Review

Hyperloop Academic Research: A Systematic Review and a Taxonomy of Issues

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Abstract: Hyperloop is a proposed very high-speed ground transportation system for both passenger and freight that has the potential to be revolutionary, and which has attracted much attention in the last few years. The concept was introduced in its modern form relatively recently, yet substantial progress has been made in the past years, with research and development taking place globally, from several Hyperloop companies and academics. This study examined the status of Hyperloop development and identified issues and challenges by means of a systematic review that analyzed 161 documents from the Scopus database on Hyperloop since 2014. Following that, a taxonomy of topics from scientific research was built under different physical and operational clusters. The findings could be of help to transportation academics and professionals who are interested in the developments in the field, and form the basis for policy decisions for the future implementation of Hyperloop.

Keywords: Hyperloop; vactrain; scientific research; taxonomy; technologies

1. Introduction

Mobility and transportation are among the most essential and important services to society. They encompass interconnected systems that are intended to cover the demand for mobility of people and goods. Transportation systems are intrinsically complex, including elements, both physical and organizational, that interact with and influence each other directly and indirectly, frequently in a nonlinear manner, and with the occurrence of feedback loops. [1]. According to this perspective, the transportation system is essentially a highly dynamic complex, large-scale, interconnected, open, socio-technical (CLIOS) system [2]. Nevertheless, present-day transportation modes (i.e., rail, road, air and waterborne transportation) are based on consolidated concepts, and improvements over the years have been essentially evolutionary, focusing on delivering a safe, efficient, reliable and accessible transportation system.

In the last decade, several transportation concepts and technologies have been identified as very promising. The impact of disruptive transportation technologies, i.e., those technologies with the potential to create disruptive innovation at industry and society level [3], has been an important area of research and development. In the transportation sector, information and communication technologies (ICT) and the Internet of Things (IoT) are bringing a revolution to the sector, with the advent of connected and automated road mobility being a notable example [4].

Hyperloop is one of those very promising and possibly disruptive future transportation technologies. Its development has received extensive media coverage over the last years following the Hyperloop Alpha white paper by Elon Musk published in 2013 [5]. Hyperloop consists of a system of tubes where vehicles (pods) travel at high speed (the original concept claims a top speed of 1220 km/h) in a low-pressure environment. Other than speed, Hyperloop's main advantage is that the partial vacuum lowers the air resistance (drag), thus, consuming less energy during acceleration and cruise [6]. An initial

feasibility study published already in 2016 identifies research topics related to Hyperloop technologies [7].

After the white paper and the initial hype, several companies in the US brought together engineers and venture capital money to perform research and development and make Hyperloop a reality [8]. Later on, the same companies expanded to Europe, and other Europe-based companies engaged in similar activities [9], including the planning and development of Hyperloop test sites.

Furthermore, recent developments regarding the need for standardizationin Europe and the US highlight the interest in the regulation of Hyperloop. In Europe, the "Sustainable and Smart Mobility Strategy" was presented in December 2020 by the European Commission and the accompanying action plan of initiatives will guide its work for the next four years. Among the objectives of this plan is to "assess the need for regulatory actions to ensure safety and security of new technologies and concepts such as Hyperloop" [10]. Before that, a new Joint Technical Committee (TC), CEN/CLC/JTC 20, was launched by the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) to address the need for the standardization of Hyperloop systems [11]. A year before, in 2019, the U.S. Department of Transportation (DOT) created the Non-Traditional and Emerging Transportation Technology (NETT) Council, an internal body with the objective of identifying and resolving gaps, either legal or regulatory, that may obstruct the deployment of Hyperloop, among other new technologies [12]. In January 2021, the NETT Council presented the "Hyperloop Standards Desk Review" with the scope of assessing the status of Hyperloop standardization activities, developing a foundation for future Hyperloop standardization efforts, and consequently, paving the way towards the development of a preliminary framework of Hyperloop system components and associated regulations and voluntary technical standards [13].

The dynamics of the technology and the progress made toward future Hyperloop deployment in Europe is highlighted by a recent mapping of activities in the industry and European institutions [14]. Nevertheless, to test the safety, efficiency and reliability of Hyperloop in the field, beyond research and development (R&D), a long enough, full-scale prototype track is necessary.

Beyond the US and Europe, in China and Korea, as patent activity shows, there is substantial R&D from CRRC Yangtze Co., the Korea Railroad Research Institute (KRRI) and the Korea Institute of Construction Technology (KICT) [14,15].

Considering the above, this study examines the status of Hyperloop scientific developments, identifying issues and challenges. It is based on initial considerations developed in [14]. Compared to that previous study, a systematic review was performed, and the fields of research were explicitly identified. Consequently, a taxonomy of scientific research issues was developed by analyzing all Hyperloop research in the literature, using the methodology developed by the European Commission's Transport Research and Innovation Monitoring and Information System (TRIMIS) [16]. Accordingly, the literature was organized in relevant clusters and for each cluster combination, the issues were identified as lower-level items in the taxonomy.

The findings could be of help to transportation academics and professionals who are interested in developments in the field, and form the basis for policy decisions for the future implementation of Hyperloop.

The paper consists of the following parts: after the introduction, the next section discusses the materials and methods used in this study, drawing from the Scopus database and a physical system decomposed into several clusters. Section 3 provides the results from the analyses grouped under the different clusters. Section 4 provides an initial taxonomy based on the performed analysis and a brief discussion. Section 5 provides the conclusions.

2. Materials and Methods

The methodology presented in this section focuses on capturing research findings, aiming at the identification of trends, and consequently, building a taxonomy of issues. The Scopus database, which has scrupulous indexing rules, was used as a source.

For the analysis, the following steps were taken:

- A search using specific keywords ("Hyperloop" or "tube transport" or "vactrain") was carried out, in the abstract, title, or keywords. Results were limited to those published after 2013 (when the modern concept of Hyperloop was introduced), and documents from health sciences were excluded due to the lexical ambiguity of "Hyperloop transport" term. The exact query used was: TITLE-ABS-KEY ("Hyperloop" OR "tube transport*" or "vactrain") AND PUBYEAR > 2013 and not SUBJAREA (MEDI OR NURS OR VETE OR DENT OR HEAL). This search performed in June 2021 resulted in 229 documents.

- An additional manual filtering of the documents one-by-one, on the basis of their title or abstract limited, resulted in 161 documents. The aim of this filtering was to eliminate those documents that were not relevant to the field due to lexical ambiguity and those that simply outlined Hyperloop-related aspects. This left 96 articles, 57 conference papers, three reviews, three notes, one letter and one book chapter.

Figure 1 shows the distribution of the documents over the considered time period.
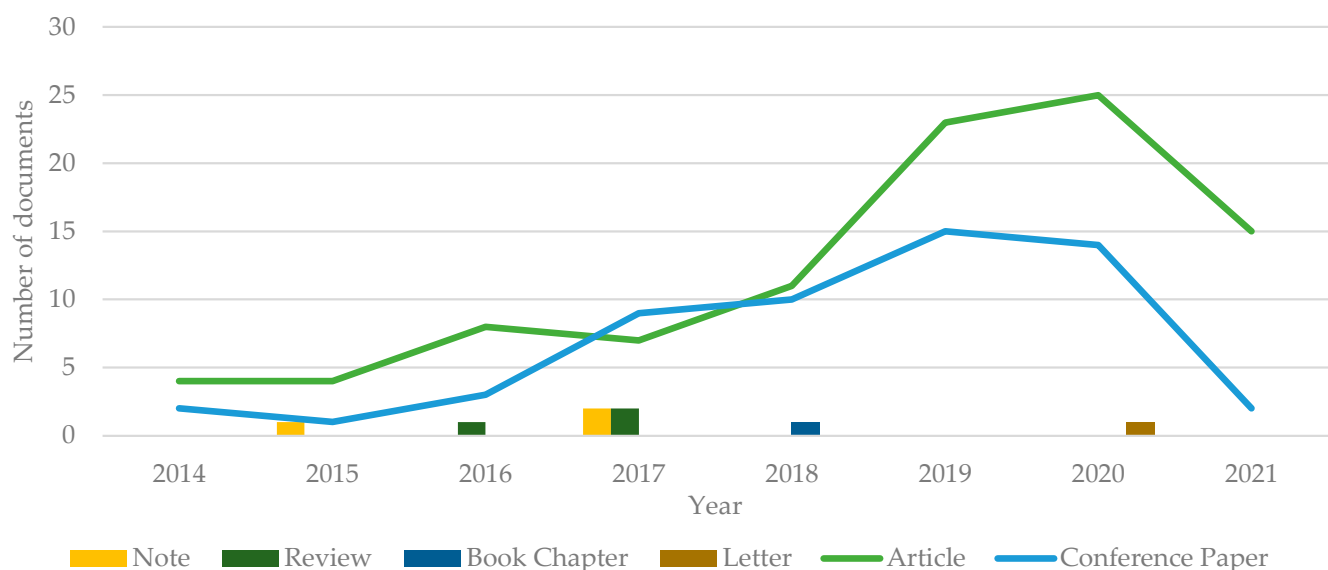
Figure 1. Evolution of Hyperloop academic research.

Figure 1 shows an overview of the results, which are destined to increase in 2021.

After this step, an analysis of all abstracts (and in case of doubt, of the full paper) took place, and the research was quantitatively assessed, focusing on several clusters. Inspired by the decomposition approach from [14], this was done by means of a system approach, breaking the Hyperloop system into five physical parts (Figure 2). These parts cover the entire hyperloop system, and outline interacting subsystems.

Figure 2. Hyperloop system decomposition (adapted from [14]).
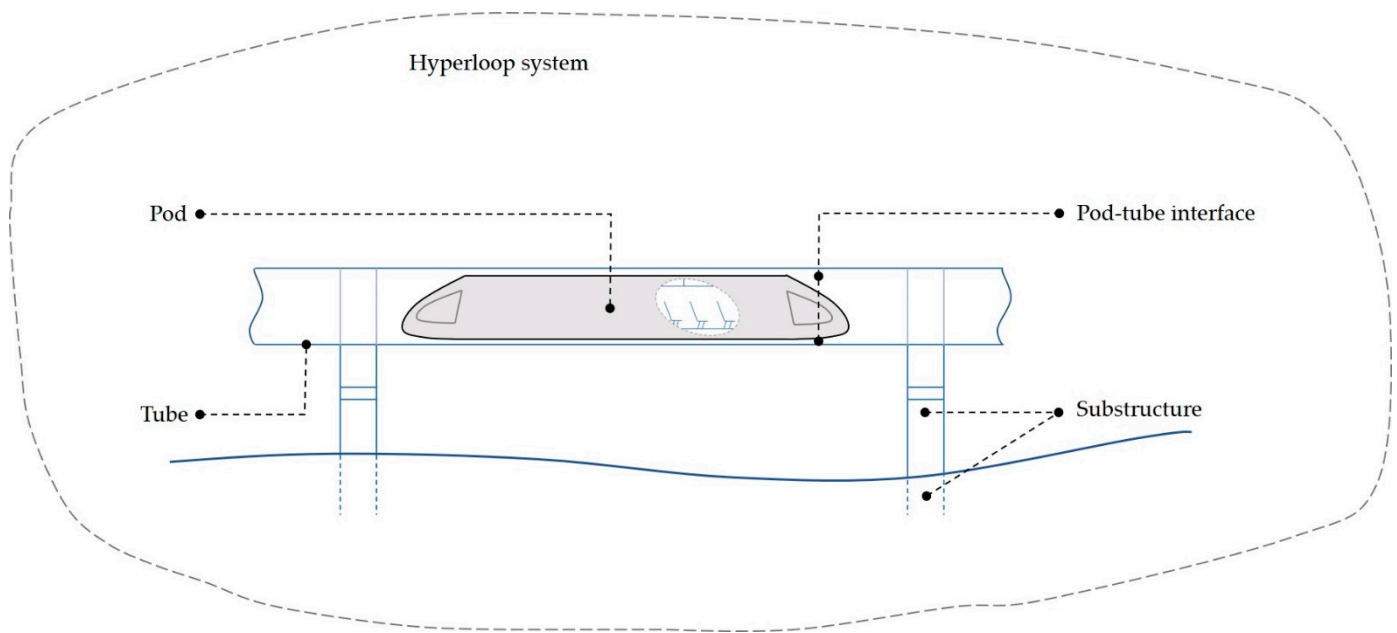
The five physical clusters are:

- Hyperloop as a system: this includes research that encompasses the entire system and that cannot be considered under other disaggregated levels. Examples may include efficiency and energy studies of the system in operation.
- Substructure (including foundations and bridge work): focuses mostly on structural engineering design for the supporting structure.
- Tube: considers aspects related to the tube structure.
- Tube pod interface: focuses on research on the interface between the tube and the pod. Examples may include aerodynamic phenomena as a consequence of the pressure variation.
- Pod: focuses on aspects related to the pod (e.g., levitation, suspension, powertrain, electronics)

In addition, five horizontal (operational) clusters (energy, operations, communications, aerodynamics, safety) were considered.

It should be noted that this decomposition (into five physical and five horizontal clusters) while meaningful, is not the only one possible. In fact, in a design process it is impossible to decompose a system uniquely [17]. Nevertheless, this provides a rather generic and complete higher-level decomposition, which can be further broken down into lower hierarchies. For example, the "pod" cluster can be further decomposed into sub-clusters, covering the powertrain, the levitation and suspension blocks, etc. Likewise, the horizontal clusters can be further elaborated to cover additional operations. In this sense, the decomposition is scalable and provides the starting point for adding more elaborated layers of detail.

These clusters, although developed independently for this study, also encompass and are aligned with the priority work areas identified by the CEN/CENELEC TC on Hyperloop standardization, which include pressures of operation, door sealing, vehicle-tube interface, communication protocols and emergency evacuation [13].

Sections 3.1–3.5 present the results for the five physical clusters. In the analyses, each paper is also linked to one of the five horizontal clusters. Finally, Sections 3.6 and 3.7 present an overview of research involving general discussions and Hyperloop network developments. These last two, are not linked to the physical clusters since they focus on discussion rather than on the development of specific technologies.

3. Hyperloop Research Breakdown

3.1. Research on the Hyperloop System

This section focuses on scientific research documents dealing with the Hyperloop system in general. Thirty-two papers were identified from the analysis.

An overview of the issues identified in the scientific literature under the five utility clusters is provided in Table 1.

Table 1. Issues identified in research on the Hyperloop system.

Authors	Year	Issue	E	O	C	A	S
Tavsanoglu et al. [18]	2021	Pod to ground wireless communication			X		
Fernández Gago and Collado Perez-Seoane [19]	2021	Geometric design and linear infrastructure planning		X			
Huang et al. [20]	2021	Optical wireless communication system			X		
Tbaileh et al. [21]	2021	Power requirements and impact on the electricity grid	X				
Han et al. [22]	2020	Wireless network architecture			X		
Brown et al. [23]	2020	Short-range communication			X		
Eichelberger et al. [24]	2020	Scheduling		X			
Zhang et al. [25]	2020	Pod to ground wireless communication			X		
Qiu et al. [26]	2020	Pod to ground wireless communication			X		
Janić [27]	2020	Energy consumption and CO_2 emissions	X				
Lafoz et al. [28]	2020	Energy Storage Systems	X				
Zhang et al. [29]	2020	Pod to ground wireless communication			X		
Khan [30]	2020	Overall system development		X			
Narayan S. [31]	2020	Solar panel power	X				
Bempah et al. [32]	2019	Photovoltaic panel configurations for tube	X				
Huang et al. [33]	2019	Lateral drift under different low pressures		X			
Jin et al. [34]	2019	Dynamic characteristics under low-pressure		X			
Thakur et al. [35]	2019	Braking and deceleration					X
Kim and Rho [36]	2019	Support facility and pods		X			
Dudnikov [37]	2019	Network operations		X			
Allen et al. [38]	2019	Pod to ground wireless communication			X		
Sutton [39]	2019	Process safety and generic safety cases					X
Kauzinyte et al. [40]	2019	Simulation with aerodynamic constraints				X	
Deng et al. [41]	2018	System simulation		X			
Nikolaev et al. [42]	2018	Electric and software system		X			
Deng et al. [43]	2017	System simulation		X			
Janzen [44]	2017	Dynamic characteristics under low-pressure		X			
Kwon et al. [45]	2017	Photovoltaic panel configurations for tube	X				
Ali et al. [46]	2017	Handover algorithm			X		
Decker et al. [47]	2017	Conceptual feasibility study		X			
Zhou et al. [48]	2016	Energy consumption	X				
Brusyanin and Vikharev [49]	2014	Conceptual functional safety assessment					X

Abbreviations: E: Energy; O: Operations; C: Communications; A: Aerodynamics; S: Safety.

3.2. Research on Hyperloop Substructure

This section focuses on scientific research documents dealing with the Hyperloop substructure. Eight papers were identified from the analysis.

An overview of the issues identified regarding Hyperloop substructure, under the five utility clusters, is provided in Table 2.

Table 2. Issues identified in research on Hyperloop substructure.

Authors	Year	Issue	E	O	C	A	S
Museros et al. [50]	2021	Structural design					X
Zhao et al. [51]	2021	Vibration instability					X
Ahmadi et al. [52]	2020	Dynamic bridge deck-pier interaction					X
Ahmadi et al. [53]	2020	Dynamic amplification factors					X
Kemp et al. [54]	2020	Floating hyperloop tunnel conceptual design		X			
Connolly and Costa [55]	2020	High speed dynamic load amplification		X			
Alexander and Kashani [56]	2018	Bridge dynamics					X
Pegin et al. [57]	2018	Superstructure dynamic coefficients		X			

Abbreviations: E: Energy; O: Operations; C: Communications; A: Aerodynamics; S: Safety.

3.3. Research on Hyperloop Tube Structure

This section focuses on scientific research documents dealing with the Hyperloop tube structure. Seven papers were identified from the analysis.

An overview of the issues identified in regard to Hyperloop tube structure, under the five utility clusters, is provided in Table 3. As can be seen, the principal topic of research is the airtightness of concrete tubes.

Table 3. Issues identified in research on Hyperloop tube structure.

Authors	Year	Issue	E	O	C	A	S
Devkota et al. [58]	2021	Concrete tube airtightness					X
Baek [59]	2020	Identification of anomalies in the tube					X
Devkota and Park [60]	2019	Concrete tube airtightness					X
Dudnikov [61]	2018	Concrete tube airtightness					X
Devkota et al. [62]	2018	Concrete tube airtightness					X
Choi et al. [63]	2016	Concrete tube airtightness					X
Park et al. [64]	2015	Concrete tube airtightness					X

Abbreviations: E: Energy; O: Operations; C: Communications; A: Aerodynamics; S: Safety.

3.4. Research on Hyperloop Tube-Pod Interface

This section focuses on scientific research documents dealing with the Hyperloop tube-interface. Forty-eight papers were identified from the analysis.

An overview of the issues identified regarding the Hyperloop tube-pod interface, under the five utility clusters, is provided in Table 4.

Table 4. Issues identified in research on Hyperloop tube-pod interface.

Authors	Year	Issue	E	O	C	A	S
Bose and Viswanathan [65]	2021	Piston effect mitigation using airfoils				X	
Lluesma-R. et al. [66]	2021	Use of compressor to mitigate aerodynamic drag				X	
Zhou et al. [67]	2021	Radial gap and flow field				X	
Hu et al. [68]	2021	Cross passage and flow field				X	
Lluesma-R. et al. [69]	2021	Drag coefficient effect on the aerodynamic performance				X	
Vakulenko et al. [70]	2021	Effect of external air exchange system				X	
Uddin et al. [71]	2021	Drag-based aerodynamic braking					X
Huang et al. [72]	2020	Transient pressure on the tube				X	
Galluzzi et al. [73]	2020	Stabilization of electrodynamic levitation systems		X			
Nick and Sato [74]	2020	Pod structure aerodynamic optimization				X	
Le et al. [75]	2020	Aerodynamic drag and pressure waves				X	
Wang et al. [76]	2020	Blockage ratio and aerodynamic drag				X	
Ma et al. [77]	2020	Air pressure and aerodynamic drag				X	
Chen et al. [78]	2020	Structural mechanics properties of tube-wall		X			
Jia et al. [79]	2020	Heat recycle duct and energy accumulation	X				

Table 4. *Cont.*

Authors	Year	Issue	E	O	C	A	S
Yang et al. [80]	2020	Blockage ratio and aerodynamic drag				X	
Mao et al. [81]	2020	Vacuum level and heat transfer characteristics	X				
Sui et al. [82]	2020	Blockage ratio and aerodynamic drag				X	
Machaj et al. [83]	2020	Power consumption analysis	X				
Zhang et al. [84]	2019	Guidance performance through curves		X			
Strawa et al. [85]	2019	Pod in low-pressure environment		X			
Nowacki et al. [86]	2019	Energy demand	X				
Zhang et al. [87]	2019	Aerodynamic noise				X	
Niu et al. [88]	2019	Aerodynamic heating				X	
Oh et al. [89]	2019	Aerodynamics and blockage ration				X	
Arun et al. [90]	2019	Conceptual aerodynamic design				X	
Li et al. [91]	2019	Embarking and disembarking process		X			
Wang and Yang [92]	2019	Electrodynamic magnetic levitation system		X			
Chaidez et al. [93]	2019	Levitation methods power requirements	X				
Jia et al. [94]	2018	Aerodynamic characteristics and pressure recycle ducts				X	
Opgenoord and Caplan [95]	2018	Aerodynamic design				X	
Zheng et al. [96]	2018	High temperature superconducting magnetic suspension		X			
Wan et al. [97]	2018	Guidance performance through curves		X			
Sayeed et al. [98]	2018	Magnetic levitation system prototype		X			
Zhang et al. [99]	2018	Levitation force		X			
Kang et al. [100]	2017	Aerodynamic drag parametric study				X	
Zhou et al. [101]	2017	Energy consumption and blockage ratio	X				
Braun et al. [102]	2017	Aerodynamic design multi-objective optimization				X	
Heaton [103]	2017	Inertial forces from earthquake					X
Opgenoord and Caplan [104]	2017	Aerodynamic design and boundary layer				X	
Wang et al. [105]	2017	Aerodynamic design				X	
Zhang et al. [106]	2016	Auxiliary pumping system		X			
Pekardan and Alexeenko [107]	2016	Thermal lift generation and drag reduction				X	
Braun et al. [108]	2016	Aerodynamic design and lift generation				X	
Zhou et al. [109]	2015	Aerodynamics and thermal-pressure coupling				X	
Zhou et al. [110]	2014	Entropy and aerodynamic heat generation				X	
Ma et al. [111]	2014	Kinetic energy loss				X	
Pandey and Mukherjea [112]	2014	Aerodynamic design				X	

Abbreviations: E: Energy; O: Operations; C: Communications; A: Aerodynamics; S: Safety.

3.5. Research on Hyperloop Pod

This section focuses on scientific research documents dealing with the Hyperloop pod. Twenty-seven papers were identified from the analysis.

An overview of the issues identified regarding the Hyperloop pod, under the five utility clusters, is provided in Table 5.

Table 5. Issues identified in research on Hyperloop pod.

Authors	Year	Issue	E	O	C	A	S
Negash et al. [113]	2021	Semi-active suspension system		X			
García-Tabarés et al. [114]	2021	Acceleration system based on a linear motor		X			
Lim et al. [115]	2020	Electrodynamic suspension		X			
Jayakumar et al. [116]	2020	Pod space frame		X			
Lim et al. [117]	2020	High-temperature superconducting (HTS) magnet		X			
Seo et al. [118]	2020	Propulsion/levitation/guidance LIM		X			
Choi et al. [119]	2019	Sub-sonic linear synchronous motor		X			
Guo et al. [120]	2019	Null-flux coil electrodynamic suspension structure		X			
Zheng et al. [121]	2019	Levitation and Linear Propulsion System		X			
Seo et al. [122]	2019	Propulsion/levitation/guidance LIM		X			

Table 5. *Cont.*

Authors	Year	Issue	E	O	C	A	S
Tudor and Paolone [123]	2019	Influence of batteries to the propulsion	X				
Bhuiya et al. [124]	2019	Three-phase inverter for powertrain		X			
Naik et al. [125]	2019	Cold Gas Propulsion System		X			
Guo et al. [126]	2019	Electrodynamic suspension		X			
Cho et al. [127]	2019	Propulsion/levitation/guidance LIM		X			
Indraneel et al. [128]	2019	Levitation		X			
Soni et al. [129]	2019	Magnetic brakes					X
Tudor and Paolone [130]	2019	Propulsion system and energy requirements	X				
Ji et al. [131]	2018	Propulsion/levitation/guidance LIM		X			
Abdelrahman et al. [132]	2018	Magnetic levitation		X			
Pradhan and Katyayan [133]	2018	Vehicle dynamics		X			
Klim and Hashemi [134]	2017	Vehicle wheels design		X			
Zhou et al. [135]	2016	Propulsion/levitation/guidance LIM		X			
Ma et al. [136]	2015	Electromagnetic braking					X
Chin et al. [137]	2015	Pod sizing		X			
Zhang [138]	2014	Life support systems					X

Abbreviations: E: Energy; O: Operations; C: Communications; A: Aerodynamics; S: Safety; LIM: Linear Induction Motor.

3.6. Discussion Papers on Hyperloop

This section focuses on scientific research documents that focus on general discussions. Thirty papers were identified from the analysis.

Table 6 provides an overview of the topics discussed.

Table 6. General discussion papers.

Authors	Year	Issue
Noland [139]	2021	Systematic technology review
Hansen [140]	2020	Technology assessment
Gieras [141]	2020	Technical/technological aspects
Sutar et al. [142]	2020	Hyperloop concept
Gkoumas and Christou [14]	2020	Policy and technical context
Barbosa [143]	2020	Technology review
Kumar et al. [144]	2019	Technical/technological aspects
Janić [145]	2019	Technical/technological/policy aspects
Lipusch et al. [146]	2019	Financing
Deng et al. [147]	2019	Technical/technological aspects
Bersano and Fayemi [148]	2019	Innovation management and design theory
Leibowicz [149]	2018	Technical/technological/policy aspects
van Goeverden et al. [150]	2018	Performance compared to air and high-speed train
Melzer and Zech [151]	2018	Social media
Ahmad et al. [152]	2017	Preliminary patent analysis
Kerns [153]	2017	Hyperloop competitions
Violette [154]	2017	Hyperloop competitions
Dudnikov [155]	2017	Tube and pod technical parameters
(No author name available) [156]	2017	Hyperloop competitions
Halsmer et al. [157]	2017	Hyperloop competitions
González-G. and Nogués [158]	2017	Technical/technological aspects
González-G. and Nogués [159]	2017	Technical/technological aspects
Bradley [160]	2016	Development cases
Rubin [161]	2016	Development cases
Anyszewski [162]	2016	Competitions
Ross [163]	2016	Hyperloop concept
Palacin [164]	2016	Viewpoint
Thompson [165]	2015	Social aspects
Abaffy [166]	2015	Financing
Kosowatz [167]	2014	Viability

3.7. Research on Hyperloop Networks

This section focuses on scientific research documents that focus on the development of Hyperloop networks. Ten papers were identified from the analysis.

Table 7 provides an overview of the topics discussed.

Table 7. Network papers.

Authors	Year	Issue
Merchant and Chankov [168]	2020	Scenario analysis in Europe
Neef et al. [169]	2020	Scenario analysis on infrastructure networks
Bertolotti and Occa [170]	2020	Agent-based model of supply chain system
Rajendran and Harper [171]	2020	Define, Measure, Analyze, Design, and Verify (DMADV) approach
Cho [172]	2019	Implications at local level
Pfoser et al. [173]	2018	Hyperloop and synchromodality
Voltes-Dorta and Becker [174]	2018	Implications at local level
Markvica et al. [175]	2018	Hyperloop impact in Europe
Schodl et al. [176]	2018	Large scale regional impact
Werner et al. [177]	2016	Implications at local level (cargo)

The relationship between vertical and decomposition clusters in the documents is shown in the chord diagram of Figure 3. The 30 documents on Hyperloop discussions and the 10 documents on Hyperloop network developments are excluded from the diagram. The left part of the figure reports the utility clusters and, on the right, the physical clusters. Visualizations of this kind highlight the most popular research topics and the relationship between them, and help to identify research insufficiencies.
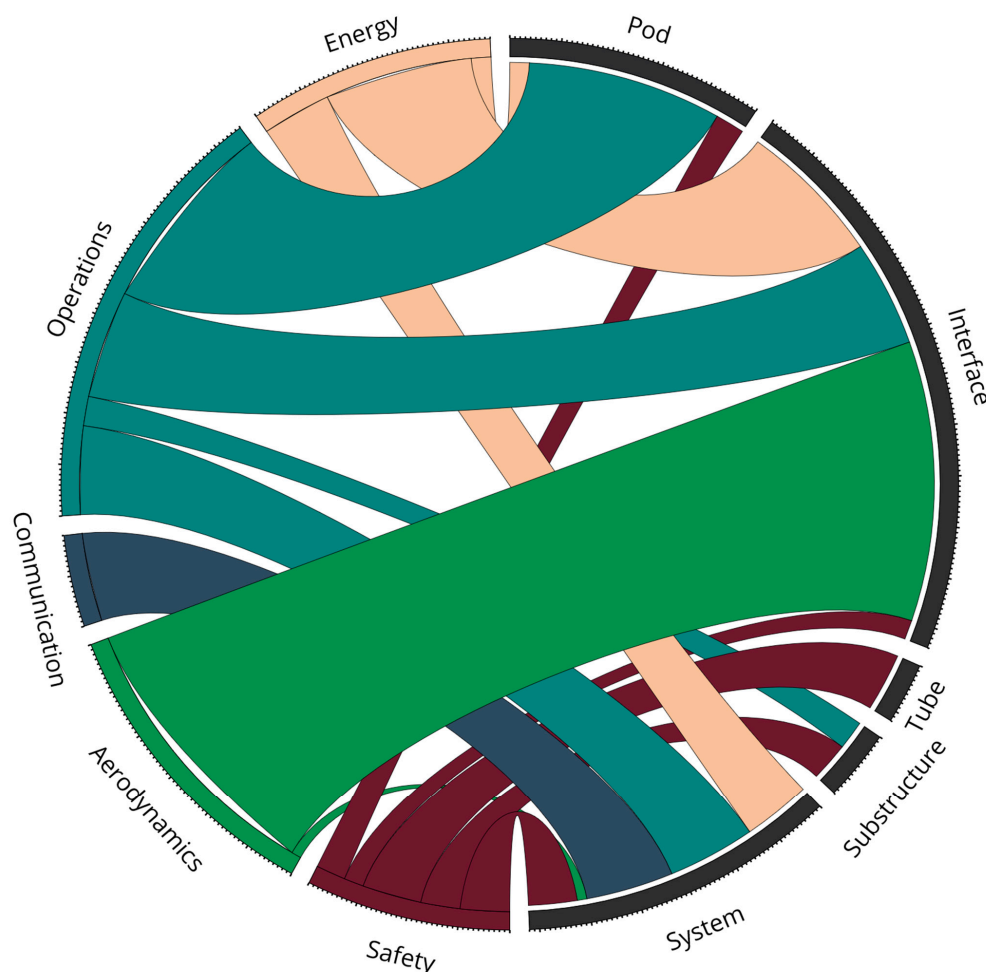
Figure 3. Hyperloop academic research clusters relation overview.

As can be seen, and with regard to the physical decomposition, the majority of research focuses on the pod-tube interface and aerodynamics (29 documents) and the pod and operations (21 documents). Communication technologies were researched in nine documents at a system level. The 21 documents focusing explicitly on safety issues, cover all horizontal areas.

4. Initial Taxonomy of Issues

The next step was to build a preliminary taxonomy of research topics. As explained in Section 3, all papers were read and grouped under the different clusters. Each paper was also flagged for the respective research issues. Table 8 aggregates the findings from the 161 documents. For the utility clusters, an overview of the emerging issues is reported, while for the physical and generic clusters, the research issues are reported in detail, aggregating the identified issues from Section 3. It should be noted that the obtained taxonomy is not unique, and further readings could identify additional elements.

Table 8. A taxonomy of overarching research clusters and research issues on Hyperloop arising from the scientific literature analysis.

		Research Clusters	**Researched Issues**
Utility cluster overview	1	Energy	Energy consumption (may include aerodynamics, but focuses on heat dissipation)
	2	Safety	Safety process, evacuation, pod tightness, breaking
	3	Communications	Pod-to-pod and pod-to-ground communication
	4	Aerodynamics	Aerodynamic phenomena
	5	Operations	Hyperloop operations and research not covered in utility clusters 1–4
Physical clusters	A	System	Optical wireless communication, pod-to-ground communication, communication signal propagation, system simulation, functional safety, process safety, safety cases, energy storage systems, lateral drift, energy consumption, network architecture, scheduling, short range communication, power requirements, impact on the electricity grid, short-range communication, scheduling, electric and software system, photovoltaic panels, handover algorithm, geometric design, linear infrastructure planning
	B	Substructure	Structural design, bridge dynamics, geotechnical, earthquake, resonant dynamic effects, vibration instability, bridge deck-pier interaction, bridge dynamics, dynamic amplification factors, dynamic load amplification, floating Hyperloop tunnel
	C	Tube	Airtightness, anomaly detection
	D	Tube-pod interface	Levitation friction, aerodynamic drag, blockage ratio, vacuum effects, piston effect mitigation, heat generation, tube/pod combined design, energy loss, aerodynamic noise, levitation force, kinetic energy, pressure recycle ducts, aerodynamic breaking
	E	Pod	Motor, propulsion, semi-active suspension, electrodynamic suspension, levitation, guidance, design, sizing, battery, tightness, Linear Induction Motor, high-temperature superconducting (HTS) magnet, batteries, wheel design, additive manufacturing, inverter for powertrain, Cold Gas Propulsion
Generic clusters	i	Discussion	Technical feasibility, financing, policy recommendations, new mobility paradigms, knowledge management, technology overview, education, competitions, general feasibility
	ii	Network	Network feasibility, financial efficiency, network simulations, network operations, scenario analysis, synchromodality, supply chain, regional impact

A variety of researched topics emerges from Table 8.

The Hyperloop as a system cluster (A) includes a lot of research on different operational aspects, in particular communications. In fact, this aspect appears to be challenging at very high speeds in tunnel structures. Some other aspects related to the geometric design and the linear infrastructure development are also covered in this cluster in an analytical manner.

The Hyperloop substructure cluster (B) includes a great deal of research from the fields of structural and bridge engineering. The major difference is the dynamic loads

imposed by the Hyperloop pods, which influence the design of substructure and need to be accounted for.

Some research deficiencies were identified. This is the case for research focusing on the Hyperloop tube cluster (C), and consequently, on infrastructure. Considering that infrastructure costs are high (especially for a new system) the lack of research in this area (e.g., materials, tube thickness) is visible.

At the same time, Hyperloop tube-pod interface cluster (D) research focuses on a variety of issues linked in particular to aerodynamic performance under low pressure.

Research focusing on the Hyperloop pod cluster (E) covers many aspects that are linked to the powertrain, suspension, magnetic levitation and guidance. A number of similarities with high-speed rail and (especially) magnetic levitation (Maglev) trains are apparent, something that may lead to research spillovers from the two transport modes.

Finally, the rather high number of discussion papers and those related to Hyperloop networks highlight the overall interest in Hyperloop as a transport mode.

5. Conclusions

Hyperloop is a proposed very high-speed ground transportation system that has great potential for the decarbonization of transportation, and it has received a great deal of attention from transportation academics. This study aimed to provide a baseline with regard to the topics and challenges identified in the scientific research, for the effective testing and deployment of Hyperloop. The presentation of the issues follows a structured methodology, and provides insights for future research. In particular, the adopted clustering is scalable, and consequently, more detailed sub-clusters could be easily identified. The performed extensive literature review, to the authors' knowledge, is the most complete of its kind.

As discussed in the previous section, based on the detailed findings and the taxonomy of issues identified under the overarching clusters, there is vast interest from the research community on this topic.

These findings could play an important role in providing input to ongoing Hyperloop standardization processes by looking into the different approaches for solving specific issues. The findings also complement proprietary technologies developed by Hyperloop promoters, since in many cases, academic research on the same topics is independent. Therefore, it can provide a fresh perspective since academic research follows different paths of knowledge compared to industry. This is more evident in specific clusters (e.g., substructure and tube) where structural engineering approaches are implemented, relying on the long-standing expertise of researchers in the specific field.

Another possible use that emerges is the opportunity to compare the taxonomy with research issues in legacy systems, e.g., high speed rail. In this way, it is possible to quickly check (a) similarities in the research in the two systems, and consequently, possible research spillovers, and (b) research issues not yet explored. The results from such an exercise could provide valuable input to standardization and certification bodies.

The findings could ignite policy initiatives focusing on future decisions regarding the Hyperloop. For this process to succeed, the continuous identification and assessment of issues will be necessary, including challenges beyond technology (e.g., social aspects, project financing), which will help to make the demonstration and deployment of Hyperloop possible. Outside policymaking, this paper helps academics and professionals who are interested in the development of Hyperloop technologies by providing digested information on scientific developments in this area.

Future research could focus on expanding this taxonomy to cover other domains of knowledge, in particular, intellectual property applications from Hyperloop promoters and nationally funded research.

Informed Consent Statement: Not applicable.

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