Infrastructure	Readiness is quantifiable. Readiness is considered in general, covering the entire autonomous vehicle phenomenon.
Milakis and Müller (2021)	Society	Backcasting approach. It covers a wide spectrum of the pillars of preparing for autonomous vehicles.
Riggs (2020)	Infrastructure	Level of awareness ensured through education. Involving different stakeholders.
Seuwou et al. (2020)	Smart city	Autonomous vehicles are presented as a necessary instrument for achieving the aims of cities. It describes obstacles and makes proposals.
Zhou et al. (2021)	Governance	It studies short-, medium-, and long-term effects. Making a distinction between socio-economic groups.
Zomarev and Rozhenko (2020)	Governance	Comprehensive review of the emergence of autonomous vehicles. They differentiate the set-out measures according to 4 potential future scenarios.

The international literature contains examples where researchers applied a comprehensive holistic approach, these served as the basis for our qualitative research. Fraedrich et al. (2019), Freemark et al. (2020), Brovarone et al. (2021), Jiang et al. (2022), CEG (2019), Fagan et al. (2021), NSW (2022), Zali et al. (2022), KPMG (2018), define the main groups and areas which determine the autonomous vehicle readiness of cities (Table 2). Beyond that, Khan et al. (2019) define the index of urban autonomous vehicle readiness. Numerous studies have examined the critical determinants of AV readiness through a variety of methodologies, including backcasting, online surveys, and expert interviews, case studies. What distinguishes our research is its focus on integrating these diverse findings into a cohesive synthesis, utilizing structured text and content analysis supported by MaxQDA 2023 software. The empirical survey of the present research relies on the factors defined by these studies.

Table 2. Studies comprehensively capturing urban autonomous vehicle readiness

Author(s)	Main groups	Methodology	Number of factors
Fraedrich et al. (2019)	Transport planning, Traffic management, Infrastructure planning, Urban planning, Participation Other aspects	interviews	18
Sperling et al. (2018)	National level, Local level	narratives	11
Freemark et al. (2020)	Land use, Environmental protection and equity / fairness, Transport system	online survey	12
Brovarone et al. (2021)	Mobility, Innovation, Telecommunications, Physical infrastructure	backcasting	37
Jiang et al. (2022)	Infrastructure, Directives, legislation and policy, Population	online survey	19
CEG (2019)	Infrastructure, Policy	narratives	12
Fagan et al. (2021)	Promotion of MaaS, Land use, Managing and reducing congestions, Data sharing, Income repositioning	case studies	22
NSW (2022)	Law and safety, Infrastructure and planning Transport services, Data, Consumer acceptance	narratives	12
Zali et al. (2022)	Social acceptance, Infrastructure, Directives and legislation, Technology and innovation	fuzzy Delphi	48
Khan et al. (2019)	Directives and legislation, Physical infrastructure, Cyber infrastructure	online survey	16
KPMG (2018)	Directives and legislation, Technology and innovation, Infrastructure, Social acceptance	questionnaire	16
Total			**223**

3. Method and Data

To achieve the research objective, qualitative research was conducted in the form of software-supported structured text and content analysis. The literature analysis included the identification of research findings which interpret urban autonomous vehicle readiness in a comprehensive holistic approach and define its key factors. The present research aims to synthesize these factors with structured text and content analysis. 223 factors in total listed in Table 2 were involved in the analysis. The factors were processed with MaxQDA 2023 software, which conducts qualitative data analysis and derives quantitative information through different metrics (Kuckartz – Rädiker 2019). In order to achieve these objectives, the first step was coding (Fig. 1).

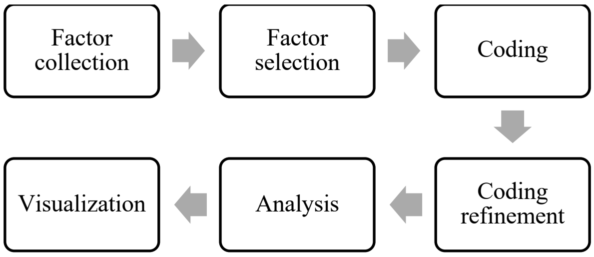

Figure 1. Framework of the primary research

In the coding process, patterns were searched during the text analysis of factors, based on which the original raw data were standardized with a predefined framework (Creswell 2013, Babbie 2016, Brait 2020). In qualitative research, codes serve as attributes, briefly summarizing the content, whether it is linguistic or visual (Saldaña 2013). By assigning the codes to the textual description of the factors, the contents described in the factors can be evaluated in a standard framework. The coding process enabled arranging the factors of urban autonomous vehicle readiness into a single structure, which contributed to exploring the patterns underlying the contents of factors. Often several codes were assigned to a coding unit by applying simultaneous coding (Saldaña 2013).

When defining the codes, it was important to minimize the analyst's subjectivity, therefore, a framework which is accepted in wide professional circles was chosen. The research relied on the areas defined in the reviewed literature. The coding process was carried out manually in two steps, in MAXQDA software. First, all main groups defined in the literature were put in the code list, resulting in 13 codes (Table 3).

Table 3. Codes definable based on the reviewed studies

Code / study	Fraedrich et al. (2019)	Freemark et al. (2020)	Brovarone et al. (2021)	Jiang et al. (2022)	CEG (2019)	Fagan et al. (2021)	NSW (2022)	Zali et al. (2022)	Khan et al. (2019)	KPMG (2018)
Policy and legislation				X	X		X	X	X	X
Technology			X					X		X
Physical infrastructure	X		X	X	X		X	X	X	X
Public readiness	X			X			X	X		X
Integration	X	X				X	X			
Data						X	X			
Safety							X			
Vehicle communication		X								
Business model						X				
Virtual infrastructure			X					X		
Planning	X						X			
Land use		X				X				
Urban mobility	X	X	X			X				

The second step is the fine tuning of codes, where the codes can be complemented with new codes and subcodes created during a deeper analysis of the texts (Saldaña 2013). In this case, a deeper analysis of the 223 factors required the inclusion of a new code, the code of vehicle communication, and the code system ultimately consisted of 14 codes:

1. Policy and legislation
2. Technology
3. Physical infrastructure
4. Public readiness
5. Integration
6. Data
7. Safety
8. Environmental protection
9. Business model
10. Virtual infrastructure
11. Planning
12. Land use
13. Urban mobility
14. Vehicle communication

4. Results

In the coding process, 446 codes in total were placed in the text system formed by the 223 analyzed factors of urban autonomous vehicle readiness. Their number and relative frequency of occurrence in the code system can be monitored and it is found that the *urban mobility* code was placed in the text system most frequently, 65 times, while the less frequent was the *environmental protection* code, only 5 times (Table 4). The variation of the occurrence of the codes is relatively high, the range is 58. Among the fourteen codes, four codes, *urban mobility*, *policy and legislation*, *technology,* and *physical infrastructure* cover over 50% of the total number of codes. In contrast, the total occurrence of the four least frequent codes (*environmental protection, integration, safety, land use*) is lower than the most frequent urban mobility code.

Table 4. The occurrence and proportion of each code in the text system

Code name	**Number of placed codes (pcs)**	**Relative occurrence of codes (%)**
Urban mobility	63	14.13
Policy and legislation	61	13.68
Technology	52	11.66
Physical infrastructure	51	11.43
Business model	36	8.07
Virtual infrastructure	36	8.07
Public readiness	29	6.50
Vehicle communication	26	5.83
Planning	21	4.71
Data	19	4.26
Land use	18	4.04
Safety	17	3.81
Integration	12	2.69
Environmental protection	5	1.12
Total	**446**	**100.00**

The code relations browser shows which code pairs co-occur frequently within the same factor (maximum distance=0) to understand the complex relation of code pair occurrences. A scale of the added heat map ranging from blue to red indicates which code pair is frequent or less frequent in the system. *Urban mobility* and *policy and legislation* codes occur most frequently within the same factor (Table 5), but there is a strong relation between the code pairs of *technology* and *virtual infrastructure*, *physical infrastructure* and *urban mobility*, and *integration* and *urban mobility*.

Table 5. Code relations browser (maximum distance=0)

Code system	Integration	Vehicle communication	Data	Safety	Environmental protection	Business model	Virtual infrastructure	Planning	Land use	Urban mobility	Policy and legislation	Technology	Physical infrastructure
Integration	0	4	0	0	0	0	0	2	0	22	8	2	2
Vehicle communication	4	0	2	4	2	0	22	6	0	12	12	18	8
Data	0	2	0	6	0	2	13	2	0	2	13	2	4
Safety	0	4	6	0	0	2	6	2	0	8	9	3	6
Environmental protection	0	2	0	0	0	4	0	0	0	10	8	2	0
Business model	0	0	2	2	4	0	0	4	0	20	28	18	3
Virtual infrastructure	0	22	13	6	0	0	0	4	0	2	6	32	18
Planning	2	6	2	2	0	4	4	0	8	12	2	2	6
Land use	0	0	0	0	0	0	0	8	0	10	6	0	14
Urban mobility	22	12	2	8	10	20	2	12	10	0	47	14	23
Public readiness	0	10	0	2	0	9	0	0	2	17	4	8	0
Policy and legislation	8	12	13	9	8	28	6	2	6	47	0	16	10
Technology	2	18	2	3	2	18	32	2	0	14	16	0	14
Physical infrastructure	2	8	4	6	0	3	18	6	14	23	10	14	0

If a visualization of the code relations browser presented in Table 5 is created, the model of the text system composed from the 223 factors of urban autonomous vehicle readiness is obtained (Figure 2). The model demonstrates the frequency of the co-occurrence of each code in the textual data. If two codes co-occur frequently, it indicates that the two codes are probably linked to each other or the same topic.

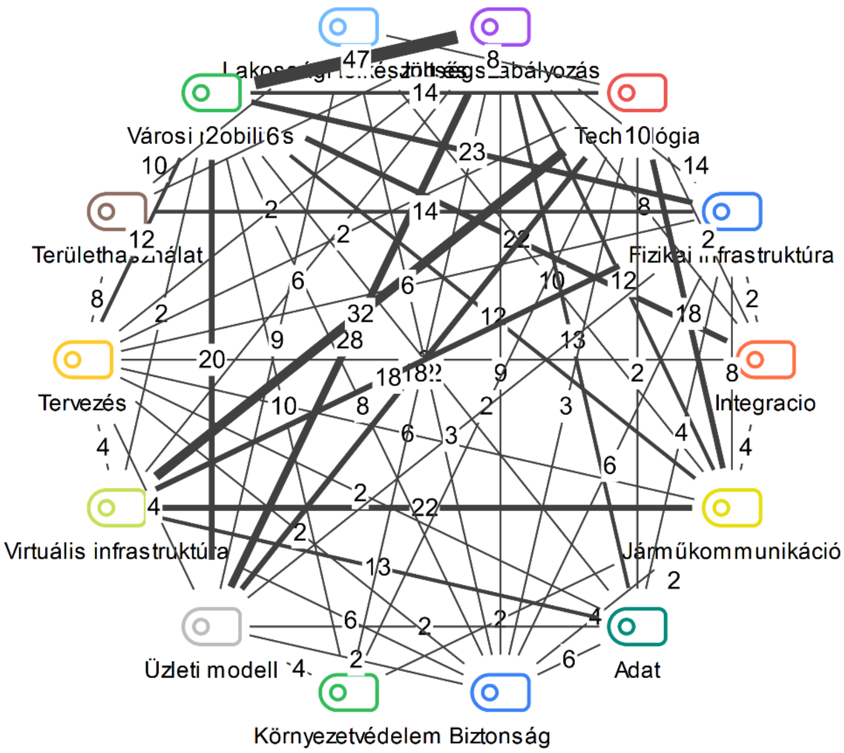

Figure 2. Code co-occurrence model

Further connections can be revealed about the text system created from the 223 factors of urban autonomous vehicle readiness based on the code map (Figure 3). The different codes are represented by circles, whose diameter is determined by the frequency of the occurrence of a given code. The line joining two codes demonstrates the frequency of the co-occurrence of the two given codes. The various colors of the code map show the clusters formed based on the distances, indicating the most significant co-movement of codes within the entire text system created from the 223 factors of urban autonomous vehicle readiness. It results in 4 clusters with the following codes:

- Cluster 1: virtual infrastructure, technology, vehicle communication codes
- Cluster 2: planning, land use codes
- Cluster 3: business model, policy and legislation, urban mobility codes
- Cluster 4: Physical infrastructure, data, safety, environmental protection, public readiness, integration codes

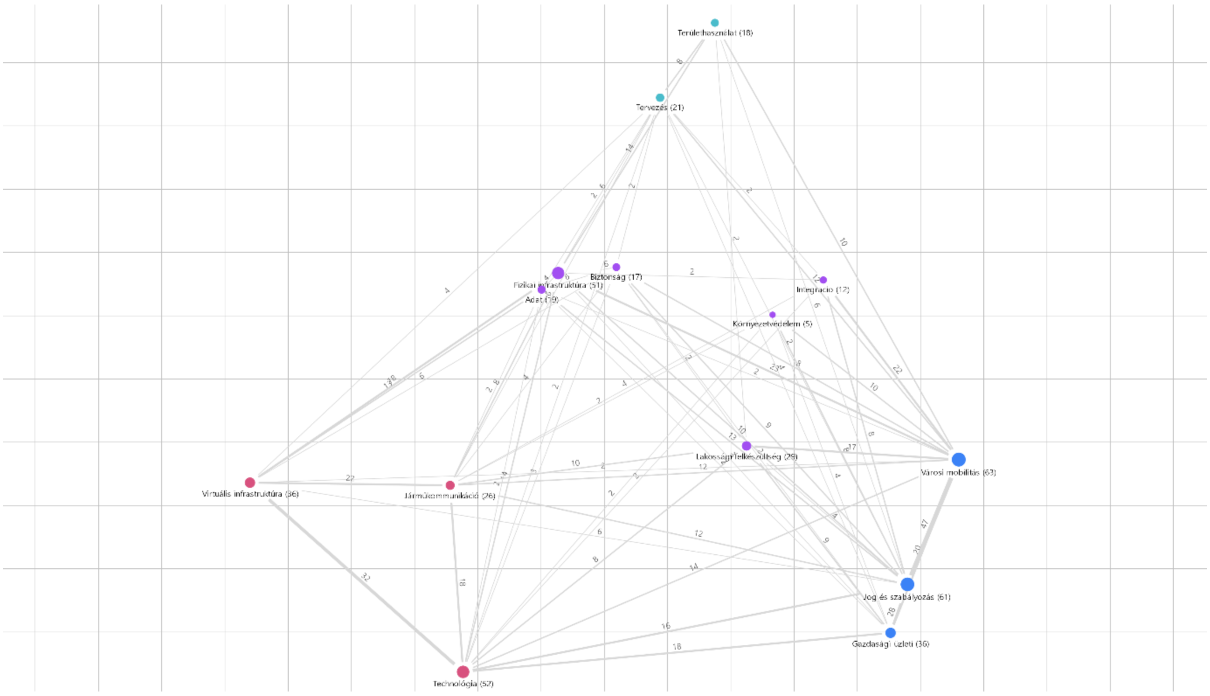

Figure 3. Code map and clusters of AV Readiness of Cities

The model, code map, clusters, and the overlaps of the factor codes of the text system enable defining the factors and key determinants of urban autonomous vehicle readiness. It is not sufficient to consider the outputs of the text system, the 223 factors must be analyzed one by one to interpret the overlap of each code. With simultaneous coding several codes can be assigned to a more complex factor based on its content. Urban autonomous vehicle readiness is an extensive topic, thus the 223 analyzed factors included one with 5 codes. It can also lead to a situation where a code itself cannot be associated with any factors despite the fact that it was completely justified to be included in the code system based on the literature review. As a result, two codes could not be connected to any factors separately: integration and environmental protection. The latter was removed from the code system. In the case of the integration code, all factors which had an integration code also got an urban mobility code, creating the "Integration and urban mobility" factor.

In the following step, the codes were examined within the clusters based on the cluster recommendations of the software. There was a large overlap among the codes proposed in cluster 1 and 2 during double-checking, thus the factors were defined on cluster level for the codes in these clusters as follows:

- 3 codes included in cluster 1, virtual infrastructure, technology, and vehicle communication codes were considered as a cluster-level factor named as *CAV technology and virtual infrastructure;*
- 2 codes included in cluster 2, planning and land use codes were considered as a cluster-level factor named as *Urban planning and land use*.

The contents of the factors under the codes within cluster 3 and 4 are so different that combinations are not justified; therefore, the codes of these clusters can be interpreted as separate factors. If the content of the factors and their connections to other codes is analyzed systematically, the key determinants which are the most important in terms of urban autonomous vehicle readiness can be given by factor (Table 6).

Table 6. Factors and key determinants of AV readiness in cities

Factors	**Key determinants**	**Reference**
A. Urban planning and land use	1. Updating transport plans 2. Adjusting infrastructural plan 3. Replanning land use	Narayanan et al. (2020), DuPuis et al. (2015), Chapin et al. (2016), Fraedrich et al. (2019), Fayyaz et al. (2022), Rahman–Thill (2023), Silva et al. (2021)
B. Physical infrastructure	4. Providing and transforming road infrastructure 5. Maintaining road network 6. Establishing P+R facilities	Duvall et al. (2019); Khan et al., 2019; KPMG, 2020; Oliver et al. (2018), Johnson (2017); Khan et al., 2019; NACTO, 2019; Saeed (2019)
C. CAV technology and virtual infrastructure	7. Installing V2I technology in roads 8. Establishing CAV-compatible crossings 9. Providing server technologies	Khan et al., 2019, Sheehan et al. (2019), Duvall et al. (2019); Johnson (2017); Saeed (2019)
D. Data	10. Data management, data analysis 11. Private data protection 12. Sharing socially useful data	Cui et al., 2018; Khan et al., 2019; Lin et al., 2018, Fagan et al 2021
E. Safety	13. High-level cyber security 14. Managing vehicle safety risks 15. Latest vehicle safety technologies	Khan et al., 2019; KPMG, 2020; Sheehan et al. (2019), Alfonso et al., 2018, Atzori et al., 2018
F. Urban mobility and integration	16. Integrating AVs into transport system 17. MaaS integration of transport system 18. Promoting the use of MaaS system	Alazzawi et al, 2018; Martinez and Viegas, 2017; Overtoom et al, 2020, Straub Schaefer, 2019
G. Legislation	19. Local rules encouraging autonomous fleet use 20. Local rules discouraging private car use 21. Local policy interventions	Barnes et al. (2017); , Duvall et al. (2019); Khan et al., 2019; Kimley-Horn (2016); KPMG, 2020
H. Business model	22. Local support encouraging autonomous fleet use 23. Local taxes and fees adding to the cost of private car use 24. Rethinking urban budget	Smahó 2021, Mares et al., 2018, Maciag, 2017, Clark et al., 2017, Fagan et al 2021
I. Public readiness	25. Informing the public about AV technologies and their urban impacts 26. Public involvement in urban AV-related decisions 27. Public involvement in new land use-related decisions	Golbabaei et al. (2020); INRIX, 2017; KPMG, 2020, Kacperski et al. (2021); Mathis et al. (2020), Threlfall, 2018, Lipson – Kurman, 2016, Litman, 2017, Bezai et al., 2021

The next section elaborates on the content of each key determinant in terms of urban development. It must be noted that most key determinants have a state-level connection, but it is not described during the presentation of key determinants due to the urban focus. Nevertheless, national-level frameworks (legislation, policy, etc.) must be regarded as an important base for planning urban interventions which specific actions must be adapted to.

A. Urban planning and land use

1. *Updating urban mobility plan*: it is particularly important to plan what role the city designates to AVS in its own urban mobility. Fitting AVs into the urban mobility fabric ensures that autonomous technology is an integral part of urban transport system, facilitating optimal and safe transport.
2. *Adjusting infrastructural plan*: the city must be prepared for the special infrastructural requirements of AVs. Roads, crossings, signs, signals, etc. may require developments to ensure the effective and safe operation of AVs.
3. *Replanning land use*: it includes reconstructing parking places, replanning streets, establishing embarkation and disembarkation zones, etc. The adjustment of land use plan allows cities to completely exploit the benefits offered by AVs, for example, more efficient traffic and increased public spaces.

B. Physical infrastructure

4. *Providing and transforming road infrastructure*: providing, transforming, and certifying road infrastructure for AVs, which refers to the implementation of the infrastructural plan. The physical infrastructure of the city is adapted to the requirements of autonomous technology.
5. *Maintaining road network*: more frequent maintenance of the elements of road infrastructure, such as signs, lights, lane markings, and potholes to make them easily detectable and perceivable for the sensors of vehicles. It is essential for the safe operation of AVs.
6. *Establishing P+R facilities*: appropriate establishment of parking places and transfer points simplifies the change from AVs to other means of transport, contributing to the efficiency of urban mobility.

C. CAV technology and virtual infrastructure

7. *Installing V2I technology in roads*: Vehicle-to-Infrastructure technology enables AVs to communicate with the infrastructure. It requires the instalment of special sensors and communication equipment in the road and other infrastructures.
8. *Establishing CAV-compatible crossings*: the aim of the crossings developed for connected and autonomous vehicles (CAVs) is to enable AVs to communicate with their environment, as well as coordinated crossing. It increases transport efficiency, minimizes the risk of collision, and contributes to the safer and smoother transport of the city.

9. *Providing server technologies*: AVs rely on advanced server technologies, such as 5G, optics, cloud solutions. The access to server technologies must be provided in cities to ensure that AVs remain in contact and make decisions based on the most recent data.

D. Data

10. *Data management, data analysis*: it is important for the city to conclude agreements to access the huge amount of data recorded by AVs (or at least a part of it) to monitor the road network in real time and make an informed decision on transport, urban development, and other urban planning matters.
11. *Private data protection*: regarding the data collected by AVs available to the city, it must be ensured that the personal information of the public is protected. Such vehicles use several sensors, cameras, and other data collecting devices, which can also record personal information.
12. *Sharing socially useful data*: data collected or generated by AVs about transport processes (congestions, accidents), environmental indicators, and other important factors can contribute to increasing the efficiency of urban mobility, the safe transport of classical and autonomous vehicles, and providing information for the public.

E. Safety

13. *High-level cyber security*: preventing attacks against vehicles and related infrastructure is a priority public security matter. The city must integrate these measures into daily processes to protect its inhabitants and the infrastructure from the repercussions of cyber risks for urban safety.
14. *Managing vehicle safety risks*: to manage the specific safety risks of AVs efficiently, the city must take an active part in risk management processes. It includes cooperation with urban police, fire brigades, and emergency services to be able to respond to emergencies promptly and capacities are not absorbed by false automatic alerts. Efficient communication and cooperation are important, including informing the public about potential risks and measures.
15. *Latest vehicle safety technologies*: V2X (Vehicle-to-Everything) technologies, establishing a data connection between the vehicle and its environment, can help increase the safety of AV passengers and the safety of people in its environment, such as pedestrians and cyclists. With the instalment of these technologies, the city can take major steps to increase the safety of mobility.

F. Urban mobility and integration

16. *Integrating AVs into transport system*: AVs must be integrated into the urban transport system in coordination with the urban mobility plan and transport infrastructure. Integration improves the efficiency of transport, decreases traffic and parking problems, and contributes to the sustainability of urban mobility.

17. *MaaS integration of transport system*: Mobility-as-a-Service (Maas) enables simple and coordinated use of various modes of urban mobility with a single mobile application. It increases the comfort of passengers and optimizes the urban transport system.
18. *Promoting the use of MaaS system*: the MaaS system can increase the efficiency of urban mobility only if the public uses it actively. Thus, the promotion of the system is key in the paradigm shift of urban transport.

G. Legislation

19. *Local rules encouraging autonomous fleet use*: the city can encourage autonomous fleet use targeted at decreasing urban mobility issues with municipality regulations and rules. Ridesharing is of special importance in the paradigm shift of urban transport.
20. *Local rules discouraging private car use*: the city can discourage private vehicle use with municipality regulations and rules. These interventions can encourage alternative mobility modes, helping the city develop environmentally friendly and efficient transport systems.
21. *Local policy interventions*: local policy can take several measures which are not exclusively regulatory but also facilitating the paradigm shift of urban transport. The city can give policy guidelines to exploit the benefits of autonomous fleets and can elaborate financial incentives in the form of a business model.

H. Business model

22. *Local support encouraging autonomous fleet use*: in terms of efficient and sustainable urban mobility, it is beneficial if autonomous fleets can be used by the public with substantial cost benefits as a part of the urban mobility mix compared to private car use. The specific forms of support must be accurately planned and introduced by the city.
23. *Local taxes and fees adding to the cost of private car use*: it is an instrument for cities to decrease private car use and encourage other modes of transport. For example, with high parking fees and zone fees the cities can decrease private vehicle use and make urban mobility more sustainable.
24. *Rethinking urban budget*: the mass adoption of AVs will affect the budget of cities negatively both directly (parking fees, fees from vehicle ownership, taxes), and indirectly (local tax revenues). It requires preparations for loss minimalization and the sustainability of management.

I. Public readiness

25. *Informing the public about AV technologies and their urban impacts*: an important condition for the widespread deployment of AVs is public acceptance, which can be facilitated if urban residents understand the operation and impacts of AV technology and receive satisfactory responses to their concerns.

26. *Public involvement in urban AV-related decisions*: it is important in the introduction of AVs that urban residents participate in decision-making processes. Considering public opinions and experience increases the acceptance of Avs and helps the city establish systems which indeed satisfy the needs and requirements of the public.
27. *Public involvement in new land use-related decisions*: the mass adoption of AVs can change the common and beloved streetscape. Public involvement can promote that the needs, expectations, and esthetic considerations of the public are reflected by the land use decisions related to AVs.

5. Discussion

Our study identified and analyzed key factors influencing the adoption and integration of autonomous vehicles (AVs) in urban environments. Our findings are consistent with previous research results, aligning well with the established literature on the adoption and integration of autonomous vehicles.

Our findings align with multiple studies emphasizing the importance of robust policy and legislation frameworks for AV deployment. For instance, CEG (2019), NSW (2022), and KPMG (2018) all highlight the necessity of clear regulations to ensure safety, public acceptance, and seamless integration into current transportation systems. Technology advancements are crucial for AV development, as supported by studies such as those by Freemark et al. (2020) and Khan et al. (2019). Continuous innovation in sensor technology, machine learning, and AI is needed to enhance vehicle performance and safety. Consistent with numerous studies, our research underscores the importance of upgrading physical infrastructure to accommodate AVs. Studies by Fraedrich et al. (2019), Jiang et al. (2022), and Zali et al. (2022) emphasize that investments in infrastructure, such as roads and traffic signals, are crucial for the successful integration of AVs into urban environments.

Public readiness is a recurring theme in the literature. Educating the public about AV benefits and addressing safety concerns are critical for acceptance. Studies by Fraedrich et al. (2019) and Fagan et al. (2021) emphasize the need for effective communication strategies to improve public perception. Integration into existing transportation systems is essential for the successful deployment of AVs. This factor is supported by studies like those by Freemark et al. (2020) and NSW (2022), which discuss the challenges and solutions for integrating AVs into urban mobility frameworks.

Our research, in line with NSW (2022) and Zali et al. (2022), identifies data management as a key factor. Efficient data collection, storage, and analysis are vital for the operational success of AVs. Safety remains a paramount concern, as noted by Zali et al. (2022). Our study reaffirms that safety protocols and rigorous testing are essential to gain public trust and regulatory approval. Brovarone et al. (2021) and Zali et al. (2022) discuss vehicle communication, which is pivotal for AV coordination and accident prevention. Our findings suggest that developing robust vehicle-to-everything (V2X) communication systems can significantly improve traffic efficiency. Zali et al. (2022) highlight the importance of sustainable business models for AV deployment. Our study supports this, emphasizing that viable economic models are necessary for widespread AV adoption. Brovarone et al. (2021) and Zali et al. (2022) emphasize virtual infrastructure. Our findings indicate that digital infrastructure, such as high-definition maps and simulation environments, is crucial for AV operation.

Our study, consistent with Fraedrich et al. (2019) and Fagan et al. (2021), underscores the need for meticulous planning. Strategic urban planning can facilitate the integration of AVs and improve urban mobility. Freemark et al. (2020) and Fagan et al. (2021) discuss land use changes due to AVs. Our study supports this, noting that AVs can transform urban landscapes by reducing the need for parking spaces and potentially repurposing land for other uses. Finally, our study aligns with Freemark et al. (2020), Brovarone et al. (2021), and CEG (2019) regarding urban mobility. AVs have the potential to revolutionize urban transport, making it more efficient and accessible.

By comparing our findings with previous research, we highlight the multifaceted approach needed to address the challenges and leverage the opportunities presented by AVs. Effective policy, technological advancements, infrastructure upgrades, public readiness, and integration strategies are all critical components for the successful adoption of autonomous vehicles in urban environments.

A potential and highly significant future research direction could involve assigning indicators to the identified key determinants, thereby making it possible to measure AV readiness at the urban level. Future research could examine case studies of cities that have successfully integrated AVs into their transport systems. Future research should investigate the long-term urban planning implications of widespread AV adoption.

6. Conclusions

The present study addressed what is required for the mass adoption of AVs in future cities and for their effective and safe operation. The question was approached by synthesizing 223 urban AV readiness factors defined in the international literature with software-supported structured text and content analysis. As a result, the factors and key determinants of urban AV readiness were defined following several iterations.

It is to be emphasized that the identified factors and key determinants are required for the widespread adoption of AVs rather than their introduction. The increasing number of available urban road test results show that the urban appearance of AVs in a small number entails a minimum task for cities, however, their appearance in an increasing volume raises more serious issues (for example, in San Francisco). Therefore, proactivity is necessary on an urban level, the first step of which should be defining the aim of the city with AVs, as it determines the necessity of further steps.

It is important to see that AV technology offers a real theoretical opportunity to address the major challenges of urban mobility (traffic jams, noise, air pollution, congestion), nevertheless, it has essential conditions. An important condition is that AV technology can be counterproductive if its business model is private ownership. In this case, the AV owner, making a rational decision, will not pay for parking but use the car in traffic (ceteris paribus), thereby increasing urban traffic.

Therefore, promoting and getting the public to accept and use autonomous fleets for ridesharing is crucial, even though it seems challenging. If we also integrate connected vehicle technology into this system, sensors in vehicles, roads, and intersections will enable much more efficient traffic management and significantly improve road capacity.

Extending sensors to cyclists, pedestrians, and other road users considerably increases urban mobility safety. Their conditions and server technologies (e.g. 5G) are given but their instalment requires strategic decision making at urban level due to their time and cost claim. It does not only apply to technology, but also to the existing physical infrastructure, moreover, it raises safety and data management issues which require significant interventions in the case of the mass adoption of autonomous vehicles.

In the case of the mass adoption of autonomous vehicles, it is recommended that the city should find the place of this new mobility form in the urban mobility system and designate its specific role. Autonomous vehicles must be integrated into the existing public transport system and if possible, it is expedient to implement the entire urban mobility in the MaaS system.

Nevertheless, the effective operation of the new urban mobility paradigm requires the decision of the urban population to reduce private car ownership and increase autonomous fleet use. It must be supported in terms of both legislation and finances, facilitating fleet use and making private car ownership more costly. Involving the public into urban-level decision making related to autonomous vehicles is essential based on the experience of test cities. This will be important if the new urban model reduces the number of vehicles on city roads and transforms asphalt areas, changing the urban landscape.

Representing the 27 key determinants with indicators offers a great opportunity for further research, thereby urban autonomous vehicle readiness could be measured based on this synthesized framework.

It is evident that the urban-level mass adoption of autonomous vehicles offers significant, at first reading maybe futuristic opportunities, which also requires considerable preparation. It is to be emphasized that these preparations are not for some autonomous vehicles to appear and travel on urban streets but for the critical mass of AVs to provide benefits rather than drawbacks for cities.

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