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Research article

Extended reality in the automotive sector: A bibliometric analysis of publications from 2012 to 2022

Cristian-Cezar Postelnicu, Răzvan Gabriel Boboc *

Department of Automotive and Transport Engineering, Transilvania University of Brașov, 29 Eroilor Blvd., 500036 Brasov, Romania

A R T I C L E I N F O

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A B S T R A C T

The present study aims to present a bibliometric analysis of publications related to "Extended Reality" (XR) in the automotive sector. XR is revolutionizing the industry in all fields, and the automotive is one of the sectors that has had much to gain from this technology and its components (Virtual Reality, Augmented Reality, Mixed Reality). Articles on XR in the automotive field that were published from 2012 to 2022 were retrieved from the Scopus database. Extracted items were analysed in terms of the document type, document language, year of publication, country, authors, affiliations, sources, citations, keywords, and research domains. The open-source tool VOSviewer was used to visualize trends in research on XR applied to automotive. The analyses of 1584 documents revealed that the total number of publications has continually increased over the last 11 years. The country producing most of the articles in this field was Germany, followed by the United States and China. The most productive journal is Transportation Research Part F: Traffic Psychology and Behaviour and the institution that issued most of the articles is Technical University of Munich. From the analysis of author keywords, the prominent research areas currently involving the use of XR technologies in automotive can be highlighted: virtual prototyping, design, manufacturing, sales, training, driver or pedestrian behaviour analysis, and ergonomics. More recently, terms like artificial intelligence and autonomous vehicles have started to be used more frequently in studies in the field. The current study reveals an expanding corpus of literature on XR-based applications for the automotive sector using bibliometric methods. Researchers and stakeholders can use this study as a useful reference to comprehend the big picture and the state-of-the-art in this area.

1. Introduction

Extended reality (XR) technology combines the physical and digital worlds, and it includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) terms. XR technology has the potential to revolutionize the industry in all its areas, including the automotive sector [1]. In this paper, we will refer to XR as a replacement term for all types of reality: VR, AR, MR, and XR. The use of XR for a variety of automotive industry applications, including vehicle design [2], testing and simulation [3], training [4], education [5], and marketing and sales [6], has attracted increasing interest in recent years. XR refers to a combination of technologies that enable users to explore a world beyond reality [7], using three-dimensional (3D) graphic elements and other sensory experiences (e.g. touch, motion) [8] to create a sense of spatial presence [9]. Immersion and presence are two closely related characteristics of XR [10].

* Corresponding author.
E-mail address: razvan.boboc@unitbv.ro (R.G. Boboc).

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The first one is an objective property of the XR system, while the second one is the subjective experience of the user to be physically present in the virtual environment [11]. These features are two of the most important ones that give XR technology the potential to be used on a large scale in various applications and scenarios.

Thus, XR allows the creation of vehicle prototypes by car manufacturers that can be easily adjusted and tested without the use of physical prototypes. As a result, it is possible to test the aerodynamic performance of a vehicle [12], fuel efficiency [13], and other critical performance measures more thoroughly and accurately, which can save time and money. XR, thanks to the cutting-edge technology of our times, can be considered a completely immersive environment, allowing the possibility to create personal, realistic, unique, and interactive experiences [7]. It also provides users the ability to interact with the virtual world that can be customized according to their requirements [14]. For instance, customers could take virtual test drives and explore the features of a car in a highly immersive and interactive way [6]. Also, they could perform experiments in different scenarios and examine different car variations [15] or various interaction techniques for the design assessment [16]. XR equipment like Head-mounted displays (HMDs) can be used to simulate external events involving other vehicles or other things that could be risky or difficult to produce in a real-world environment [17]. Similar levels of immersion can be achieved with multi-projection systems like Cave Automatic Virtual Environment (CAVE) [18].

Additionally, XR is a promising training tool for assembly tasks [19] or, in the last years, for familiarizing drivers with automated vehicles [20,21] and to ease the transition from manual to autonomous driving scenarios [22]. This can be useful for both manufacturers and regulators, as it can help to improve the safety and performance of autonomous vehicles. Also, the use of XR to train artificial intelligence (AI) algorithms of autonomous vehicles seems to be a promising research direction [23].

The benefits of XR in the automotive domain should be attributed to design, virtual prototyping, manufacturing, virtual assembly, and training, as presented by Ref. [24]. Besides these, various other applications in connection with these areas can be mentioned: education – teaching/learning tools for students from Automotive programs [25,26], road safety – preventing life-threatening situations [27], logistics – increasing the effectiveness of processes [28], ergonomics – testing and validation of cooperation workplaces [29]. Thus, XR offers attractive ways through which one can interact with digital content, having the ability to enhance one's senses and understanding.

The goal of this bibliometric analysis is to give a quantitative summary of the XR-related studies and publications that have been published between 2012 and 2022 in the automotive industry. A bibliometric analysis is a type of study that employs statistical analysis to evaluate and measure the influence and impact of publications or research within a particular field and it is often considered the most suitable for studying the evolution of areas of scientific research [30,31]. It can be useful to understand research effort, structures, growth, and impact [32], such as trends in article and journal performance, collaboration patterns, intellectual structures of a specific domain [33], research priorities and references, research networks and geographical location [34]. In this line, the current analysis aims to provide insight into the current and future direction of XR in the automotive industry by comprehending the status of the field, the important players, and their contributions.

Bibliometric analysis was utilized to examine contemporary themes and discover future research topics about XR application in different fields of the industry: health [35], tourism [36], apparel industry [37], construction [38], engineering education and training [39], lean industry [40], built environment [41] and so on. However, to the best of our knowledge, a bibliographic study that covers the application of XR in the automotive field does not yet exist, even though there are numerous review articles addressing different issues: XR in the context of automated driving [42], XR development in automotive market research [43], network driving simulation [44], simulated driving research [45], or road safety [27].

Thus, in order to fill the gap in the scientific literature on bibliometric analysis of XR applications in the automotive sector, the following questions were investigated in this study:

What are the general patterns of publications in the automotive field using XR technologies?

Who are the most productive authors, to what extent do they collaborate and what is the distribution of papers by number of authors?

What are top-cited publications, what authors are most cited, and what institutions are they affiliated with?

What are the sources that published most on the topic and what types of publications are more active?

What are the most significant keywords used in the research related to XR applied to automotive?

2. Materials and methods

2.1. Data source and search strategy

In this study, the Scopus database was used to conduct the bibliometric analysis. Scopus is one of the largest databases of abstracts and citations for academic research literature, including scientific journals, conference proceedings, and books and it covers a wide range of disciplines, including engineering, medicine, social sciences, art, and humanities. For bibliometric analysis, Clarivate Analytics' Web of Science (WoS) and Elsevier's Scopus are the main sources for citation data [46]. Even though WoS was the first data source available and it is well-recognized in the academic community, Scopus has become a good alternative [47], having wider, inclusive and comprehensive coverage of content [48], in some domains, higher than WoS [49,50]. Moreover, Scopus provides available individual profiles for all authors, institutions, and serial sources [51], and it contains a more recent and broader range of journals [52]. In this paper, a single database was used to retrieve the data to avoid errors caused by the integration of data from different databases, having different formats, as stated also in study by Mühl et al. [53].

The search performed in the Scopus database aimed to identify documents related to virtual reality, augmented reality, mixed reality, and extended reality, but at the same time related to automotive, driving, transportation, and vehicle terms. Transportation is a key part of the automotive industry, while driving is not explicitly included, but it is a critical part since this field will not exist without drivers. The term "vehicle" was also included since the goal of the automotive industry is to produce vehicles that people can drive. The authors have specifically chosen the four terms to better include the documents from the database, since the information was filtered only based on Title, Abstract and Keywords fields.

The search was performed using the following query: TITLE-ABS ("virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality") AND TITLE-ABS-KEY (automotive OR driving OR transportation OR vehicle) AND PUBYEAR >2011 AND PUBYEAR <2023 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")). The abbreviations used in the query are detailed in the next section. The search generated 3860 documents during the chosen timespan. The search was carried out on August 7, 2023. The publication records were extracted as a.CSV file using the advanced search option offered by Scopus. The file was imported into MS Excel and VOSviewer software (version 1.6.18) [54] was used for mapping analysis.

2.2. Inclusion and exclusion criteria

Starting with the 3860 documents, we investigated if each paper was specifically related to the XR domain and also to the automotive field. We read all the abstracts and based on its content we could identify if the desired conditions were met. We excluded any paper that did not meet the desired conditions, and we also excluded papers where a state of the art or a review was presented, even if the previous conditions were met. We only considered research papers that had contributions to the automotive and XR fields, and in the end, we selected a total of 1584 that met the desired conditions.

The inclusion criteria were as follows: articles in the field of automotive research using XR technology, and the publication timespan was set from January 1, 2012 to December 31, 2022. Conference review ("cr"), review papers ("re"), book chapters ("ch"), books ("bk"), notes ("no"), short surveys ("sh"), erratum ("er"), editorials ("ed"), letters ("le"), retracted papers ("tb"), and articles that were not related to the selected keywords were excluded. Thus, only journal articles ("ar") and conference papers ("cp") were included. The initial query that did not include the restrictions mentioned above related to paper types returned a total number of 4693 documents. Fig. 1 shows the methodology for identifying and selecting the studies. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was used for retrieving articles [55]. The authors mention that they used the PRISMA guidelines only to extract the relevant scientific papers, but the article is structured as a bibliometric analysis, not as a systematic literature review. Bibliometric analysis is a way of measuring, tracking, and analysing scholarly literature in a specific manner by employing a set of quantitative approaches [31]. It highlights a field's bibliometric and intellectual structure by examining the social and structural linkages between various research components (e.g., authors, countries, institutions, and topics) [33].

2.3. Data analysis

The selected documents were analysed with specialized software and the following bibliometric indicators were obtained: type of document, the language of the document, year of publication, number of documents/authors, number of publications by country and country cooperation, number of papers by affiliation, number of papers by authorship and the authors' cooperation, number of citations, number of papers by source and co-citation analysis, co-occurrence of keywords.

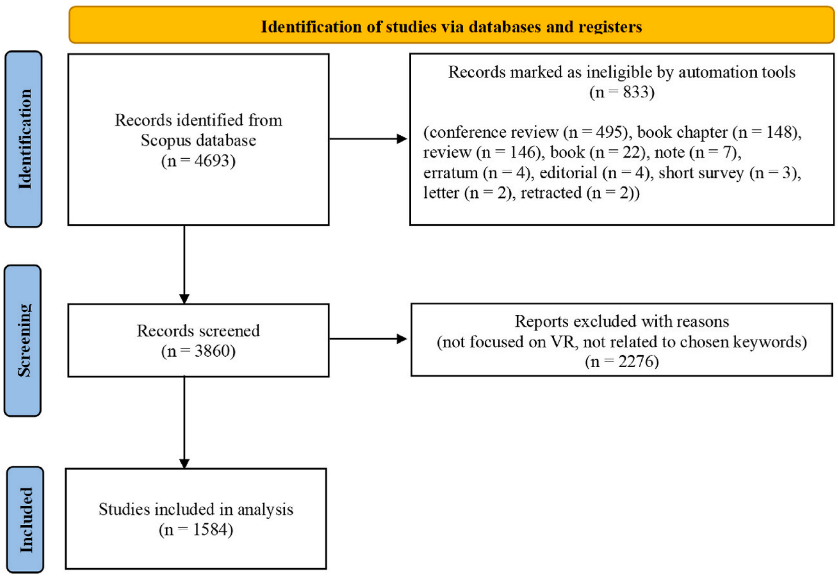


Fig. 1. Overview of the methodology applied to bibliometric analysis.

The bibliometric analysis procedure was carried out according to the following steps.

- Database selection: Scopus;
- Search within Article title, Abstract, and Keywords; Article title, Abstract;
- Setting timespan: January 01, 2012 to December 31, 2022;
- Data collection: a.csv file downloaded from Scopus;
- Data analysis: VOSviewer and Microsoft Excel;
- Results: presented in the form of tables, charts, or diagrams.

3. Results and discussion

In this section, the research results and discussion of the bibliometric analysis will be presented, providing a descriptive overview of the quantitative scientific production in the XR-based limited only to the automotive industry.

3.1. Summary of bibliometric information

The results of the bibliometric analysis revealed that there were 1584 articles obtained from Scopus written by 5064 different authors and published in 777 sources. The publications are dominated by "conference papers" (60.80 %) and "journal articles" (39.20 %) (Fig. 2a). The papers have been written mostly English language (1531 records, 96.65 %), followed by Chinese (36, 2.27 %), German (5, 0.32 %), Japanese (3, 0.19 %), Portuguese (3, 0.19 %) and other languages with a share of less than 0.1 %, like Spanish, French, Persian, or Korean. The types of papers that are retracted are illustrated in Fig. 2b.

The results show that XR research in the automotive field has experienced significant growth over the last decade. About 59 % of the total number of papers were published within the last 4 years when the number of articles per year exceeded 200 (Fig. 3a). Most articles were published in 2020 (15.47 %). Regarding the number of authors per year, the increase is similar (Fig. 3b), with the most authors in 2022 (16.36 %).

3.2. Distribution of papers by region

The publications in XR-based applications for the automotive sector originated from 67 countries. Among these countries, 30 are in Europe, 23 in Asia, 5 in Africa, 4 in North America, 3 in South America, and 2 in Oceania. Fig. 4 presents the global distributions of the selected articles. Europe is the most productive continent with 45.50 % of the total number of publications, followed by Asia (31.38 %), North America (17.73 %), Oceania (2.88 %), South America (1.57 %), and Africa (0.94 %). A number of 26 countries (38.81 %) have produced between 1 and 5 publications, 22 countries (32.83 %) have produced between 6 and 19 publications, and 28.36 % of them (19 countries) have produced more than 20 publications. Approximately 18.88 % (n = 299) of the included studies are from Germany, 17.99 % (n = 285) are from the United States and 15.28 % (n = 242) belong to China. Among the countries with publications between 6 and 19, the most productive ones are Portugal (18 publications), Singapore (16 publications) and Switzerland (with 15 publications). It can be observed that the largest contributions are given by countries that are highly developed economically and technologically, such as those from the G7 group or BRICS group [56]. Eighty-one percent of the studies are from nations in these two groups. Table 1 presents the top 10 countries that had contributions and shows the number of publications and number of citations. It is noteworthy that the total number of citations is valid for the date of August 7, 2023, when the authors retrieved the data from the Scopus database.

To get a better visualization of the most productive countries, we provide the cooperation network in Fig. 5. The analysis was developed in VOSviewer software. The minimum number of documents for each country was set to 10, resulting in 30 countries that met the threshold. For each country in Fig. 5, the circle size represents the volume of publications, and the connections represent collaboration with other countries. There are seven main clusters: the first one relates to Germany (yellow colour), the second one

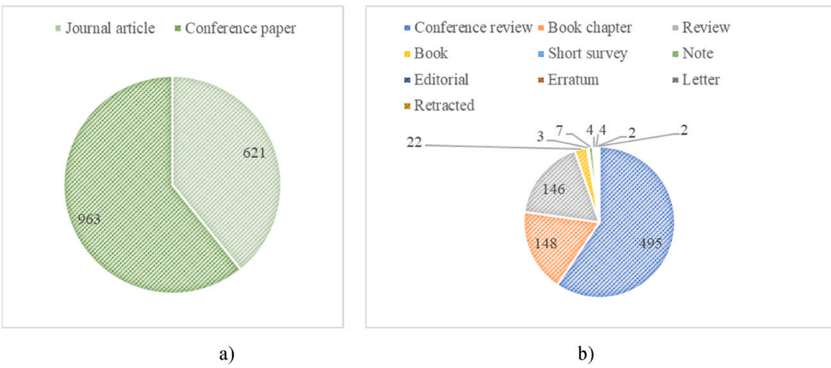
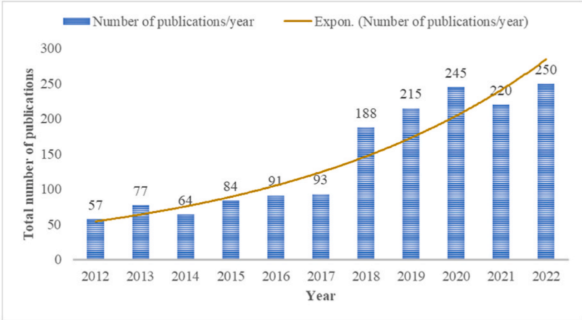
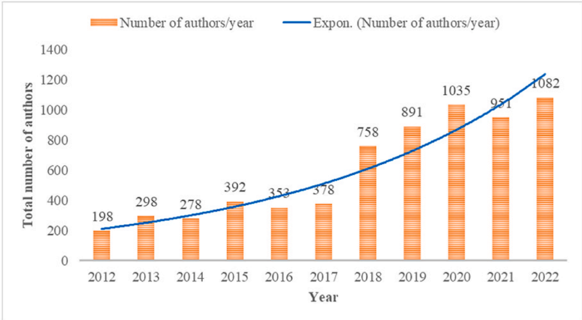


Fig. 2. Distribution of papers by type: a) selected paper; b) removed papers.



a)



b)

Fig. 3. Evolution of the number of publications (a) and authors (b) over time.

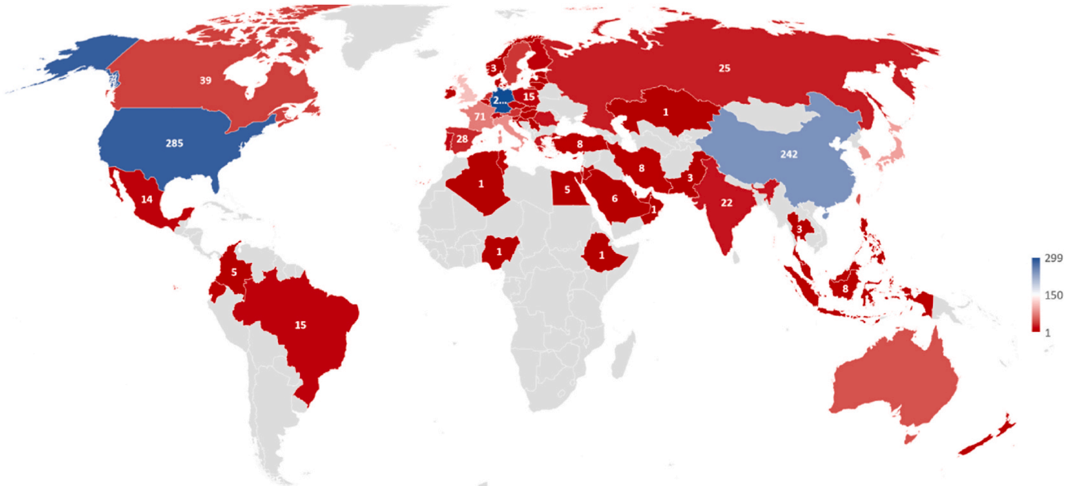


Fig. 4. Number of publications by country.

relates to the United States (green colour), the third one relates to China and Australia (purple colour), the fourth cluster relates to South Korea and Italy (red colour), then Japan and France (blue colour), Spain and India (turquoise colour), and Portugal (orange colour). Germany is the most influential country with a total link strength (TLS) of 93, followed by the United States and China. As is expected, the image illustrates a tendency for co-authorship in cross-country collaboration. While the United States has collaborations with countries from all over the world, Germany has mainly collaborations with countries from Europe.

3.3. Distribution of papers by affiliation

A total of 1870 entities were found in relation to the research institutes that the publications are associated with. Of these, 1745 (93.32 %) institutions published between 1 and 5 articles, 96 (5.13 %) published between 6 and 10 studies, and 1.55 % of them (n =

Table 1
Top 10 contributing countries.

Rank	Country	Papers	Citations
1	Germany	299	2767
2	USA	285	2678
3	China	242	832
4	United Kingdom	112	921
5	Japan	93	448
6	South Korea	86	494
7	Italy	81	487
8	France	71	458
9	Australia	48	563
10	Taiwan	48	479

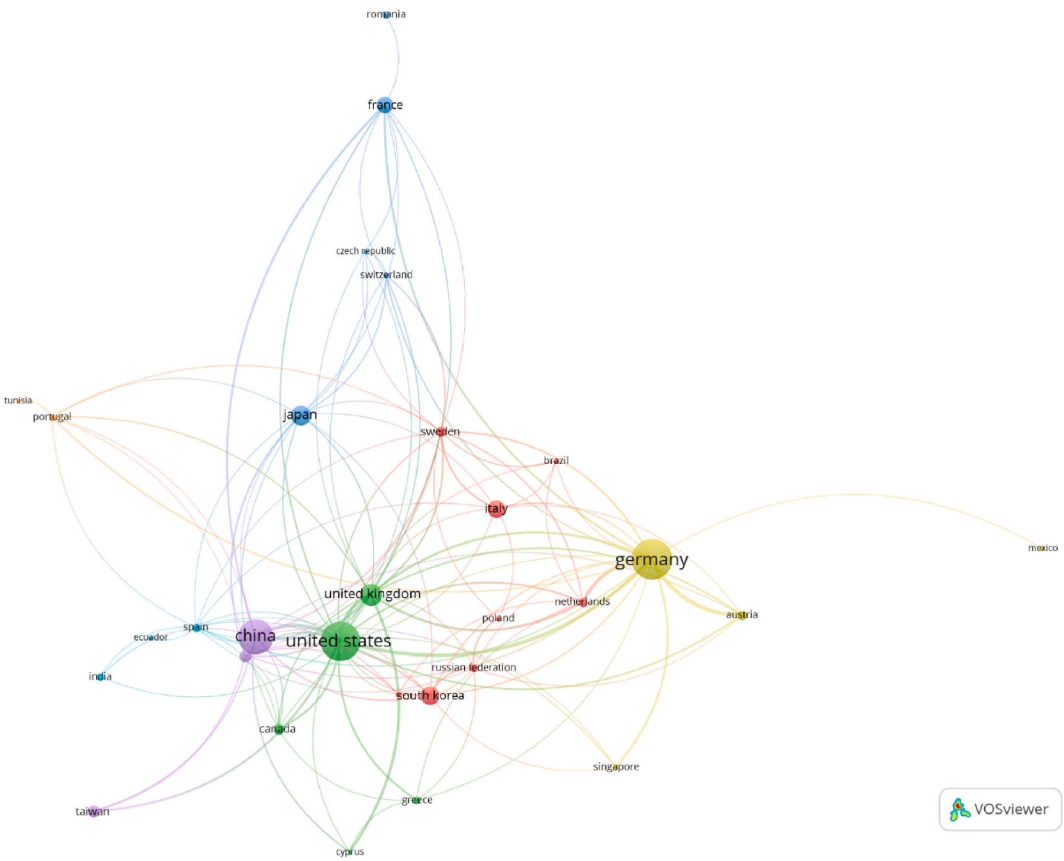


Fig. 5. Cooperation network between countries.

Table 2
Top 10 institutions in which articles were published.

Rank	Institution	Country	Publications	%
1	Technical University of Munich	Germany	42	2.65
2	Virginia Polytechnic Institute and State University	USA	41	2.59
3	Technische Hochschule Ingolstadt	Germany	31	1.96
4	CNRS	France	30	1.89
5	Ulm University	Germany	27	1.70
6	Daimler AG	Germany	19	1.20
7	Electronics and Telecommunications Research Institute	South Korea	19	1.20
8	Tongji University	China	15	0.95
9	University of Nottingham	United Kingdom	15	0.95
10	University of Patras	Greece	13	0.82

29) published more than 10 papers. Table 2 presents information on the top 10 most productive organizations. The Technical University of Munich is the most productive academic institution, with 42 publications, followed by Virginia Polytechnic Institute and State University (41 publications). The top 10 institutions published 252 papers (15.91 % of the total number of published articles). Most of the institutions involved in the research related to XR technologies applied to automotive are universities, but there are also other institutions, such as private or governmental organizations, research centres, and institutes.

3.4. Authors and their cooperation

As mentioned above, the 1584 references were published by 5064 authors. The number of authors ranged from 1 to 18 authors per study. The mean number is 4.18 authors per document. Table 3 presents the overview of the publications depending on the number of authors and the number of citations obtained for each category. Most of the articles are written by 3, 4, or 5 authors, and this is also the case in terms of the number of citations. A percent of 99.72 % (n = 5050) of authors published between 1 and 9 articles and 0.28 % (n = 14) of them published more than 10 studies.

Table 4 presents a list of the first 10 authors who have the highest number of published articles in the field. Details about their affiliation, country, the number of papers, the total number of citations, and the Scopus h-index of the authors for the selected papers are given. By analysing the data Joseph Gabbard is the most productive author, with a total number of 27 publications. He is the first author of 3 papers and his Scopus h-index is 9. The paper [57] received the most citations (175). Andreas Riener is the second most prolific author, with 26 studies and a total number of 303 citations. The most cited work is [58], having 70 citations in Scopus. Enrico Rukzio is the third on the list, with 22 publications and a Scopus h-index of 8. His most cited paper is [59] with 77 citations.

The pattern related to author cooperation is presented in Fig. 6. The co-authorship analysis was performed in VOSviewer and it shows the network of the 75 authors who exceeded the minimum count of 5 publications. It can be seen that 4 clusters can be distinguished and illustrated with different colours. Joseph Gabbard is the most influential author with a TLS of 44. Even if most are published with colleagues from the same institution or organization, there is also a collaboration between authors from different organizations belonging to different countries. We can mention two examples: Joseph Gabbard, from Virginia Polytechnic Institute and State University, USA, with Tamara von Sawitzky, from Technische Hochschule Ingolstadt, Germany [60]; Missie Smith, from Oakland University, USA, with Gary Burnett, from University of Nottingham, UK [61].

3.5. Document citation

Table 5 displays a list of the most cited documents including the following information: title, the source where it was published, the total number of citations, the number of citations in 2022, Field-Weighted citation impact (FWCI), which is an indicator of mean citation impact [62], and Normalized Citation Impact Index (NCII). FWCI shows how frequently one document is cited compared to similar works and is calculated with the following formula:

$$FWCI_i = \frac{c_i}{e_i} \tag{1}$$

where c_i is the number of citations received by publication i and e_i is the expected number of citations per publication received by similar publications.

NCII takes into account the longevity of the publications [63] and was calculated as:

$$NCCI_i = \frac{c_i}{l_i} \tag{2}$$

where c_i is the number of citations received by publication i and l_i is the longevity of the publication (in years).

Table 3
Publication distribution according to the number of authors.

No. of authors	No. of publications	%	No. of citations	Mean citation/document
1 author	79	4.99	134	1.70
2 authors	193	12.18	841	4.36
3 authors	372	23.48	2571	6.91
4 authors	355	22.41	2765	7.79
5 authors	255	16.10	1912	7.50
6 authors	169	10.67	930	5.50
7 authors	70	4.42	961	13.73
8 authors	41	2.59	569	13.88
9 authors	25	1.58	440	17.60
10 authors	17	1.07	140	8.24
12 authors	3	0.19	0	0.00
13 authors	2	0.13	5	2.50
14 authors	1	0.06	1	1.00
17 authors	1	0.06	77	77.00
18 authors	1	0.06	51	51.00

Table 4
Top 10 most-productive authors.

Author	Affiliation, country	Papers	Citations	Scopus h-index
Gabbard, Joseph, L.	Virginia Polytechnic Institute and State University, USA	27	441	9
Riener, Andreas	Technische Hochschule Ingolstadt, Germany	26	303	10
Rukzio, Enrico	Universität Ulm, Germany	22	210	8
Kim, Kyong-Ho	Electronics and Telecommunications Research Institute, Daejeon, South Korea	19	223	8
Colley, Mark	Universität Ulm, Germany	19	118	6
Warren, Zachary E.	Vanderbilt University	13	318	10
Sarkar, Nilanjan	Vanderbilt University	13	318	10
Wade, Joshua W.	Vanderbilt University	13	318	10
Riegler, Andreas	University of Applied Sciences Upper Austria, Austria	12	102	7
Charissis, Vassilis	Glasgow Caledonian University	12	68	5

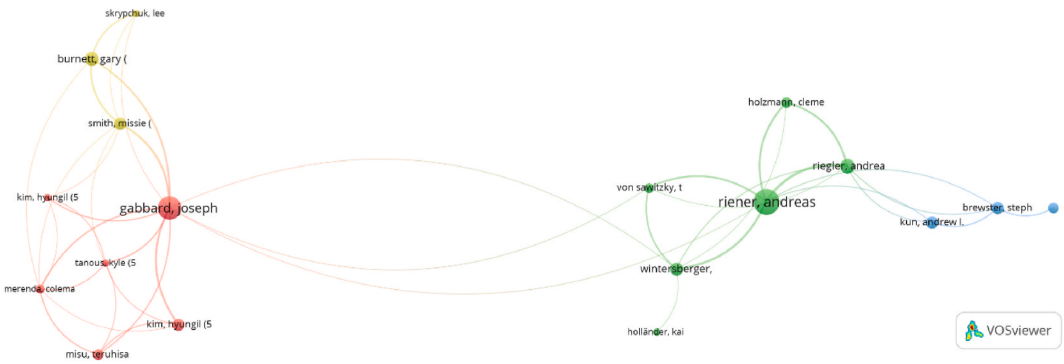


Fig. 6. Authors cooperation network.

Table 5
Top 10 highly cited papers.

Ref.	Title	Source	Citations	Citations in 2022	FWCI	NCII
[64]	Augmented Reality Meets Computer Vision: Efficient Data Generation for Urban Driving Scenes	International Journal of Computer Vision	237	53	11.01	47.4
[65]	Augmented reality system for operator support in human–robot collaborative assembly	CIRP Annals - Manufacturing Technology	176	30	7.94	25.14
[57]	Behind the glass: Driver challenges and opportunities for AR automotive applications	Proceedings of the IEEE	175	31	7.51	19.44
[66]	Eyes on a car: An interface design for communication between an autonomous car and a pedestrian	AutomotiveUI 2017 - 9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, Proceedings	149	33	15.85	24.83
[24]	Future directions for the development of virtual reality within an automotive manufacturer	Applied Ergonomics	138	19	8.99	19.71
[67]	Augmented reality tools for industrial applications: What are potential key performance indicators and who benefits?	Computers in Human Behavior	121	42	6.93	24.20
[68]	Augmented Reality (AR) Applications for Supporting Human-robot Interactive Cooperation	Procedia CIRP	120	28	18.57	17.14
[69]	Social influence on route choice in a virtual reality tunnel fire	Transportation Research Part F: Traffic Psychology and Behaviour	120	12	2.47	13.33
[70]	Brain Dynamics in Predicting Driving Fatigue Using a Recurrent Self-Evolving Fuzzy Neural Network	IEEE Transactions on Neural Networks and Learning Systems	114	20	4.05	16.29
[71]	Designing take over scenarios for automated driving: How does augmented reality support the driver to get back into the loop?	Proceedings of the Human Factors and Ergonomics Society	111	20	15.76	12.33

Source of publications

Among these top 10 high-impact articles, two were published in Accident Analysis and Prevention, two in Transportation Research Part F: Traffic Psychology and Behaviour, and two in Proceedings of the Human Factors and Ergonomics Society. The paper [64] had the greatest total citation score (237 citations) at the time of the analysis and it is also the first if the average number of citations per year is considered (47.4). The papers presented in the table were published between 2014 and 2018.

A ranking of the top 10 cited journals has been created (Table 6) to indicate the influence of various journals since they have a greater scientific impact. The following information was presented in the table: source name, ISSN, publisher, number of articles on the chosen topic, percentage of the total number of items, the total number of citations obtained by those articles, the impact factor of the journal, quartile ranking and CiteScore based on Scimago Journal Ranking (JCR 2021). The journal Transportation Research Part F: Traffic Psychology and Behaviour published the most papers from the total number of papers in the selected time frame (n = 22, 1.39 %). Accident Analysis and Prevention is the second in the ranking in terms of the number of works, followed by Applied Sciences.

To make a difference between journal articles and conference papers, Table 7 displays the top 10 of the most productive conference Proceedings. Details related to the title of the conference proceeding, publisher, number of articles received by the paper published in the proceeding, what percentage it represents of the total number of articles and the total number of citations obtained by the articles published in the respective volume. Lecture Notes In Computer Science published the most documents (n = 85), a percentage of 5.37 % of the total number of papers. The second conference volume that published the most articles is Adjunct Proceedings of International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, with 58 articles.

The total number of 1584 articles were published in 777 sources. Of these, 738 sources (94.98 %) published between 1 and 5 papers, 21 (2.70 %) published between 6 and 10 papers, and 18 (2.32 %) published more than 10 articles. Fig. 7 shows the annual distribution of articles according to the 10 most influential publications, whether it is a journal or a conference proceeding.

The bibliographic coupling analysis illustrated in Fig. 8 considers the minimum number of 5 documents of a source. Of the 777 sources, 49 meet the threshold and resulted in 8 clusters that are highlighted in different colours. The higher number of documents for a source is indicated by the size of the circles and the level of the relationship with other authors is determined by the distance. Proceedings of Conference on human factors in computing systems has the highest TLS (128). Among journals, Transportation Research Part F: Traffic Psychology and Behaviour obtained the most citations, but the connection with other sources is not so strong.

3.6. Subject area publications

Table 8 revealed the top 10 subject areas as they were classified in the Scopus database. It was found that the maximum contribution on the topic of automotive-related XR research was done by the Computer Science research field, followed by Engineering and Mathematics. Please note that some of the publications belong to more than one subject area thus the total number of publications does not correspond to the 1584 selected documents.

Fig. 9 presents the co-occurrence map of the author's keywords using the full counting method. Of the 5175 keywords, 95 meet the threshold of 10 occurrences. It results in a network of keywords grouped in 6 clusters. These clusters reveal topics with many interconnected elements. The frequency of use of a keyword determines the circle's size. Shorter distances between keywords indicate stronger links between them. The connection is given by the number of times the terms appear together. As shown in the diagram, "virtual reality ", "augmented reality", and "vehicles" are some of the most commonly used terms. "Virtual reality" has 498 occurrences, and the value of TLS of 1002, "augmented reality" has 364 occurrences, and TLS is 524, "vehicles" has 86 occurrences, TLS = 332, "driving simulator" has 78 occurrences, TLS = 99, "mixed reality" has 68 occurrences, TLS = 109, and "autonomous vehicles" has 66 occurrences, and a value for TLS of 172. The red cluster is related to virtual reality aspects and driving simulation, including head-mounted display and visualization. The blue cluster is related to augmented reality, head-up displays, artificial intelligence, navigation, and industry 4.0. The green cluster contains terms referring to vehicles, intelligent systems, and human-computer interaction. The aspects related to pedestrian behaviour and safety are grouped in the yellow cluster and those related to autonomous vehicles are included in the purple one. Finally, the turquoise cluster contains terms related to head-mounted displays and simulators.

Table 6
Top 10 most active journals.

Rank	Journal	ISSN	Publisher	No. of articles	%	No. of citations	IF[a] (2021)	Quartile	CiteScore 2021
1	Transportation Research Part F: Traffic Psychology and Behaviour	1873–5517	Elsevier	22	1.39	634	4.349	Q2	7.4
2	Accident Analysis And Prevention	1879–2057	Elsevier	19	1.20	413	6.376	Q1	8.9
3	Applied Sciences	2076–3417	MDPI	14	0.88	80	2.838	Q3	3.7
4	IEEE Transactions on Intelligent Transportation Systems	1524–9050	IEEE	12	0.76	232	9.551	Q1	13.7
5	IEEE Access	2169–3536	IEEE	12	0.69	136	3.476	Q2	6.7
6	IEEE Transactions on Visualization and Computer Graphics	1077–2626	IEEE	11	0.69	211	5.226	Q1	11.4
7	Applied Ergonomics	0003–6870	Elsevier	9	0.57	359	3.94	Q2	6.8
8	Virtual Reality	1359–4338	Springer	8	0.51	80	4.697	Q1	7.8
9	Sensors	1424–8220	MDPI	8	0.51	48	3.847	Q2	6.4
10	Sustainability	2071–1050	MDPI	8	0.51	41	3.889	Q4	5.0

[a] IF – Impact factor.

Table 7
The top 10 most active conference Proceedings.

Rank	Title (conference proceeding)	Publisher	No. of articles	%	No. of citations
1	Lecture Notes In Computer Science (Including Subseries Lecture Notes In Artificial Intelligence And Lecture Notes In Bioinformatics)	Springer Nature	85	5.37	368
2	Adjunct Proceedings - International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications	ACM	58	3.66	1081
3	Advances In Intelligent Systems And Computing	Springer Nature	28	1.77	117
4	Proceedings of SPIE - The International Society for Optical Engineering	SPIE	28	1.77	38
5	ACM International Conference Proceeding Series	ACM	26	1.64	208
6	Proceedings of IEEE Intelligent Vehicles Symposium	IEEE	22	1.39	185
7	Procedia CIRP	Elsevier	20	1.26	276
8	Conference on Human Factors in Computing Systems – Proceedings	ACM	19	1.20	311
9	IEEE Conference on Virtual Reality and 3D User Interfaces	IEEE	16	1.01	145
10	Digest of Technical Papers - SID International Symposium	SID	14	0.88	58

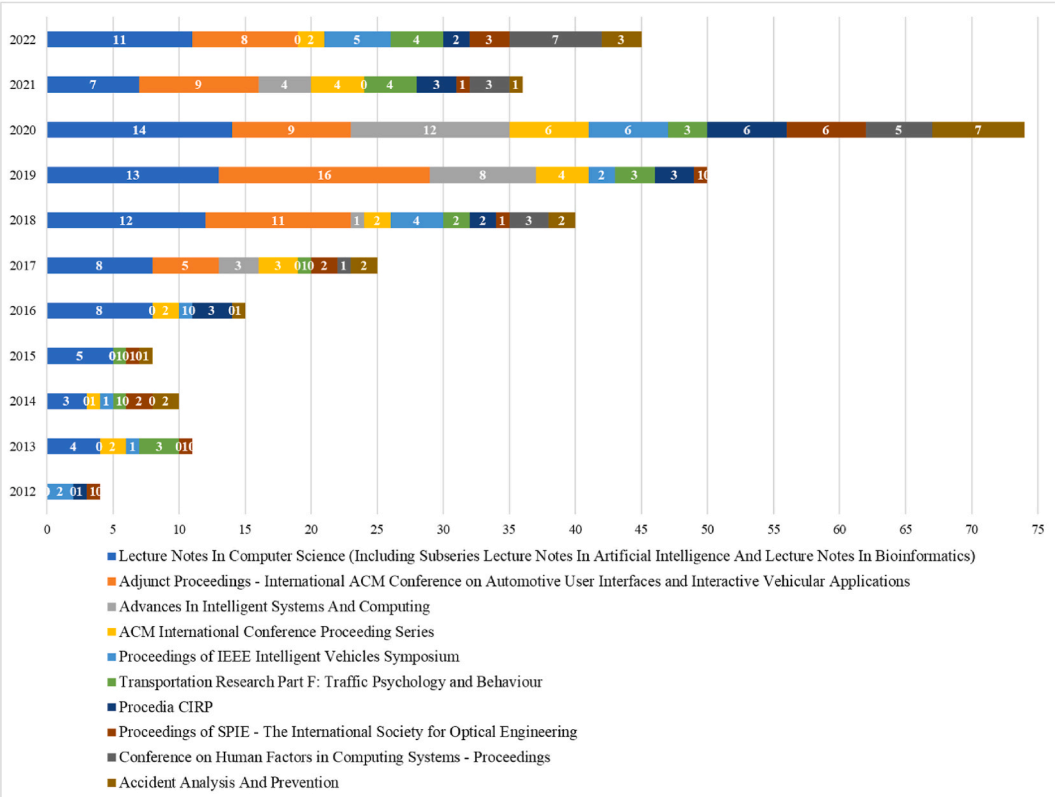


Fig. 7. Number of publications per year by top 10 most active sources.

Fig. 10 shows the top 12 keywords from January 1, 2012, to December 31, 2022. Besides the established terms ("augmented reality" and "virtual reality"), with most of the occurrences, growing trends can be observed for topics related to mixed reality, safety, training, head-mounted display (HMD), head-up display (HUD), driving simulator, or pedestrian. It can be also seen that keywords like artificial intelligence and autonomous driving started to be used later (from 2015) in automotive research, which corresponds to the industrial revolution of recent years. Examples of applications for mixed reality include training of operators [72], analysing worker's experience [73], testing automated driving functions [74], assessing driver's social presence [75], and virtual prototyping [76]. The use of HUD use in scientific studies has been continuously increasing since 2012, with a peak in 2019 [77–81], and HMDs were included since 2016 [82–85]. The use of driving simulators has a similar evolution [86–90].

After clustering the author keywords, the most prominent research fields currently involving the use of XR technologies in the automotive sector can be highlighted. These emerging technologies are used in many fields of automotive, starting from virtual prototyping, design, manufacturing, sales, training, driver or pedestrian behaviour analysis, ergonomics and safety, having an impact

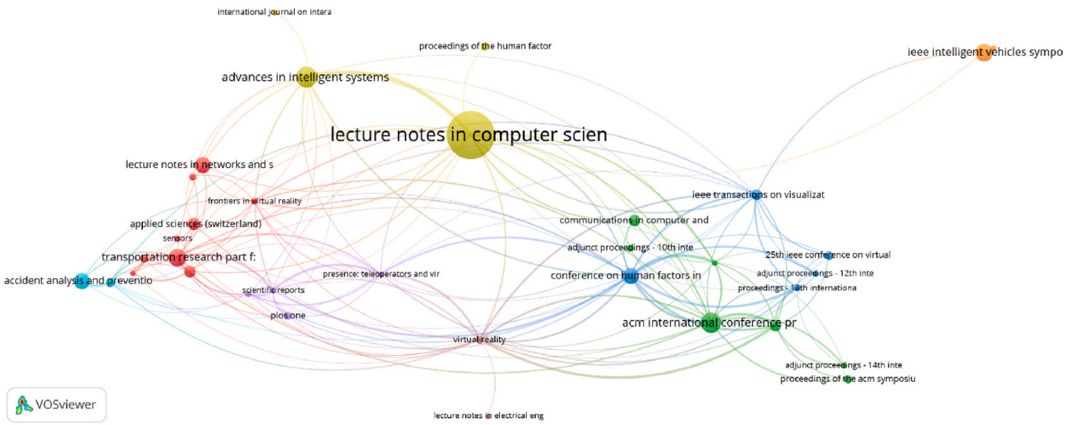


Fig. 8. Bibliographic coupling analysis of highly cited sources.

Table 8
The top 10 subject areas.

Rank	Subject area	No. of publications	%
1	Computer Science	1042	65.78
2	Engineering	852	53.79
3	Mathematics	292	18.43
4	Social Sciences	176	11.11
5	Physics and Astronomy	165	10.42
6	Materials Science	131	8.27
7	Medicine	88	5.56
8	Decision Sciences	74	4.67
9	Psychology	48	3.03
10	Environmental Science	47	2.97

even in the recently developing field of self-driving vehicles. It is obvious that various challenges restrain the large-scale adoption of the technology in the industries and implicitly the automotive industry [91,92]. These findings are in line with other systematic review papers related to automated driving [42,93,94], AR in the automotive field [95], driving simulators [96–98], or driving behaviour [99]. Through the bibliometric investigation, we found that there is a lack in the scientific literature of a systematic review that studies XR applications in the automotive field. Thus, this paper might be a good starting point for a systematic literature review.

Looking ahead, it is evident that the integration of XR in the automotive sector has great potential, but it also comes with a few challenges. To guide future research endeavours in this field, we outline a future research agenda with a specific focus on key topics based on keyword analysis. The following should be a concise summary of the research agenda with the aim of assisting academics and practitioners in understanding the relationship between XR and automotive.

- safety enhancement: investigating the potential of XR technologies to enhance safety in autonomous driving scenarios; exploring XR-based solutions for better situational awareness, obstacle detection, and collision avoidance; assessing the impact of XR on driver distraction and cognitive load in various driving conditions; creating adaptive XR interfaces that prioritize safety during critical situations;
- training and skill development: investigating the effectiveness of XR solution to enhance training for automotive employees; comparing the outcomes of XR training with traditional methods and identifying best practices; exploring the integration of AI-based simulations in XR training environments, providing adaptive scenarios and personalized feedback to improve skill acquisition; exploring the full potential of XR in vehicle maintenance and repair processes, including remote diagnostics, augmented repair guidance, and predictive maintenance;
- optimizing HMDs and HUDs: investigating advanced optical and ergonomic designs for HMDs and HUDs to maximize comfort and usability and to minimize visual fatigue and motion sickness; analysing user preferences and acceptance of different HMD and HUD technologies to guide design decisions and improve integration in vehicles;
- enhancing driving simulators with XR: developing XR-enhanced driving simulators that closely mimic real-world driving conditions, enabling more realistic training and testing scenarios for autonomous vehicle development; investigating the use of AI in driving simulators to create dynamic and adaptive environments, simulating unpredictable real-world conditions;
- pedestrian interaction and safety: exploring XR-based solutions to improve pedestrian safety in urban environments; designing XR interfaces that enhance pedestrian visibility and communication with autonomous vehicles; studying the impact of XR on pedestrian trust and behaviour when interacting with autonomous vehicles;

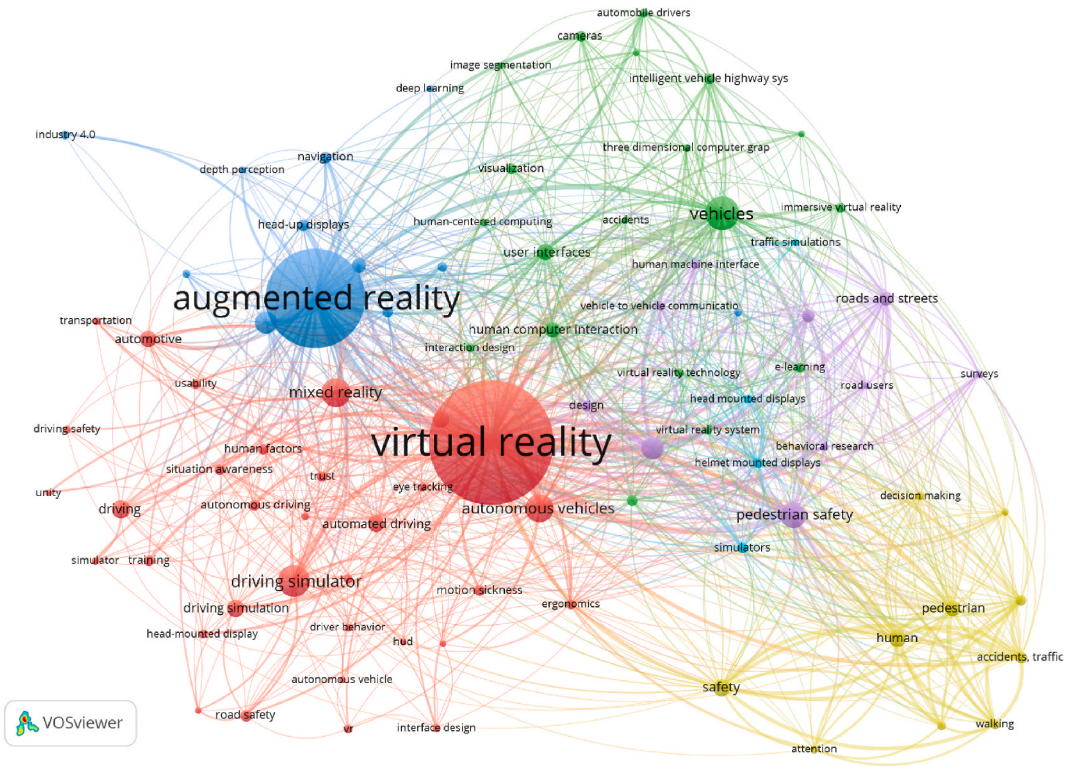


Fig. 9. Co-occurrence network of keywords.

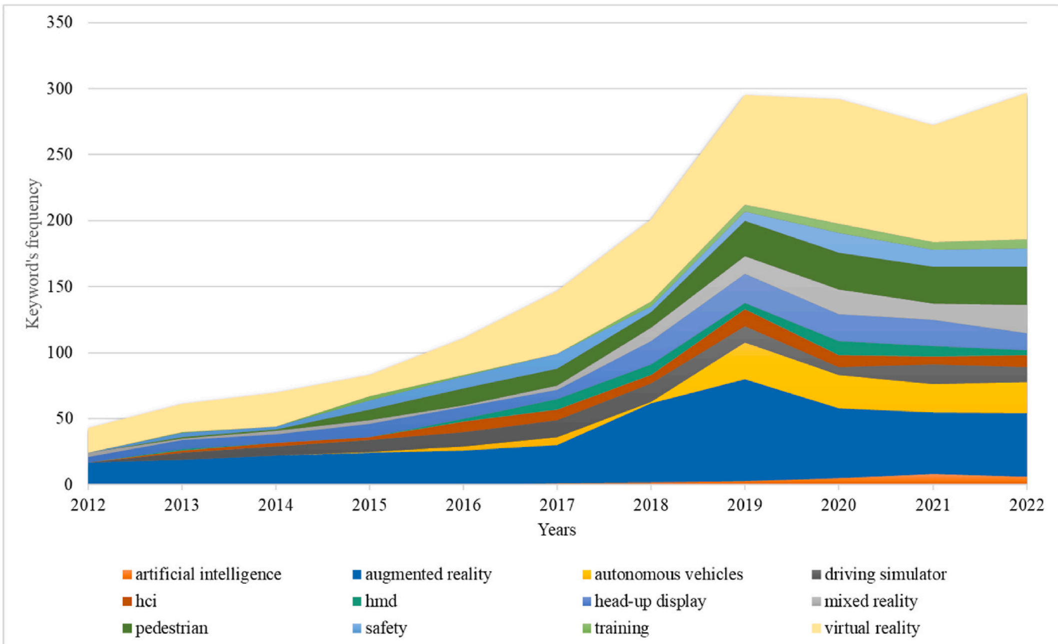


Fig. 10. Evolution of top 12 keywords within the analysed papers in the chosen period.

- AI integration for autonomous driving: examining the role of AI in autonomous driving systems, including AI-driven decision-making processes and real-time data analysis to improve safety and efficiency; investigating the ethical implications of AI-based XR interfaces in autonomous vehicles, including issues related to accountability and transparency;

- improving human-computer interaction: analysing the user experience and ergonomics of XR interfaces in vehicles, considering factors such as user preferences, comfort and usability; developing adaptive HCI designs that tailor XR interactions to individual driver preferences and needs; improving customer experiences, allowing them to virtually test and visualize a vehicle before buying it; designing user-centred XR interface, especially for individuals with varying abilities, to ensure the universal accessibility of vehicles.
- enhancing collaboration: providing XR solutions capable of connecting professionals from different fields in one virtual space to discuss and exchange opinions.
- privacy-preserving: addressing concerns related to data collection and user privacy when developing XR solutions for vehicles.

Interdisciplinary cooperation between computer scientists, psychologists, and ethicists as well as automobile engineers will be essential for pursuing these research directions. To ensure the ethical application of XR technologies in the automobile industry, it is also crucial to uphold a strong ethical framework throughout research and development. This research agenda will contribute to the promoting of innovation and helping to create mobility solutions that are safer, sustainable, and more effective in the XR era.

4. Limitations

The data collection was limited to the Scopus database. Even if it provides a diversity of publications in different areas, future works should also consider other databases that are more comprehensive but maintain the high quality of the publications. Also, the study analysed the work quantitatively, and the content of the articles was not studied, which is a characteristic limitation of bibliometric analysis. Because the volume of the analysed publications is very large, there is the possibility of including articles that do not entirely fit the topic, even if the authors tried to select only the proper documents based on the defined criteria. With all these small lapses, we think that the analysis is conclusive enough.

5. Conclusions

Virtual reality, one of the promising technologies underlying Industry 4.0 [100], has shown its ability to bring many benefits to the automotive industry, including improving design and engineering, enhancing showroom experiences, increasing personalization, providing training and cost-effective solutions through virtual prototypes.

The present study provided an overview of the research in the last eleven years in the field of XR-related applications in the automotive industry. The bibliometric analysis of the literature shows a rapid increase in research and development activities in the field. The results demonstrate a growing interest in the use of XR technology and a high level of international collaboration between authors and organizations. The results also point to an increase in interdisciplinary research, which brings together experts from different fields.

Overall, the study offers insightful information about the state of XR for automotive research today. The main conclusions that can be drawn are the following.

- most of the analysed documents are conference papers, written in the English language;
- there is an increasing trend in the number of publications over the selected period, but the growth has accelerated in the last 5 years;
- the representatives of the continents of Asia, North America, and Europe (China, United States, Germany) are in the first place in terms of the number of publications and there is a close collaboration between them;
- Germany dominates in terms of the number of institutions to which authors who have published articles in the field are affiliated;
- most articles have 3 authors, their number being almost equal to those with 4 authors, and they obtained the most citations;
- the documents with the most citations are published in conference proceedings;
- as sources of publication, the ones with the most articles and citations are those from Elsevier; in the case of conference proceedings, Lecture Notes In Computer Science have by far the most articles.

The study may be of interest for researchers and stakeholders to comprehend the big picture of VR-based applications for the automotive sector and the current state in this field.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Cristian-Cezar Postelnicu: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Răzvan Gabriel Boboc:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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