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Vulnerability of road transportation networks under natural hazards: A bibliometric analysis and review

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ABSTRACT

The vulnerability of the road transportation networks' infrastructures worldwide that can adversely be affected by the extreme weather conditions needs comprehensive assessment for reliable performance, mitigating the traffic hindrance and risks of accidents. Despite many efforts a clear understanding of the vulnerability of road transportation networks remains deficient. Based on this fact, this work bibliometrically analyzed the vulnerability of road transportation networks using 635 state-of-the-art articles published (Scopus database) during 1975–2020. The main purpose was to examine all-inclusively the evolution of diverse scientific studies in this field to ascertain the future research trends and benefits. In addition, the recent research progress and future drifts concerning the vulnerability of transportation networks were evaluated based on the published papers contributed by authors from various nations and co-incidences of authors' keywords. The proposed bibliometric analyses disclosed that the publications related to the vulnerability in transportation networks have significantly been increased since 2013. Approximately 70.6% countries showed research collaborations or partnership with at least one country. The USA and China presented a significant increase in the research trends in this area. It was found that the vulnerability studies have evolved significantly to include multi-dimensional evaluations, optimization approaches, multi-objective algorithm in order to minimize the disaster impacts and a GIS-based framework to create automated solution on the impacts of transportation network due to natural disasters. There has been a gradual acceptance that the benefit-cost ratios associated with vulnerability reduction are greatly favorable for the mitigation of the disaster risk to make economic sense.

1. Introduction

At present, the operation and progress of modern society relies heavily on the road networks. Extreme weather conditions or natural calamities can disrupt the transportation network significantly. Natural hazards like floods, landslides, earthquakes, and tsunami have significant impacts on the transportation systems' ability to provide a safe, efficient, and accessible mode of transportation. Several efforts have been made assess the magnitude of such impacts on the transportation mobility [1–6], road safety [7] and transport infrastructures [8]. Allen et al. [9], showed that flood can remarkably change the spatial distribution of traffic load on the road networks due to detour, thus significantly reducing the travel speed. Transportation being one of the critical networks [10] its failure can cause additional strain on other networks especially during the emergency situations [11]. In this regard, the term

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"vulnerability" refers to the measure of the consequences of network failures during various unpredicted incidences [12,13]. In other words, it is the road networks susceptibility to incidents that bring significant drop in the road transport serviceability.

The concept of vulnerability of the road transport system can be traced back to the study by Berdica [14]. Few works addressed the concept of vulnerability of the road transport network and infrastructures [13,15,16]. Many other studies have been conducted to identify the vulnerability of the road transport networks on specific events like earthquake [17,18], floods [15,19,20], seismic [21], debris flow [22,23], landslides [24–26] and tsunamis [27]. There are few studies in the scientific publication analysis have been conducted related to emergency management [28], resilience [29–31] and accessibility [32]. The detail analyses of the existing state-of-the-art scientific publications that specifically focus on transport networks in different areas of vulnerabilities have been conducted by Sugishita & Asakura [33]; Kim et al. [34]; Lima & Bonetti [35]; and Kadaverugu et al. [36]. Despite much attention on vulnerability of the road transport network, a comprehensive analysis of various published papers specifically on vulnerability assessment metric remains deficient. In this perception, we explored the research trends in the area of vulnerability of road transport networks assessment by selecting 635 articles published in Scopus database during the year 1975–2020. This paper is composed of five broad sections. Sections 2, 3, 4 and 5 describe the methodology, results, discussion, and conclusion, respectively.

2. Methods

A bibliometric analysis evaluates the current state-of-the-art research in a certain field using various academic publication databases. The procedure consists of three steps including (i) online database searching; (ii) article screening; and (iii) final refinement and analyses. In this study, the data was mined from Scopus database during 30 March to May 05, 2021. The Scopus database was chosen for the search because of its extensive coverage of articles, enabling the authors to cover diverse areas than the Web of Science could achieve [38]. Keywords search such as "transport vulnerabilities", "disasters", "road network" were used to retrieve the appropriate articles from the Scopus database published during 1975–2020. The critical literature review revealed that the published articles on the vulnerability of road transport networks are primarily divided into three research areas; wherein the first one involves the natural disasters, the second one deals with the road safety like accidents and last one entails the health-related disaster such as Covid 19. Thus, a total of 3898 publications were traced to identify the most challenging and diverse area. A careful scrutiny of all these articles enabled the present researchers to focus on the vulnerabilities of transport networks during natural disasters, thus 650 papers were selected. The number of journal articles and conference papers was 376 and 274, respectively. It is worth noting that the review papers were eliminated by adding additional terms to search string such as review, overview, scientometric, bibliometric, highlight, and perspective. Complete elimination of the irrelevant articles allowed us to end up with 635 selected publications for further analysis. Fig. 1 shows the basic architecture of the proposed approach. Table 1 indicates the facets of the search string used in this study.

The features including the annual publications, regional publication distribution, source title of publications, authors, co-occurrences of author keywords, and total citation analysis were used to assess the information extracted from the Scopus database. The extracted data were analyzed using diverse approaches such as Microsoft Excel 2019 to provide frequency analysis and to generate relevant graphs; VOSViewer version 1.6.16 to provide bibliometric maps with network visualization and overlay visualization for keywords and co-authorships; and Harzing's Publish or Perish software version 7 for calculating the citation metrics. The VOSViewer version 1.6.16 was used to generate the visual results and bibliometric maps of collaborations between countries and co-occurrences of author keywords [39]. Furthermore, total number of papers (TPs), number of cited papers (NCPs), total citations (TCs), mean citations per paper (C/P), mean citations per cited paper (C/CP), citations per year (CPY), citations per paper (CPP), h-indices (h), and g-indices (g) were identified to extend the proposed bibliometric analyses.

3. Current publication status for vulnerabilities of road transport

3.1. Publication growth by year

Analysis of the scientific publications based on the year of publication helped the researchers to determine the growth evolution on the cited topic [40,41]. Fig. 2 shows the exponential growth of the scientific publications during 1975–2020. The evolution trajectory of the chart clearly revealed the rapid increase of the publications from 2014 until 2020. Such exponential rise can be attributed to the renewed research interests that have been generated in the area of vulnerability of road transport networks. In addition, the publications development during 1975–2020 were clubbed into three domains like slow growth with four average number of annual publications (1975–2008), steady growth with 27 average number of yearly publications (2009–2013) and rapid growth with 61 average number of publications per annum (2014–2020). The regression coefficient of the exponential graph was found to be 0.9814, indicating a positive growth trend in the proposed research area.

Fig. 3 displays the temporal distribution of the publications tendency (number of publications and number of citations against years) based on the 635 extracted papers from the Scopus database over 45 years (during 1975–2020).

The earliest publication was traced back to the one by Salvador [42] in which computer simulation was performed to analyze the effects (including economic effect) of various changes in port operating conditions due to emergency situations either natural disasters or man-made problems. The highest productivity was found in the year 2019 with a total of 84 documents. The highest citation was observed in 2015 with 873 total citations. Furthermore, the growth evolution was found to occur in three phases slow, steady and rapid wherein the peak citation for the publications happened in 2002 (660 total citations), 2010 (561 total citations) and 2015 (873 total citations). Table 2 enlists the citation matrix per year based on the retrieved documents.

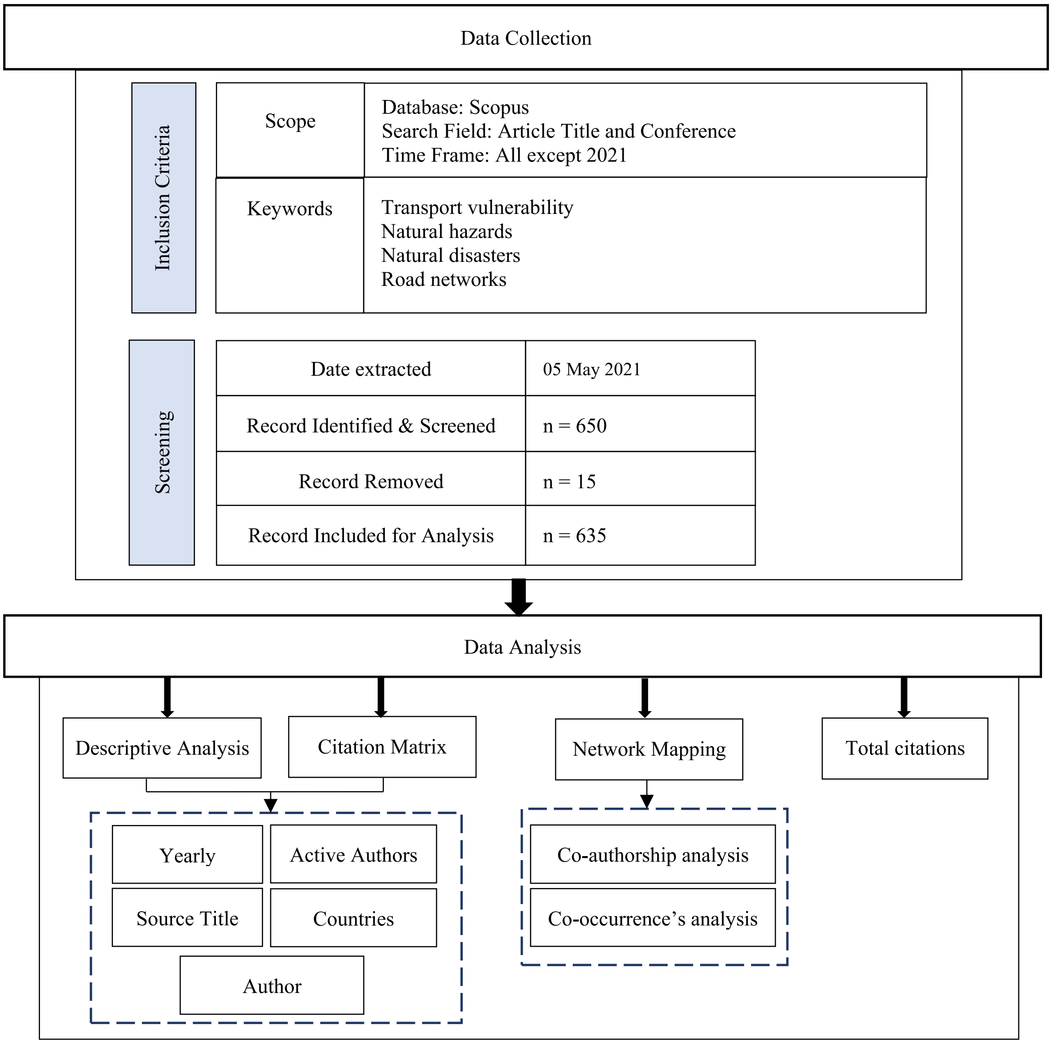

Fig. 1. Proposed research framework (adopted from Ref. [37].

Table 1
Search of string for appropriate selection of the review topic.

No.	Search string	Document results
1.	TITLE-ABS ((“transport × vulnerabilit*" OR “transport × vulnerable*" OR “natural hazard*" OR “natural disaster*" OR disaster × OR hazard*) AND (“road network*" OR “transport × network*" OR “road infrastructure*" OR “transport × infrastructure*" OR “transport × system*" OR “road system*"))	3898
2.	TITLE-ABS ((“transport × vulnerabilit*" OR “transport × vulnerable*" OR “natural hazard*" OR “natural disaster*") AND (“road network*" OR “transport × network*" OR “road infrastructure*" OR “transport × infrastructure*" OR “transport × system*" OR “road system*")) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (EXCLUDE (PUBYEAR, 2021))	650
3.	TITLE-ABS ((“transport × vulnerabilit*" OR “transport × vulnerable*" OR “natural hazard*" OR “natural disaster*") AND (“road network*" OR “transport × network*" OR “road infrastructure*" OR “transport × infrastructure*" OR “transport × system*" OR “road system*")) AND NOT EID (2-s2.0-85,091,567,885 OR 2-s2.0-85,080,899,487 OR 2-s2.0-85,089,137,493 OR 2-s2.0-85,078,462,882 OR 2-s2.0-85,086,143,293 OR 2-s2.0-85,079,607,990 OR 2-s2.0-85,077,802,308 OR 2-s2.0-85,078,804,403 OR 2-s2.0-85,068,795,017 OR 2-s2.0-85,074,669,766 OR 2-s2.0-85,066,787,169 OR 2-s2.0-84,975,801,351 OR 2-s2.0-84,904,016,533 OR 2-s2.0-84,916,910,869 OR 2-s2.0-84,894,559,856) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (EXCLUDE (PUBYEAR, 2021))	635

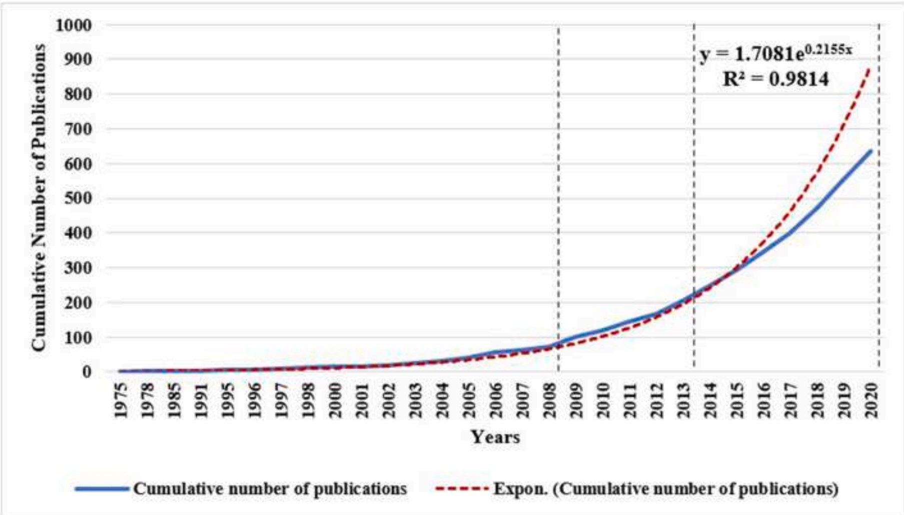

Fig. 2. Evolution of publications during 1975–2020.

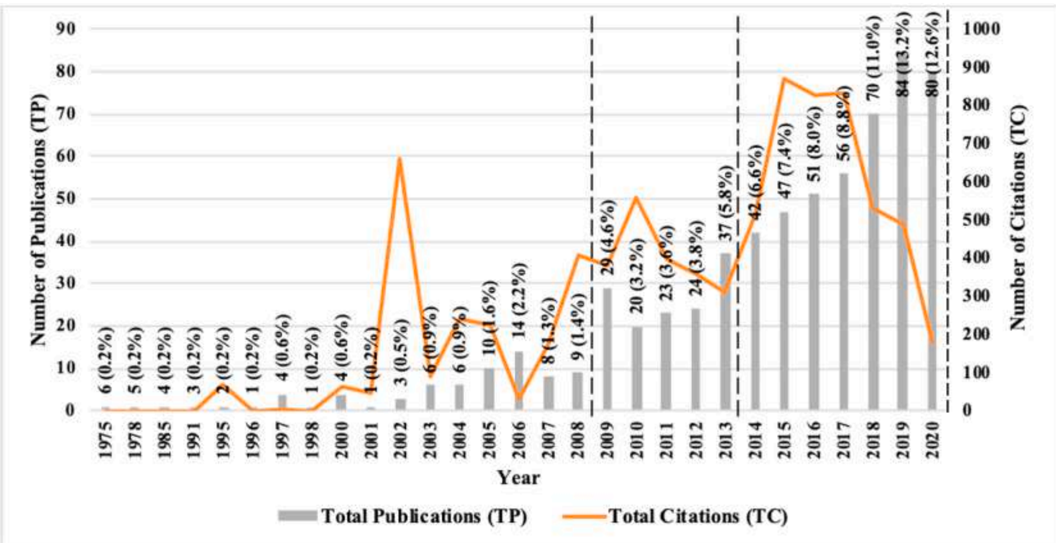

Fig. 3. Number of annual publications and citations indexed in Scopus during 1975–2020.

Table 2
Number of publications during 1975–2020.

Year	TP	%	NCP	TC	C/P	C/CP	CPY	CPP	h	g
2020	80	12.60%	46	182	2.28	3.96	182.00	3.96	7	10
2019	84	13.23%	57	487	5.80	8.54	243.50	5.80	11	19
2018	70	11.02%	51	532	7.60	10.43	177.33	7.60	12	21
2017	56	8.82%	46	835	14.91	18.15	208.75	14.91	15	28
2016	51	8.03%	39	829	16.25	21.26	165.80	16.25	14	28
2015	47	7.40%	41	873	18.57	21.29	145.50	18.57	13	29
2014	42	6.61%	31	517	12.31	16.68	73.86	12.31	15	22
2013	37	5.83%	27	310	8.38	11.48	38.75	8.38	10	17
2012	24	3.78%	17	360	15.00	21.18	40.00	15.00	8	18
2011	23	3.62%	19	398	17.30	20.95	39.80	17.30	7	19
2010	20	3.15%	13	561	28.05	43.15	51.00	28.05	5	20
2009	29	4.57%	20	383	13.21	19.15	31.92	13.21	8	19
2008	9	1.42%	6	410	45.56	68.33	31.54	45.56	5	9
2007	8	1.26%	8	172	21.50	21.50	12.29	21.50	6	8
2006	14	2.20%	8	33	2.36	4.13	2.20	2.36	4	5
2005	10	1.57%	5	224	22.40	44.80	14.00	22.40	3	10
2004	6	0.94%	5	240	40.00	48.00	14.12	40.00	5	6
2003	6	0.94%	4	92	15.33	23.00	5.11	15.33	4	6
2002	3	0.47%	2	660	220.00	330.00	34.74	330.00	2	2
2001	1	0.16%	1	47	47.00	47.00	2.35	47.00	1	1
2000	4	0.63%	3	65	16.25	21.67	3.10	16.25	2	4
1998	1	0.16%	0	0	0.00	0.00	0.00	0.00	0	0
1997	4	0.63%	2	2	0.50	1.00	0.08	0.50	1	1
1996	1	0.16%	0	0	0.00	–	0.00	0.00	0	0
1995	1	0.16%	1	68	68.00	68.00	2.62	68.00	1	1
1991	1	0.16%	0	0	0.00	–	0.00	0.00	0	0
1985	1	0.16%	0	0	0.00	–	0.00	0.00	0	0
1978	1	0.16%	0	0	0.00	–	0.00	0.00	0	0
1975	1	0.16%	0	0	0.00	–	0.00	0.00	0	0
Total	635									

3.2. Publications by resource titles

The major resource titles with a minimum of eight publications are shown in Table 3. The journal named Transportation Research Record was found to be most productive, publishing 29 papers with a coverage of 4.57% of the entire papers next to Natural Hazards (with 18 papers at a coverage of 2.83%) and International Journal of Disaster Risk Reduction (with 15 papers at a coverage of 2.36%). Conversely, three sources of publications received the highest number of citations which were, Transportation Research Part A Policy and Practice (552 total citations), Reliability Engineering and System Safety (318 total citations), and Transportation Research Record (318 total citations).

3.3. Regional publication distribution

Fig. 4 illustrates the distribution of publication in various countries within the geographical region. This analysis was carried out to understand the demographic distribution of the research concerning the vulnerabilities of road transportation networks during natural disasters. A total of 41 countries were clustered according to seven continents like Asia, Europe, North America, South America, Africa, Oceania, and Antartica. The highest publications were found to appear from Europe (20) followed by Asia (13) and 2 from each of other continents.

Fig. 5 shows the pattern of total publications for most productive countries with minimum of total publications 8. The citation analysis for the respective countries is presented in Table 4. USA is the dominant country that published on vulnerabilities of road transport during the disaster with a total of 209 publication (32.9% of TPs), followed by China with a total of 84 publications (13.2% of TPs).

Fig. 6 shows the networks visualization map of co-authorships among countries. In the VOSviewer, all the nearby countries revealed stronger correlations, indicating thicker lines [40]. In addition, the closer is the distance between the countries the stronger is the collaboration among them. About 70.6% of countries had collaborative publications with at least one country. Outcomes based on the co-authorships exhibited highest international collaborations of 18 between USA and other nations with the total link strength of 34, followed by UK (11 association to other countries and 17 total link strength), China (8 association to other countries and 26 total link strength) and Japan (8 linkage to other countries and 10 total link strength)..

Table 3
Most active source title with minimum TP of 8.

No.	Source Title	TP (%)	Publisher	Cite Score	SJR 2019	SNIP 2019	NCP	TC	C/P	C/CP	h	g	The Most Cited Paper (MCP)	TC of MCP	Authors of MCP
1.	Transportation Research Record	29 (4.57%)	US National Research Council	1.8	0.54	0.786	25	318	10.97	12.72	8	17	Vulnerability assessment methodology for swiss road network	80	A. Erath, J. Birdsall, K. W. Axhausen, R. Hajdin
2.	Natural Hazards	18 (2.83%)	Springer Nature	5	0.814	1.306	15	263	14.61	17.53	9	16	Using historical documents for landslides, debris flow and stream flood prevention. Applications in Northern Italy	65	D. Tropeano, L. Turconi
3.	International Journal of Disaster Risk Reduction	15 (2.36%)	Elsevier	4.4	0.964	1.756	14	274	18.27	19.57	10	14	Transportation network vulnerability analysis for the case of a catastrophic earthquake	60	N. Khademi, B. Balaei, M. Shahri, M. Mirzaei, B. Sarrafi, M. Zahabiun, A.S. Mohaymany
4.	Computer Science Lecture Notes and Subseries Lecture Notes in AI and Bioinformatics	10 (1.57%)	Springer Verlag	N/A	N/A	N/A	8	125	12.50	15.63	4	10	Evacuation planning: A capacity constrained routing approach	70	Q. Lu, Y. Huang, S. Shekhar
5.	Transportation Research Part A Policy and Practice	10 (1.57%)	Elsevier	7.1	2.109	2.403	10	552	55.20	55.20	9	10	Measuring capacity flexibility of a transportation system	104	E.K. Morlok, D.J. Chang
6.	Natural Hazards and Earth System Sciences	9 (1.42%)	Copernicus	5.1	1.005	1.37	8	56	6.22	7.00	5	7	Estimating network related risks: A methodology and an application in the transport sector	16	J. Hackl, J.C. Lam, M. Heitzler, B.T. Adey, L. Hurni
7.	Reliability Engineering and System Safety	8 (1.26%)	Elsevier	8.8	1.925	2.654	8	318	39.75	39.75	6	8	Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability	168	T. Adachi, B.R. Ellingwood

Notes: SJR: SCImago Journal Rank; SNIP: Source Normalized Impact per Paper.

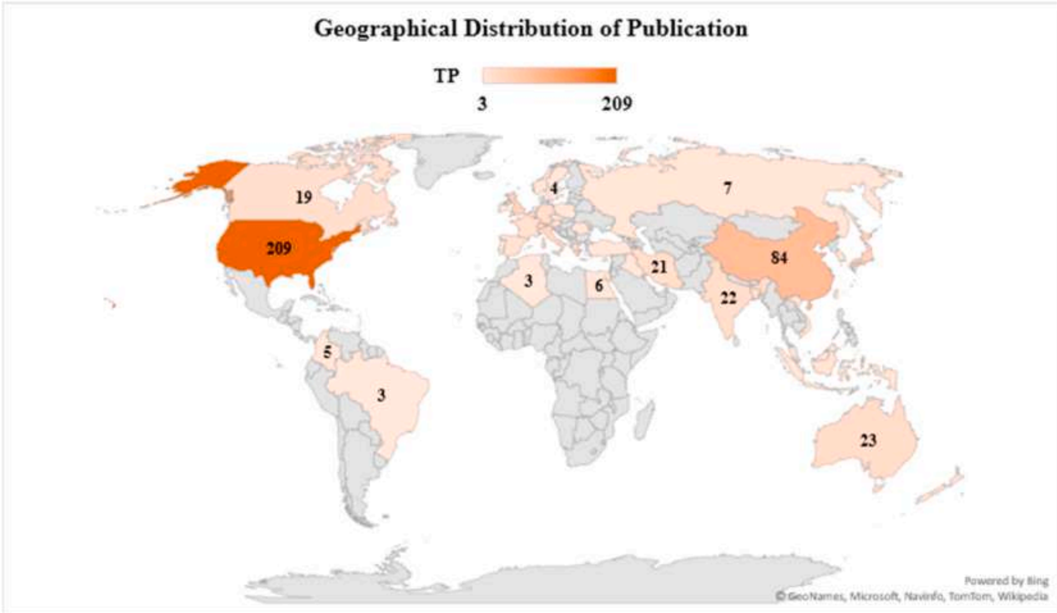

Fig. 4. Geographical distribution of the publications.

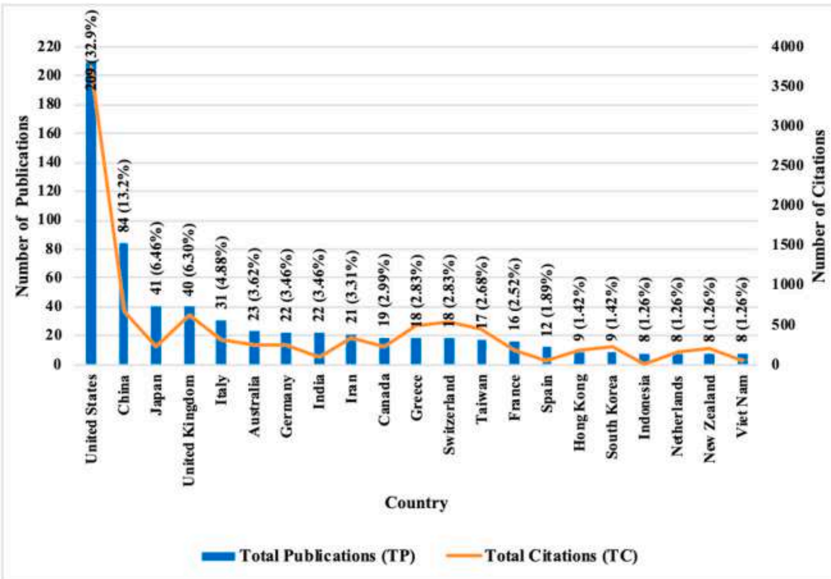

Fig. 5. Countries with the minimum of 8 publications.

Table 4
Most leading countries with minimum of 8 publications.

No.	Country	TP (%)	NCP	TC	C/P	C/CP	h	g
1.	United States	209 (32.91%)	163	3738	17.89	22.93	29	56
2.	China	84 (13.23%)	57	672	8.00	11.79	13	24
3.	Japan	41 (6.46%)	26	236	5.76	9.08	10	14
4.	United Kingdom	40 (6.30%)	30	621	15.53	20.70	10	24
5.	Italy	31 (4.88%)	23	308	9.94	13.39	9	17
6.	Australia	23 (3.62%)	18	241	10.48	13.39	10	15
7.	Germany	22 (3.46%)	17	249	11.32	14.65	8	15
8.	India	22 (3.46%)	16	98	4.45	6.13	5	9
9.	Iran	21 (3.31%)	15	346	16.48	23.07	7	18
10.	Canada	19 (2.99%)	16	220	11.58	13.75	8	14
11.	Greece	18 (2.83%)	14	496	27.56	35.43	8	18
12.	Switzerland	18 (2.83%)	14	531	29.50	37.93	8	18
13.	Taiwan	17 (2.68%)	12	454	26.71	37.83	6	17
14.	France	16 (2.52%)	12	193	12.06	16.08	7	13
15.	Spain	12 (1.89%)	9	48	4.00	5.33	4	6
16.	Hong Kong	9 (1.42%)	6	173	19.22	28.83	6	9
17.	South Korea	9 (1.42%)	6	237	26.33	39.50	3	6
18.	Indonesia	8 (1.26%)	3	7	0.88	2.33	2	2
19.	Netherlands	8 (1.26%)	8	153	19.13	19.13	6	8
20.	New Zealand	8 (1.26%)	8	196	24.50	24.50	6	8
21.	Viet Nam	8 (1.26%)	7	56	7.00	8.00	4	7

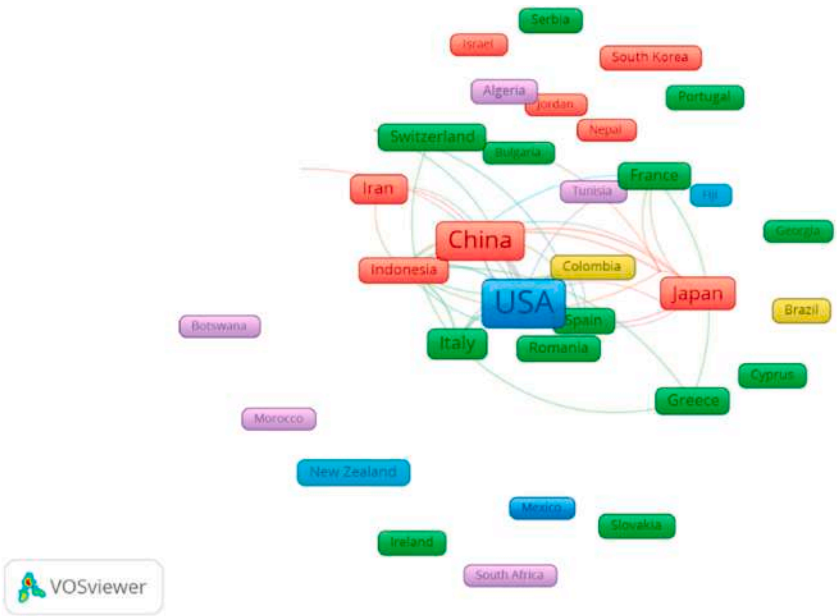

Fig. 6. A screenshot of the bibliometric map created based on co-authorship with network visualization mode.

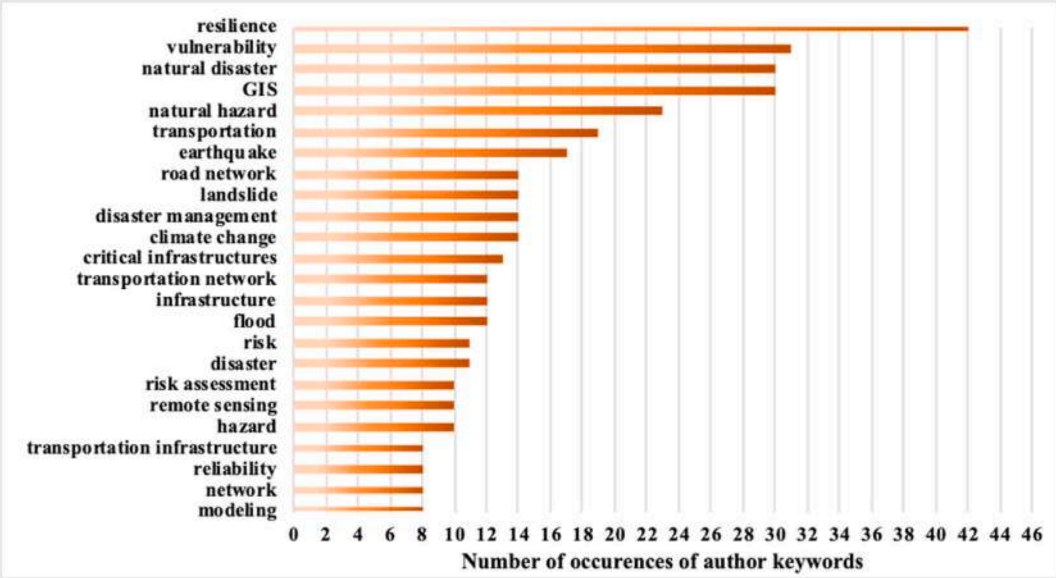

Fig. 7. Most leading keywords with minimum of 8 total occurrences during 1975–2020.

3.4. Publication by authors

Table 5 shows the list of authors having a minimum of 4 publications in the research area of transportation networks vulnerability during disasters with their respective affiliations, citation matrix and their most cited paper. The authors were affiliated to 10 countries as follows: United States of America (4 authors), Switzerland (4 authors), Spain (3 authors), Australia (2 authors), Iraq (2 authors), Taiwan (2 authors), Italy (1 author), Saudi Arabia (1 author) and Japan (1 author). Adey, B.T. and Hackl, J are the most prolific authors in this research area with 7 total publications and both are affiliated to ETH Zurich. An article co-authored by Hackl and Adey [43] received 24 citations and this article became the most cited one. A publication co-authored by Shekhar [44] received the most citations of 177 followed by Pradhan [45] with 157 citations. An article written by three authors Alazawi, Abdljabar and Mehmood [46] received 81 citations..

3.5. Authors' keywords analysis

From the retrieved documents from the Scopus database with an initial 1531 author keywords were recorded. After re-labeling the synonymic and congeneric words, a total of 1502 author keywords were obtained. Fig. 7 displays the outcomes obtained from the author keywords analysis with minimum 8 occurrences. The "resilience" and "vulnerability" were observed to be the most frequent used keywords in the published documents, followed by natural disaster, GIS, natural hazard, transportation, and earthquake. Furthermore, the keywords resilience and vulnerability were the key indicators in the performance analysis of transportation systems.

Fig. 8 shows an overlay of the visualization map of authors' keywords obtained from the VOSviewer analyses. Minimum 2 occurrences of keywords were set, thereby obtaining 204 keywords that meet the minimum threshold occurrences for the mapping in the VOSviewer.

Fig. 9 shows the analyses of co-keywords used with resilience and vulnerability. The "resilience" keyword displayed 42 occurrences with the total link strength of 100 and "vulnerability" keyword showed 31 occurrences with the total link strength of 74. Other keywords such as "geographic information system" exhibited 30 occurrences with total link strength of 55, "natural disaster" showed 30 occurrences with total link strength of 40 and "natural hazard" revealed 23 occurrences with total link strength of 51. Other keywords connected to resilience and vulnerability with the minimum link strength of 3 was also identified.

Vulnerability and resilience demonstrated a significant interest in the field of transportation networks vulnerability assessment to achieve the sustainable development goals of infrastructures. Vulnerability is a measure of a road network's susceptibility to the serviceability degradation due to various interruptions [47]. In contrast to the term resilience, the vulnerability means the ability of the road transportation network to withstand major incidents [48,49]. The term "resilience" was first introduced in 2011 b y Cimellaro et al. [50]. Very recently is used by Qiang & Xu [51]. The term "vulnerability" was first introduced in 2006 b y Kanungo et al. [24,25] and most recently used by Hardiansyah et al. [49].

Lately, the vulnerability studies has evolved substantially to include multi-dimensional vulnerability and resilience evaluations [52], optimization approach to minimize the vulnerability under budget constraints [53], optimal evacuation route planning [49], multi-objective algorithm in shelter location planning under uncertainty of road networks [54], tropical cyclones influence on maritime network assessment [55] and development of a GIS-based framework to create automated solution on the impacts of transportation network due to natural disasters [56]. The analyses of vulnerability and resilience of the transportation road networks

Table 5
Authors with a minimum of 4 publications.

Author's Name (Scopus ID)	Affiliation	Country	TP (%)	NCP	TC	C/P	C/CP	*h*	*g*	Title of the Most Cited Paper (MCP)	TC of the MCP
Adey, B.T. (6,602,448,661)	ETH Zürich, Zurich ZH	Switzerland	7 (1.10%)	6	56	8.00	9.33	4	7	Determination of Near-Optimal Restoration Programs for Transportation Networks Following Natural Hazard Events Using Simulated Annealing	24
Hackl, J. (56,644,396,200)	ETH Zürich, Zurich ZH	Switzerland	7 (1.10%)	6	56	8.00	9.33	4	7	Determination of Near-Optimal Restoration Programs for Transportation Networks Following Natural Hazard Events Using Simulated Annealing	24
Cimellaro, G.P. (21,739,197,700)	Politecnico di Torino, Turin	Italy	5 (0.79%)	5	35	7.00	7.00	3	5	Probabilistic framework to evaluate the resilience of engineering systems using Bayesian and dynamic Bayesian networks	20
Lien, Y·N. (7,006,541,755)	Asia University Taiwan Wufong	Taiwan	5 (0.79%)	5	36	7.20	7.20	3	5	A multi-hop walkie-talkie-like emergency communication system for catastrophic natural disasters	17
Padgett, J.E. (15729739800)	Rice University, Houston	USA	5 (0.79%)	4	8	1.60	2.00	2	2	Assessing the accessibility of petrochemical facilities during storm surge events	4
Pradhan, B. (12,753,037,900)	Sejong University, Seoul	South Korea	5 (0.79%)	5	354	70.80	70.80	5	5	Suitability estimation for urban development using multi-hazard assessment map	157
Shekhar, S. (35,513,450,400))	University of Minnesota Twin Cities, Minneapolis	USA	5 (0.79%)	5	438	87.6	87.6	5	5	Capacity Constrained Routing algorithms for evacuation planning: A summary of results	177
Thompson, R.G. (56,754,264,400)	University of Melbourne, Parkville	Australia	5 (0.79%)	5	33	6.6	6.6	4	5	Improving regional road network resilience by optimised traffic guidance	10
Abdljabar, M.B. (54,390,736,200))	Mustansiriyah University, Baghdad	Iraq	4 (0.63%)	4	181	45.25	45.25	4	4	Intelligent disaster management system based on cloud-enabled vehicular networks	81
Alazawi, Z. (54,390,694,800)	Mustansiriyah University, Baghdad	Iraq	4 (0.63%)	4	181	45.25	45.25	4	4	Intelligent disaster management system based on cloud-enabled vehicular networks	81
Calle, E. (7005657673)	Universitat de Girona, Girona	Spain	4 (0.63%)	2	10	2.5	5.0	2	3	Improving the resilience of transport networks to large-scale failures	6
Frangopol, D.M. (57,189,751,409)	Lehigh University, Bethlehem	USA	4 (0.63%)	2	25	6.25	12.5	2	4	Long-term resilience and loss assessment of highway bridges under multiple natural hazards	18
Heitzler, M. (55,906,758,700)	ETH Zürich, Zurich ZH	Switzerland	4 (0.63%)	4	27	6.75	6.75	3	4	Estimating network related risks: A methodology and an application in the transport sector	16
Huang, J.S. (7,407,193,896)	Chunghwa Telecom Co. Ltd., Yangmei	Taiwan	4 (0.63%)	4	19	4.75	4.75	3	4	Design of contingency cellular network	8
Hurni, L. (6,603,125,833)	ETH Zürich, Zurich ZH	Switzerland	4 (0.63%)	4	27	6.75	6.75	3	4	Estimating network related risks: A methodology and an application in the transport sector	16
Mehmood, R. (25,643,246,000)	King Abdulaziz University, Jeddah	Saudi Arabia	4 (0.63%)	4	181	45.25	45.25	4	4	Intelligent disaster management system based on cloud-enabled vehicular networks	81
Rajabifard, A. (6,603,307,682)	University of Melbourne, Parkville	Australia	4 (0.63%)	4	27	67.75	6.75	3	4	Improving regional road network resilience by optimised traffic guidance	10
Segovia, J. (7,102,633,140)	Universitat de Girona, Girona	Spain	4 (0.63%)	2	10	2.5	5.0	2	3	Improving the resilience of transport networks to large-scale failures	6
Shibasaki, R. (7,003,648,498)	The University of Tokyo, Tokyo	Japan	4 (0.63%)	3	61	15.25	20.33	3	4	Prediction and simulation of human mobility following natural disasters	24
Vilà, P. (7,003,966,679)	Universitat de Girona, Girona	Spain	4 (0.63%)	2	10	2.5	5.0	2	3	Improving the resilience of transport networks to large-scale failures	6
Wang, H. (55,964,470,100)	Oregon State University, Corvallis	USA	4 (0.63%)	4	52	13	13	3	4	Agent-based tsunami evacuation modeling of unplanned network disruptions for evidence-driven resource allocation and retrofitting strategies	32

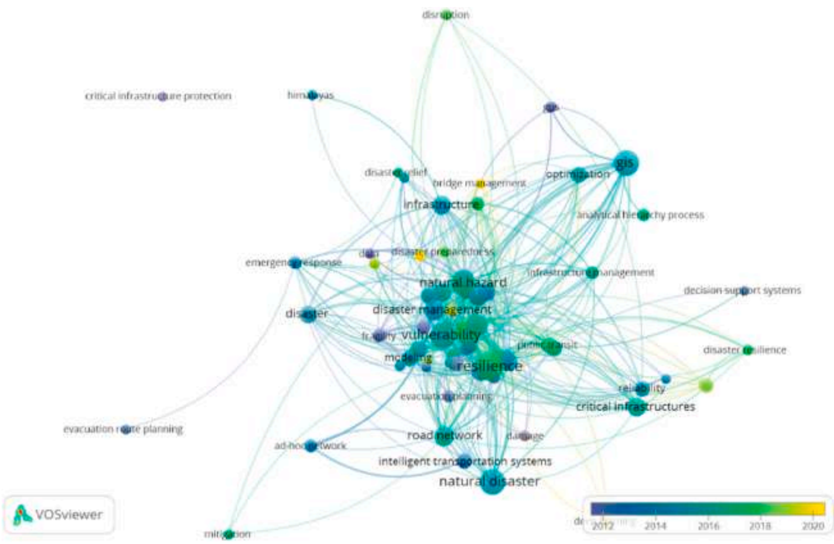

Fig. 8. Authors' keywords analyses in the papers published in the period of 1975–2020 related to the vulnerabilities of transportation networks during disaster.

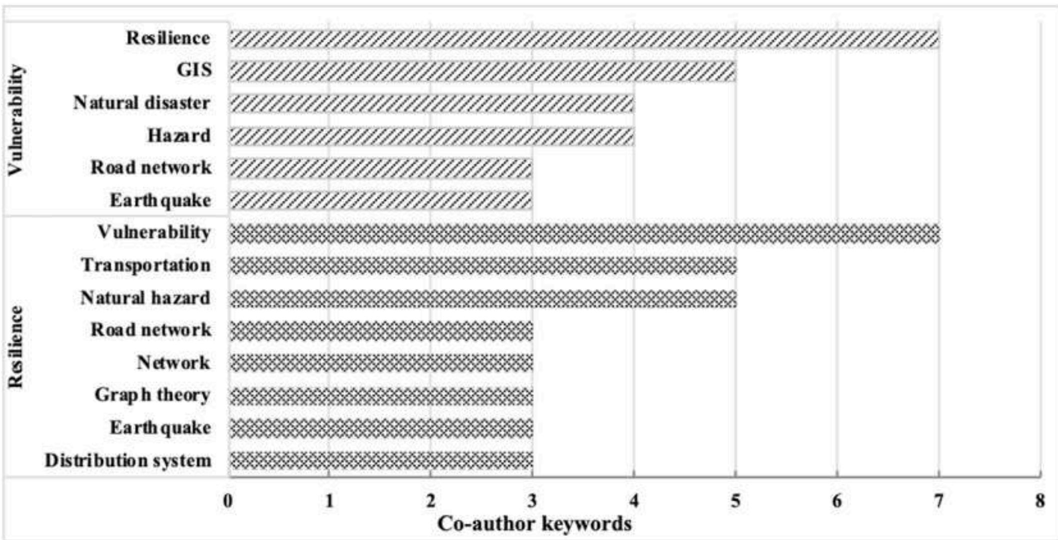

Fig. 9. Co-keywords used with resilience and vulnerability.

became vital in the context of natural disasters. In addition, studies on the resilience aspect have been expanded into complex urban networks [57], public transit system [58] and urban transport networks [59].

3.6. Total citation analysis

A systematic identification of various publications in the Scopus database revealed an overall increase in their maximum of number of citations. Table 6 shows 20 topmost cited articles out of 635 documents analyzed in this work. These topmost cited papers were published during 2000–2010 (45%) and 2011 to 2020 (55%). In addition, the citations of an article were normalized by a parameter TC/TS wherein TC is the total citations and TS is time period since the paper is published. The third paper in the list (published in 2015) received the highest citations per year (48.33), followed by the fist article published in 2010 with 43.36 citations per annum, the 9th paper published in 2017 showed 39.25 citations per year, and the 6th article published in 2016 had 35 annual citations.

The emergency supplies pre-positioning was the topmost cited article in the field [60] which received the 43.36 citations per year (477 total citations over the analysis year). Opricovic & Tzeng [61] article was the second most cited one entitled multi-criteria planning of post-earthquake sustainable reconstruction. The paper entitled suitability estimation for urban development using multi-hazard assessment map by Bathrellos et al. [45] received 39.25 citations per year with 157 total citations over the analysis year. In addition, Shekhar and Pradhan were found to be the most prolific authors for two papers (Table 6). Both co-authored paper of

Table 6
Topmost 20 cited articles.

No.	TC	Title	Source	Type	Author	Year	Citations/Year	Citations/Author
1	477	Pre-positioning of emergency supplies for disaster response	Transportation Research Part B: Methodological	Article	C.G. Rawls, M.A. Turnquist	2010	43.36	239
2	373	Multicriteria planning of post-earthquake sustainable reconstruction	Computer-Aided Civil and Infrastructure Engineering	Article	S. Opricovic, G.-H. Tzeng	2002	19.63	187
3	287	Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: Examples using digital aerial imagery and ASTER data	ISPRS Journal of Photogrammetry and Remote Sensing	Conference Paper	Kääb, A.	2002	15.11	287
4	177	Capacity Constrained Routing algorithms for evacuation planning: A summary of results	9th International Symposium on Spatial and Temporal Databases, SSTD 2005	Conference Paper	Q. Lu, B. George, S. Shekhar	2005	11.06	59
5	175	Humanitarian logistics network design under mixed uncertainty	European Journal of Operational Research	Article	S. Tofighi, S.A. Torabi, S.A. Mansouri	2016	35	58
6	168	Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability	Reliability Engineering and System Safety	Article	T. Adachi, B.R. Ellingwood	2008	12.92	84
7	161	Transportation security and the role of resilience: A foundation for operational metrics	Transport Policy	Article	A. Cox, F. Prager, A. Rose	2011	16.1	54
8	157	Suitability estimation for urban development using multi-hazard assessment map	Science of the Total Environment	Article	G.D. Bathrellos, H.D. Skilodimou, K. Chousianitis, A.M. Youssef, B. Pradhan	2017	39.25	31
9	156	Modeling integrated supply chain logistics in real-time large-scale disaster relief operations	Socio-Economic Planning Sciences	Article	A. Afshar, A. Haghani	2012	17.33	78
10	136	Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience	IEEE Transactions on Power Systems	Article	C. Shao, M. Shahidehpour, X. Wang, X. Wang, B. Wang	2017	34	27
11	130	Contra-flow transportation network reconfiguration for evacuation route planning	IEEE Transactions on Knowledge and Data Engineering	Conference Paper	S. Kim, S. Shekhar, M. Min	2008	10	43
12	126	Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports	Computers and Industrial Engineering	Article	S. Hosseini, K. Barker	2016	25.2	63
13	113	Multi-Criteria Analysis Framework for Potential Flood Prone Areas Mapping	Water Resources Management	Article	G. Papaioannou, L. Vasiliades, A. Loukas	2015	18.83	38
14	104	Measuring capacity flexibility of a transportation system	Transportation Research Part A: Policy and Practice	Article	E.K. Morlok, D.J. Chang	2004	6.12	52
15	91	Geo-morphological hazard analysis along the Egyptian Red Sea coast between Safaga and Quseir	Natural Hazards and Earth System Science	Article	A.M. Youssef, B. Pradhan, A.F.D. Gaber, M.F. Buchroithner	2009	7.58	23
16	85	Mobile Emergency Generator Pre-Positioning and Real-Time Allocation for Resilient Response to Natural Disasters	IEEE Transactions on Smart Grid	Article	S. Lei, J. Wang, C. Chen, Y. Hou	2018	27.33	21
17	81	Intelligent disaster management system based on cloud-enabled vehicular networks	2011 11th International Conference on ITS Telecommunications, ITST 2011	Conference Paper	Z. Alazawi, S. Altowaijri, R. Mehmood, M.B. Abdljabar	2011	8.1	20
18	80	Vulnerability assessment methodology for Swiss road network	Transportation Research Record	Article	A. Erath, J. Birdsall, K. W. Axhausen, R. Hajdin	2009	6.67	20
19	74	Analyzing resilience of urban networks: A preliminary step	Natural Hazards and Earth System Science	Article	S. Lhomme, D. Serre, Y. Diab, R. Laganier	2013	9.25	19

(*continued on next page*)

Table 6 (*continued*)

No.	TC	Title	Source	Type	Author	Year	Citations/ Year	Citations/ Author
		towards more flood resilient cities						
20	74	A network efficiency measure for congested networks	EPL	Article	A. Nagurney, Q. Qiang	2007	5.29	37

Shekhar entitled evacuation route planning using heuristic method Lu [44] and Kim [62] both received total citations of 177 and 130, respectively. A heuristic algorithm called Capacity Constrained Route Planner (CCRP) was developed by Lu et al. [44] as sub-optimal solution for evacuation planning problem. Kim et al. [62] proposed the heuristic algorithm using contra-flow lane reversal as a potential solution to reduce road congestion during the evacuation in the context of security and natural disasters. In addition, Pradhan co-authored a paper with Youssef et al. [63] that discussed the GIS-based geo-morphological hazard mapping in the Red Sea area between Safaga and Quseir, Egypt, receiving 91 citations. Bathrellos et al. [45] studied the GIS- and AHP-based multi-hazard map to identify suitable areas for urban development which received 157 citations.

4. Discussions on vulnerability of transportation networks research

We analyzed the spatial and temporal development in various studies concerning vulnerabilities of transportation networks. The findings revealed that the vulnerability studies on transportation networks started to increase in the year 2000 and then significantly increased in the year 2013 onwards (Fig. 1). The trend of annual publication and active countries in the related publications can be associated to the occurrences of natural disasters (Figs. 10 and 11). Figs. 10 and 11 showed the temporal natural disasters by type

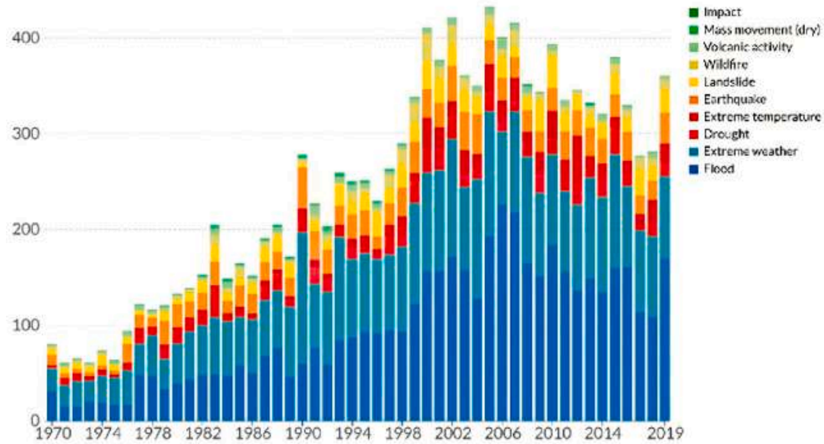

Fig. 10. Global reported natural disasters by type during 1970–2019 (https://ourworldindata.org/natural-disasters).

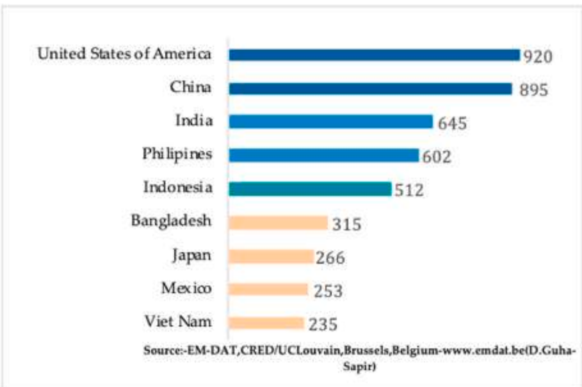

Fig. 11. Global occurrences from natural disasters during 1970–2020 (http://www.emdat.be/).

during 1970–2019 and the occurrences of natural disasters by countries during 1970–2020, respectively. The reported natural disasters showed a peak in the beginning of year 2000 with their dominance in USA and China. This explained the increase in the trend of publication over the year and related countries (discussed in Sections 3.1 and 3.3). The results suggested that continuous occurrences of the natural disasters require better knowledge of the vulnerability, leading to the development of methodologies to assess various factors and indicators of vulnerability..

Hazard-related knowledge is now substantial at local and global scale due to several reasons such as high number of affected people by disasters [64], and intense effect of climate change [65–67]. It affirmed that the vulnerability assessment can be an effective strategy for determining the possible impacts of natural disasters on society. There has been a gradual acceptance that the benefit-cost ratios associated with vulnerability reduction are greatly favorable for the mitigation of the disaster risk to make economic sense. Therefore, sustainable road design and management require a broad perspective to consider a road network's ability thereby withstanding the natural disaster. Essentially, the term vulnerability signifies the capacity of the road network in continuing the operation after any interruption. In other words, it determines the sensitivity of the road networks against specific disasters that might impair the service or accessibility levels [19]. To validate this idea, various scholars have consistently responded to the occurrence of disasters in terms of the vulnerability [21,26,68] and resilience [51,69–71], thus strategizing various mitigation procedures.

During the strike of any disaster, some of the vital transport networks' nodes might lose all functionality, thus significantly reducing their reliability and efficiency. Generally, a fragility function is used in the impact assessment on critical infrastructures due to natural hazards like tsunami [27], and earthquake [72–76], providing an informed decision on the possible mitigation strategies. The Bayesian network method was used in the seismic vulnerability assessment of an urban road network by quantifying the structural damage and transportation functional loss [21]. Postance et al. [77] displayed the use of indirect impacts such as economic losses due to travel delay and extended hazard impact footprints, in identifying the critical road segments due to landslide hazards in a nation-wide scale of transportation network. Pregnolato et al. [78] used an integrated framework of the flood and transport that could relate the flood depth and vehicle speed to develop a road criticality index. Cantillo et al. [79] identified a critical link using an economic analysis that considered logistical cost. Innovative techniques have been developed for the thorough identification of the vital nodes wherein manifolds of indicators are combined via Improved Topological Potential Entropy (ITPE) model [80], Susceptible–Infected–Recovered (SIR) model [81], and Improved Structural Holes (ISH) [82]. Zhang et al. [26] developed a vulnerability index of transportation network based on the combination of two components including landslide susceptibility index and traffic consequence index. In another study, the critical network links were identified by considering the traffic flow and travel time in vulnerability index [49]. The researchers developed the network model in SATURN software to identify the critical links that required the capacity improvement based on level of congestion. Toma-Danila et al. [56] developed the Network-risk mode which was an open GIS toolbox to estimate the impact of natural hazards on transportation systems at full scale urban networks. An extended critical link analysis was performed from a single link to multiple links being disrupted using Metaheurestic Simulated Annealing with objective function to minimize vulnerability rather than minimizing travel time or efficiency under budget constraint situation [53]. Recently, an improved weighted k-shell (IWKS) system has been introduced [83] for identifying the vital nodes in the multimodal transportation networks (highway, railway, aviation and waterway) wherein three indicators are considered like the nodes multiplicity of transport (weights), self-governing nodes transport capacity (proximity centrality), and nodes connection (degree).

Natural hazards are the complex phenomena wherein one region can be affected by multiple natural hazards. Based on this fact, Bathrellos et al. [45] produced a single hazard map based on the multi-hazard information such as landslide, flood and seismic activity using the analytical hierarchy process (AHP) and geographical information system (GIS) which is beneficial for the urban development. Robielos et al. [84] expanded the vulnerability assessment by developing a multi-disaster vulnerability assessment framework at three levels of geopolitical unit such as household, barangay, and city. Argyroudis, Mitoulis, et al. [85] classified multiple hazards that provided an integrated framework consisting of hazard, vulnerability and restoration analysis for the quantitative resilience assessment of critical infrastructure. Later, Argyroudis Nasiopoulos et al. [72] extended it by introducing a new cost-based resilience assessment. A sustainable risk management framework was proposed by Chamorro et al. [86] to account for social vulnerability of population, the physical vulnerability of roads and the environmental context due to volcanic hazards on rural roads. All these works provided a significant contribution to the emergency intervention forces and planning.

The vulnerability evaluation of the road network followed two distinct traditions including topological analysis and system-based analysis [87]. This review identified six metrics of transport network vulnerability assessment and classified them as system performance, system demand, system resiliency, system capacity, area-based and system geometry. Table 7 shows the findings of the review.

It was indi cated that a rapid urban development can increase the risks during a disaster. Undoubtedly, emergency relief to mitigate the impact of disasters became significant. However, the critical challenge lies on how to better anticipate the occurrences of disasters by incorporating the potential threat into effective planning and policies. This review showed that studies on vulnerability of road transportation networks are still in progress within the wider field of critical infrastructures, communities, planning, and policies. In essence, continuous efforts on the transportation networks vulnerability research are expected to improve the understanding, leading to an effective practice in the disaster risk reductions. Failure in recognizing the growing literatures in the vulnerability and resilience may put policymakers at risk of adopting ineffective strategies that may lead to wastage of country resources. The present and upcoming literatures will be particularly useful in the disaster plans in the preparation stage, prioritization of resources for mitigation, adaptation and rehabilitation, and recovery stage.

Table 7
Review on most cited papers.

Assessment type	Type of hazards	Methods	Exposure	Data	Output	Adaptation interventions
System performance	Landslide hazard [77]	Network susceptibility analysis	National transport network	National OD data, Geosure data: feature environmental factors that are associated with known landslide activity.	Nationwide Impact (Cost and travel time), Landslide Impacts Footprints	Explore the severity and distribution of impacts considering other hazard phenomena (e.g. flooding and severe wind storms)
	Flood [78]	High resolution climate simulation	Urban transport network	Flood depth (water depth) Vehicle speed, network travel model (OD data), capacity	Travel delays (travel time increase & speed reduction), Economic cost	Link hardening: improved drainage or raising the level of the link
	Seismic [88]	Probabilistic systemic risk analysis, MCS-based method	Taxonomy and typology of road (taxonomy: bridges, tunnels, embankments, road pavements, bridge abutment)	Road blockage	Performance curve, Fragility curve	The approach can consider other interactions such as failure of pipelines, collapse of adjacent electric poles, malfunction of lighting and signalling systems
	Earthquake [61]	Fuzzy membership functions	"lifeline" systems	Dead people, Injured people, Collapse houses, Damaged houses, Population	Performance matrix for earthquake restoration scenarios	Long- term reconstruction project for earthquake-affected area
	Earthquake [89]	Scenario-based possibilistic-stochastic framework	Logistics network	Earthquake scenarios: destruction ratios of structures and facilities in different regions under each scenario, Relief items needed by each family after disaster, and Cost of setting up local distribution centres and central warehouses	Storing cost, Transportation time	Networks under mixed possibilistic-stochastic uncertainty
	Transport-related failure [90]	Subnetwork approach	National road networks	Travel time, Travel cost, Distance and detour length	Failure consequences	Identification of alternative detour modes
	Transport-related failure [91]	Traffic network equilibrium model	Congested networks	Links, Nodes, and Demand	Importance and rankings of links and nodes	The identification of critical network components, whose removal, be it through natural disasters, structural failures, and/or terrorist attacks, etc., has implications for the network system
	Earthquake [92]	Fault tree analysis and a shortest-path algorithm	Municipal water system, electrical power system	Service area of the electrical power and water distribution systems, location and function of key facilities, peak ground acceleration	Probability distribution of serviceability, water system dependency on electrical power	Infrastructure system interactions in evaluating the seismic vulnerability and risk to a networked system, as well as the utility of back-up power systems in electric power facilities
System demand	Hurricanes [60]	Two-stage stochastic mixed integer program (SMIP), Lagrangian l-shaped method (LLSM)	Transportation networks	Emergency commodities Transport costs Facility size	Cumulative probability of demand for emergency commodities	Facilities location
	General [44]	Capacity constrained route planner (CCRP)	Evacuation network	Number of evacuees Evacuation routes	Quality of solution and run-time with respect to number of evacuees, source nodes and network size	Large transportation networks in urban scenarios
	Explosion of hazardous materials [2]	FRATAR model, VANETS (vehicular ad hoc networks), cloud computing	Transportation systems	Numbers of trips	Number of vehicles evacuated	Intelligent disaster Management system

(*continued on next page*)

Table 7 (*continued*)

Assessment type	Type of hazards	Methods	Exposure	Data	Output	Adaptation interventions
	Natural disasters [93]	Mathematical model	Transportation systems	Supply and demand, number of facilities, facility capacity, vehicle capacity, required items for survivors of a disaster	Unsatisfied demand percentage	Vehicle routing and pick up or delivery schedules; but also considers finding the optimal locations for several layers of temporary facilities
	Extreme flooding [94]	Deterministic approach	Road networks	Travel demand, Geographical Information Systems properties, and network topological indicators	Number of real trips that can be completed	Robustness of road networks to extreme floodin
	Flash floods [95]	Climate models, network science, geographical information systems (GIS), and stochastic modeling	Infrastructure networks	Daily precipitation	Percentage drops in static and dynamic network properties	Climate change adaptation
	Nuclear power plant failure [62]	Graph theory	Evacuation route	Population data, road networks	Evacuation time	Contraflow problem of evacuation route
System resiliency	Multiple hazard- flood and earthquake [85]	Fragility functions Numerical simulations	River crossing bridge	Hazard scenarios- earthquake and flood	Asset resilience index	Combined hazards assessment
	Natural disasters [96]	Column-and-constraint generation (C&CG) framework	Power grid system	Natural gas data and electricity data	Expansion cost	Interactions among power grid expansion states and extreme events
	Terrorism [97]	Direct static economic resilience (DSER)	Transportation systems	Transportation mode shifts, passenger journeys	Changes in passenger journeys	Passenger transportation system's resilience to terrorism
System capacity	General [98]	Dijkstra's shortest-path algorithm, scenario decomposition (SD) algorithm	Road networks	Distribution system boundaries, distribution nodes for mobile emergency generator, staging locations	Capacity utilization rate, meg travel time	Utilisation of mobile emergency generator (meg)
	Natural disasters and terrorist actions [99]	Fixed traffic pattern approach (MAXCAP model), adjusted traffic pattern approach (ADDVOL model)	Freight transportation system	Traffic data, traffic capacity	Traffic pattern in terms of capacity flexibility	Providing path options significantly
	General [100]	Bayesian networks	Inland waterway port	Historical data of cargo handling	Resilience capacity	Generating risk scenarios using Bayesian networks
Area based	Flood [101]	GIS, fuzzy analytical hierarchy process (FAHP)	Flood-prone areas	Historical flood inundation	Flood maps	Low-cost detection surveys of flood-prone areas, preliminary analysis of flood risk mapping
	Multi hazard [45]	Analytical hierarchy process (AHP), geographical information system (GIS)	Drainage basin	Hazard assessment maps for landslides, floods, and earthquakes	Single multi hazard maps	Suitable areas for urban development
	Geomorphological hazard [63]	GIS-based geomorphological hazard mapping	Drainage basin	Historical climatic data- temperature, humidity, and rainfall	Hazard maps	These maps can help to initiate appropriate measures to mitigate the probable hazards in the area
System geometric	Glacier flow, permafrost creep and land sliding [102]	Digital elevation models (DEM)	High-mountain mass transport	High-mountain terrain (digital aerial imagery and advanced spaceborne thermal emission and reflection radiometer data)	Geometric terrain changes	Monitoring glaciers and selected comparable fast rock glaciers in remote areas
	River flood [103]	Web-GIS	Urban networks	Number of nodes and edges	Resistance capacity, absorption capacity and recovery capacity of networks	Alternative road locations

5. Conclusion

This paper comprehensively reviewed the recent trends and future directions of transport vulnerability wherein 635 important articles from the Scopus listing (published during 1975–2020) were critically analyzed. It was demonstrated that the field of research concerning the transport networks vulnerability has grown considerably and gained significant scholarly attention as evidenced by the increase in the number of publications since 2013. Most of the articles were found to publish in the Transportation Research Record, Natural Hazards, and International Journal of Disaster Risk Reduction. Furthermore, it was discovered that two articles that received the most citations were published in Transportation Research Part A Policy and Practice and Reliability Engineering and System Safety, indicating their topical importance. The collaborative relationship is becoming closer across research institutions and scholars from USA and China published maximum papers with strong partnerships worldwide. The strength and weakness of the road transport networks and infrastructures development being the two significant indicators is emphasized in the performance analysis. Additionally, the current analysis on authors' keywords revealed that the road transportation networks vulnerability studies exist in three focus areas such as pre-disaster, during disaster and post-disaster. It is established that sundry studies on the road transportation networks vulnerability must evolve to new innovative approaches thereby providing new insight into the field. In short, the current bibliometric analyses related to the vulnerability of road transportation networks provided taxonomy for the evolution of diverse scientific studies in the field. However, the future research directions regarding the vulnerability of transportation networks look very promising and challenging. Innovative techniques for the vulnerability assessment under the multiple hazard situations have been ever-growing. The scale of multiple hazards has negative socio-economic and safety impact on the local community with catastrophic effect on the structural damages. The interaction of these factors can pose a significant challenge in determining the priorities for restoration strategies. Continuous research efforts are needed to address these challenges, providing better-informed decisions and effective risk remedial strategies.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Sitti Asmah Hassan, and Hamizah Amalina Amlan. The first draft of the manuscript was written by Sitti Asmah Hassan and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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.

Data availability

Data will be made available on request.

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