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Technological trends in mountain logistics: A patent analysis

Mehari Beyene Teshome [a], Matteo Podrecca [b,c], Guido Orzes [a,b,*]

[a] Competence Centre for Mountain Innovation Ecosystems, Free University of Bozen-Bolzano, Bolzano, Italy
[b] Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy
[c] Department of Management Information and Production Engineering, University of Bergamo, Bergamo, Italy

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ABSTRACT

Transportation and logistics in mountain regions are difficult due to the harsh weather conditions and complex terrain. It is crucial to have specialized expertise and advanced technologies to tackle such challenges. However, the field has unexplored domains, and available solutions are not holistically charted, necessitating a nuanced understanding of the innovation landscape and growth trajectories. This study aims to undertake a patent analysis on mountain transportation and logistics to unveil emerging trends, map technological advancements, and contribute to enhancing transportation systems. Relevant patent documents were extracted from the Derwent Innovation Index database through a keyword search combined with specific International Patent Classification categories. From these documents, technological fields were identified and grouped using the Latent Dirichlet Allocation technique, resulting in 12 clusters. Among them, seat and suspension control systems, intelligent vehicle control systems, electrical systems and electric vehicles, bicycle frame design, and safety devices are likely to attract notable interest in the future. The findings contribute to the academic discourse and hold practical implications for industry and policy stakeholders, offering a nuanced understanding of technological trends crucial for addressing transportation challenges in mountain terrains.

1. Introduction

Mountain regions, characterized by elevated landforms and rugged terrain, encompass significant portions of the world's land and population areas (Du, 2009; Liu et al., 2019). These zones have a profound impact on global ecosystems and economic development, as they provide resources to downstream domains, support agriculture and industry, and offer recreational opportunities and cultural heritage to communities (Di Giacobbe, Di Ludovico, & D'Ovidio, 2021; Milićević, Bošković, & Lakićević, 2021; Moretti et al., 2023; Price & Kim, 1999). Therefore, the preservation and sustainable development of mountain areas are not only desirable, but essential for maintaining ecological balance and ensuring the well-being of both local communities and urban populations (Carroll-Foster & Li Pun, 1993; Moretti et al., 2023). In this regard, transportation and logistics (T&L) play a crucial role, serving as essential drivers for the progress and growth of such territories (De Langen, Figueroa, Van Donselaar, & Bozuwa, 2017; Huang, 2016).

However, mountain areas present unique challenges due to their steep slopes, valleys, harsh weather patterns, and complex geological features, which make T&L activities particularly arduous (Jung & Kim, 2022; Wankmüller et al., 2020). These challenges result in higher transportation infrastructure costs, longer travel times, increased fuel consumption, elevated risks of accidents, and limited accessibility to remote zones, thus hindering the movement of goods and people (Lu, Shang, Wei, & Wu, 2021; Walnum & Simonsen, 2015). Moreover, development policies often have different effects in heterogeneous contexts, such as in mountainous regions, potentially limiting growth opportunities therein (Feng, Wang, Du, Wu, & Wang, 2019; Li, Chu, Yang, Wu, & Huang, 2024; Ye, Li, Li, Tao, & Wu, 2024). For these reasons, T&L patterns in these areas are distinct from those in plain settings and require tailored efforts to address the problems posed by the terrain (Du, 2009).

Recent studies have highlighted a wide array of transportation vectors and solutions aimed at overcoming the aforementioned obstacles. Examples include aerial ropeway transportation systems (Alshalalfah, Shalaby, Dale, & Othman, 2012; Pernkopf & Gronalt, 2021; Reichenbach & Puhe, 2018); unmanned aerial vehicles (UAVs), also known as "drones" (Holzmann, Wankmüller, Globocnik, & Schwarz, 2021; Liu, Pan, Zhang, Zhang, & Shao, 2022b; Pedersen et al., 2021; Silvagni,

* Corresponding author at: Competence Centre for Mountain Innovation Ecosystems, Free University of Bozen-Bolzano, Franz-Innerhofer-Platz 8, 39100, Bozen-Bolzano, Italy.
E-mail address: guido.orzes@unibz.it (G. Orzes).

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Tonoli, Zenerino, & Chiaberge, 2017; Wankmüller et al., 2020); and cargo bicycles (Gonzalez-Calderon, Posada-Henao, Granada-Muñoz, Moreno-Palacio, & Arcila-Mena, 2022). Furthermore, in the Industry 4.0 era, the T&L industry is transforming with the aid of disruptive advancements such as big data, the Internet of Things, cloud computing, artificial intelligence (AI), and machine learning (ML). These technologies are considered enablers of operations optimization and efficiency improvement (Chen, Chen, & Yang, 2022; Govindan, Cheng, Mishra, & Shukla, 2018; Lekić, Rogić, Boldizsár, Zöldy, & Török, 2021; Núñez-Merino, Maqueira-Marín, Moyano-Fuentes, & Castaño-Moraga, 2022; Wang, Zhang, & Zhang, 2020; Zhu, Liu, & Shi, 2022), aside from assisting firms in minimizing their environmental impact by implementing greener practices (Hao, Liang, Yang, Wu, & Hao, 2024a; Tao, Lu, Ye, & Wu, 2024).

Against this rapidly evolving context, scholars have highlighted the presence of unexplored domains (Marchet, Melacini, & Perotti, 2014; Reis, Costa, Marques, Pinto, & Mateus, 2024) and a lack of comprehensive dashboards that provide evidence of the actual development state of T&L systems for mountain areas (Botín-Sanabria et al., 2022). This scenario poses at least three challenges. First, potential users often cannot identify the most suitable solution for their needs because of limited knowledge of the available options (Mejri, Ben-Othman, & Hamdi, 2014). Second, policymakers lack an overall vision to inform actions targeted at supporting mountain T&L (Long, Yang, & Su, 2023; Lyons & Davidson, 2016). Third, organizations interested in advancing mountain technologies struggle to understand where to prioritize efforts due to uncertainty regarding the current progress (Fulzele & Shankar, 2022). Mapping the innovation landscape in mountain logistics and transportation is, therefore, essential for decision-making and to bridge the gap between expectations and reality (Abbas, Zhang, & Khan, 2014); it helps users stay updated on the latest technological advancements that improve efficiency, safety, and convenience in transportation means. Additionally, it aids organizations evaluate the competitiveness of different actors in mountain transportation technology, fostering strategic planning and cooperation initiatives (Spitsberg, Brahmandam, Verti, & Coulston, 2013).

An effective approach for gaining an overall picture of the research and development (R&D) arena on mountain logistics involves conducting a patent analysis using ML techniques (Erzurumlu & Pachamanova, 2020; Park, Yoon, Kim, & Seol, 2021; Steyvers & Griffiths, 2007). On the one hand, ML tools enable the processing of vast amounts of data by identifying patterns and relationships that would be difficult or impossible to detect using traditional approaches (Qiu, Wu, Ding, Xu, & Feng, 2016). On the other, patent documents are valuable data sources, as they provide information on real-world trends, technological interdependencies, and leading players, thus allowing for a detailed understanding of the issues at hand (Ercan & Kayakutlu, 2014; Hao et al., 2023; Yoon, Woo, & Sohn, 2024). Patent analysis can also support the intellectual property (IP) management strategies—including licensing and technology transfer—of organizations involved in mountain T&L (Spitsberg et al., 2013). Furthermore, understanding patent trends and activities helps policymakers formulate effective policies and regulations to sustain innovation and address challenges in mountain T&L (Albino, Ardito, Dangelico, & Petruzzelli, 2014; Feng et al., 2019; Hao, Liang, et al., 2024a; Niu, Zhang, Luo, & Feng, 2023; Ye et al., 2024; Yu, Wang, Lin, & Su, 2024).

Motivated by this background, we undertake an in-depth patent analysis that employs Latent Dirichlet Allocation (LDA) to provide a holistic view of technological trends and advancements in mountain T&L. Specifically, this study attempts to answer the following research question:

What is the state of development in the field of mountain transportation and logistics?

The results of our patent analysis show 12 clusters representing distinct, specialized areas within mountain transportation vectors. Among them, the domains of seat and suspension control systems, intelligent vehicle control systems, electrical systems and electric vehicles, bicycle frame design, and safety devices have potential significance in the future of mountain T&L. Meanwhile, the data show that the fields of vehicle body structures, mountain bike parts and accessories, and mechanical power transmission are reaching a state of saturation or becoming obsolete.

The remainder of this paper is structured as follows. In Section 2, we present the background of our study pertaining to mountain T&L, patent analysis, and topic modeling. In Section 3, we detail our methodological procedures, from data collection to topic modeling. In Section 4, we present our results, highlighting both our descriptive findings and the thematic classification of technological areas in the mountain T&L field. In Section 5, we summarize the main takeaways from this study. Finally, in Section 6, we reflect on the main implications and limitations, as well as outlooks for future research.

2. Background

2.1. Transportation and logistics in mountain areas

Mountain regions, which cover a substantial portion of the earth's surface and host about 10 % of the global population (Du, 2009; Liu et al., 2019), gained relevance in global discourse following the United Nations Conference on Environment and Development (UNCED) in 1992 (Carroll-Foster & Li Pun, 1993; Price & Kim, 1999). This discussion focused on balancing mountain ecosystems and promoting income-generating activities, as well as improving infrastructure and social services without impacting the environment. To this end, the T&L sector plays a crucial role in the development of these areas by fostering connectivity (Huang, 2016); achieving sustainable mountain development requires strategically integrating T&L systems that balance economic progress with environmental preservation and enhance residents' quality of life (Bhatta, Shrestha, Neupane, Jodha, & Wu, 2019; Kacher & Singh, 2021; Nussbaumer et al., 2017). For this reason, T&L in such challenging mountain zones has emerged as an area of interest for industry practitioners and academic researchers.

Mountain T&L refers to the specialized management and movement of goods and people in mountain regions, which have different characteristics from flat areas (Carreras, De Soto, & Muñoz, 2019). It involves planning, organizing, and executing transportation activities tailored to the unique challenges posed by rugged landscapes, steep gradients, adverse weather conditions, and limited accessibility (Wankmüller et al., 2020). This includes using various modes of transportation, such as roads, rail, cableways, and aerial systems, to facilitate the efficient and reliable movement of goods and passengers across mountain landscapes (Jansky, Ives, Furuyashiki, & Watanabe, 2002).

Despite the pronounced importance of T&L, operational challenges pose formidable obstacles to the smooth flow of goods and compromise the quality of customer service (Burda, Zidova, & But, 2023; Serdyukova, Bashirzade, & Pakhomova, 2020) due to a complex interplay of geographical, topographical, and spatial factors (Alrejjal, Farid, & Ksaibati, 2022; Alshalalfah et al., 2012; Gonzalez-Calderon et al., 2022; Liu et al., 2019; Liu et al., 2022c; Long, Yoshida, Li, & Gasparatos, 2022; Lv, Li, Zhang, Liu, & Kong, 2022; Orjuela-Castro, Sanabria-Coronado, & Peralta-Lozano, 2017; Ravazzoli, Streifeneder, & Cavallaro, 2017). Extensive research has been conducted to address these challenges in mountain areas, covering various aspects, such as the design of T&L infrastructure (D'Alonzo et al., 2023; Pernkopf & Gronalt, 2021; Silvagni et al., 2017), optimization of operational activities (Jung & Kim, 2022; Kelley, Kuby, & Sierra, 2013; Liu et al., 2022a; Liu, Pan, et al., 2022b; Wankmüller et al., 2020; Yang et al., 2021), technological solutions (Karani, Balaskas, & Kaliampakos, 2022; Zilio et al., 2022), safety and accident analysis (Alrejjal & Ksaibati, 2022; Gu et al., 2022; Karani et al., 2022; Liu, Zhu, He, & Li, 2022c; Yang, Wang, Easa, & Yan, 2022), logistics impact assessments (Gonzalez-Calderon et al., 2022; Long et al., 2023; Yang, Qiu, Fang, Xu, & Zhu, 2019), and understanding travel mode preferences (Liu, Min, Shi, & He, 2024). Taken together, these studies have identified the complexities of T&L in mountain regions and suggested innovative approaches to overcoming them.

The proposed solutions underscore a pivotal shift toward leveraging advanced technologies, such as UAVs for last-mile delivery and the development of specialized vehicles tailored to off-road transportation challenges (Liu, Lei, Zhang, & Wu, 2018; Wankmüller et al., 2020; Yang et al., 2021). These advancements are complemented by a growing emphasis on sustainable transportation practices, including the use of eco-friendly modes such as electric vehicles and the implementation of green T&L strategies to mitigate the environmental impact of transportation activities in mountain regions (Gruchmann, 2019). Moreover, the potential of emerging digital technologies, such as big data and ML algorithms, to enhance T&L processes in mountain areas is increasingly being recognized (Iyer, 2021; Perego, Perotti, & Mangiaracina, 2011; Serdyukova et al., 2020). Hence, to improve business performance and competitiveness in mountain regions, it is crucial to focus on innovations that modernize mountain transport facilities, foster transport availability, and optimize transport planning (Gajdošíková, Gajdošík, & Maráková, 2018).

However, to effectively implement these innovative technologies, the unique characteristics of mountain terrains compared to flat landscapes must be carefully considered. Thus, particular attention must be paid to the technologies' scalability and adaptability, maintenance requirements, infrastructure compatibility, weather conditions, energy efficiency, sustainability, and regulatory and policy framework (Gajdošíková et al., 2018; Georgatzi, Stamboulis, & Vetsikas, 2020; Hao, Liang, et al., 2024a; Wu, Huang, Zhang, & Zhou, 2024).

In this context, a structured exploration and categorization of technological advancements can yield valuable insights and frameworks for developing and deploying tailored innovative solutions to the challenges and opportunities inherent in mountain T&L. However, there is a gap in the literature on this aspect. To bridge this gap, this study comprehensively maps and analyses technological advancements in the mountain T&L field.

2.2. Patent analysis as an approach to innovation dynamics mapping

Patents are not only legal documents; they are valuable sources of data and key indicators of innovative activities. Academically, their standardized and detailed structure facilitates objective analysis and identification of real-world trends (Lerner, Strojwas, & Tirole, 2005; Merges & Nelson, 1994; Narin, Noma, & Perry, 1987); and the details they provide on filing dates, inventors, applicants, international classifications, and geographic origins, among other data, are crucial for understanding the evolving landscape of technological advancements (Ardito, D'Adda, & Petruzzelli, 2018a; Kim & Lee, 2015; Su et al., 2023), including their scope and impact, as well as for identifying their patterns. For companies, patents provide a foundation for gaining a competitive edge in the market, for instance, by enabling informed decision-making and fostering opportunities for collaboration and investment (Agostini, Nosella, & Teshome, 2019; Ardito, Petruzzelli, Albino, & Garavelli, 2022; Hao, Wen, Zhu, Wu, & Hao, 2024b; Tao et al., 2024). Moreover, patents can enable policymakers to assess the effects of their innovation-related regulatory efforts (Feng et al., 2019; Niu et al., 2023; Wang, Wu, Liu, & Wang, 2024; Ye et al., 2024).

However, performing accurate patent analysis might be an overwhelming task, particularly when dealing with massive datasets (Ernst, 1999). To overcome this issue and to improve the efficiency and reliability of the process, researchers have employed various techniques and tools. Some studies used bibliometric and network examination methods to unveil aspects such as technological trends, alliances, and collaborative efforts (e.g., Bhatt, Lai, Drave, Lu, & Kumar, 2023; Chang, Wu, & Leu, 2010; Tang et al., 2012). Others have resorted to diffusive models to forecast future development patterns (Yoon, Park, Kim, Lee, & Lee, 2014). Additionally, scholars have adopted a value chain perspective to understand the innovation dynamics at various levels of the supply structure (e.g., Sick, Bröring, & Figgemeier, 2018). Relevant examples of these methods in the field of T&L can be found in the study of electric vehicles (Golembiewski, Vom Stein, Sick, & Wiemhöfer, 2015), smart logistics (Trappey et al., 2017), and fuel cell technologies (Chen, Chen, & Lee, 2011), among others.

More recently, the integration of big data and ML techniques has marked a significant advancement in this area (Alsubari et al., 2022; Bart, Porteous, Perona, & Welling, 2008; Ji, Yu, Fung, Pan, & Long, 2018; Kyebambe, Cheng, Huang, He, & Zhang, 2017; Niebles, Wang, & Fei-Fei, 2008; Reis, Correia, Murai, Veloso, & Benevenuto, 2019; Suominen, Toivanen, & Seppänen, 2017); advanced topic modeling approaches are becoming instrumental in enhancing our understanding of complex information frameworks (Abdelrazek, Eid, Gawish, Medhat, & Hassan, 2023; Chauhan & Shah, 2022; Ding & Chen, 2014; Kherwa & Bansal, 2017; Landauer, Foltz, & Laham, 1998). By considering latent semantic structures based on word co-occurrence, these methods can sift through large volumes of text to identify thematic details and patterns that traditional analyses may overlook. Thus, topic modeling extends human analytical capabilities by allowing the processing and interpretation of vast amounts of information more efficiently (e.g., Momeni & Rost, 2016; Park et al., 2021). It excels in uncovering hidden topics within large text datasets and providing insights into underlying aspects that simple keyword analysis or frequency counts might miss (Blei, Ng, & Jordan, 2003). In the context of patents, topic modeling enables recognition of interconnections between different technological aspects and detection of emerging areas, thereby facilitating a deeper understanding of the innovation landscape and pinpointing potential domains for future R&D efforts (Ghaffari et al., 2023; Kang, Wei, Liu, & Wang, 2021).

According to Jelodar et al. (2019), the most relevant topic modeling approaches include Latent Semantic Indexing (LSI), Latent Dirichlet Allocation, and Hierarchical Dirichlet Process (HDP). LSI groups together documents and words with similar meanings (Deerwester, Dumais, Furnas, Landauer, & Harshman, 1990). This method of textual data classification is based on Singular Value Decomposition—that is, it creates a term-document matrix (Kontostathis & Pottenger, 2006; Zelikovitz & Hirsh, 2001). However, it has a limitation in dealing with large datasets in which a word can have multiple meanings (Chauhan & Shah, 2022). To overcome this issue, Blei et al. (2003) proposed the LDA, which reveals hidden structures within texts and can be easily applied to new documents. The text collections within LDA refer to the following terms (Blei et al., 2003 – Fig. 1):

- *word*: a discrete unit of data;
- *document*: a group of N words, $w = (w_1, w_2, \ldots, w_N)$, where w_N refers to the nth word in a document; and
- *corpus*: a collection of M documents, denoted by $D = (w1, w2, \ldots, wM)$.

LDA builds on the assumption that every document can be depicted

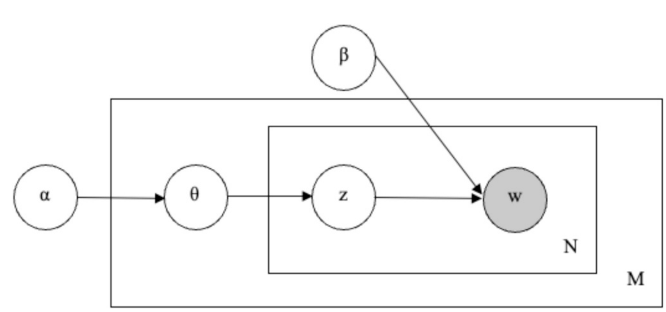

Fig. 1. Graphical model representation of LDA (Blei et al., 2003).

as a probabilistic distribution across latent topics. It further asserts that the topic distribution across all documents adheres to a shared Dirichlet prior. Additionally, each latent topic within the LDA model is conceptualized as a probabilistic distribution across words, and the distributions of words within topics are subject to a common Dirichlet prior (Jelodar et al., 2019). Therefore, applying the LDA approach to patent data results in two matrices: the matrix of probabilities of observing a word given the topic, and the matrix of topic prevalences in each of the documents. The information in these two matrices is the basis for labeling topics, visualizing them, and conducting further analysis (Ma et al., 2021).

However, LDA is characterized by the need for the user to manually identify the ideal number of topics. To overcome this need, Teh, Jordan, Beal, and Blei (2004) proposed a nonparametric Bayesian model, HDP, which automatically generates the number of topics from a group of data. Nonetheless, over time, this technique has shown some drawbacks, such as computational complexity, excessive sensitivity to tuning parameters, and frequent production of a number of topics that is either too large or too small, making it difficult for users to interpret and manage the topics effectively (Chauhan & Shah, 2022). Given these aspects, LDA remains the most used approach to identifying thematic areas that are hidden within collections of text documents (Silva, Galster, & Gilson, 2021). It has been used by Chauhan and Shah (2022), Ghaffari et al. (2023), and Kang et al. (2021), among others. In this study, we resorted to LDA to map the thematic structures underlying mountain T&L.

3. Data source and methodology

The study's methodology includes data collection, initial filtering, pre-processing, and topic modeling (see Fig. 2). As stated, we utilized patent documents as our primary data source due to their detailed information on innovations in specific technological domains (Hao et al., 2023; Singh, Chakraborty, & Vincent, 2016); and we conducted LDA to find the latent structure of technological areas under mountain T&L.

3.1. Data collection and initial filtering

Patent data were collected from the Derwent Innovation Index database. To extract relevant patent documents for analysis, we combined keywords with International Patent Classification (IPC) codes (Kwon, Jun, Lee, Choi, & Lee, 2022). Integrating keyword searches with IPC codes refines search outcomes within a particular technological domain, ensuring the retrieval of more pertinent patents (Shalaby & Zadrozny, 2019). We searched for relevant patent documents using the keyword "mountain*" combined with IPC classification codes for transportation (i.e., B60–B68). The keyword was searched within the patents' titles, abstracts, and claims to ensure that no relevant documents would be missed during the analysis (Xie & Miyazaki, 2013). The search yielded 19,472 patent applications. Since, according to Ghaffari et al. (2023), the abstracts of patent documents contain the essential technical information and technology used in the invention, the textual content of the patent abstracts was considered for the topic modeling analysis, and patents that lacked abstracts were excluded. Furthermore, considering the growing focus on promoting sustainable development in mountain regions after UNCED in 1992 (Carroll-Foster & Li Pun, 1993; Price & Kim, 1999), only patent applications between January 1992 and September 2023 (when the search was conducted) were selected for our initial database, which resulted in 16,681 patent applications. Their abstracts were categorized based on their IPC classifications, and sample abstracts were reviewed for each category to check their relevance. This allowed us to refine our sample and exclude certain IPC classifications unrelated to mountain transport vectors. The excluded classes were B63, which pertains to ships or other waterborne vessels and their related equipment; B65, which involves conveying, packing, storing, and handling thin or filamentary materials; B67, which is about opening or closing bottles, jars, or similar containers, as well as liquid handling; and B68, which is related to saddlery and upholstery. After the irrelevant patent documents were filtered out, the final database consisted of 7084 patents.

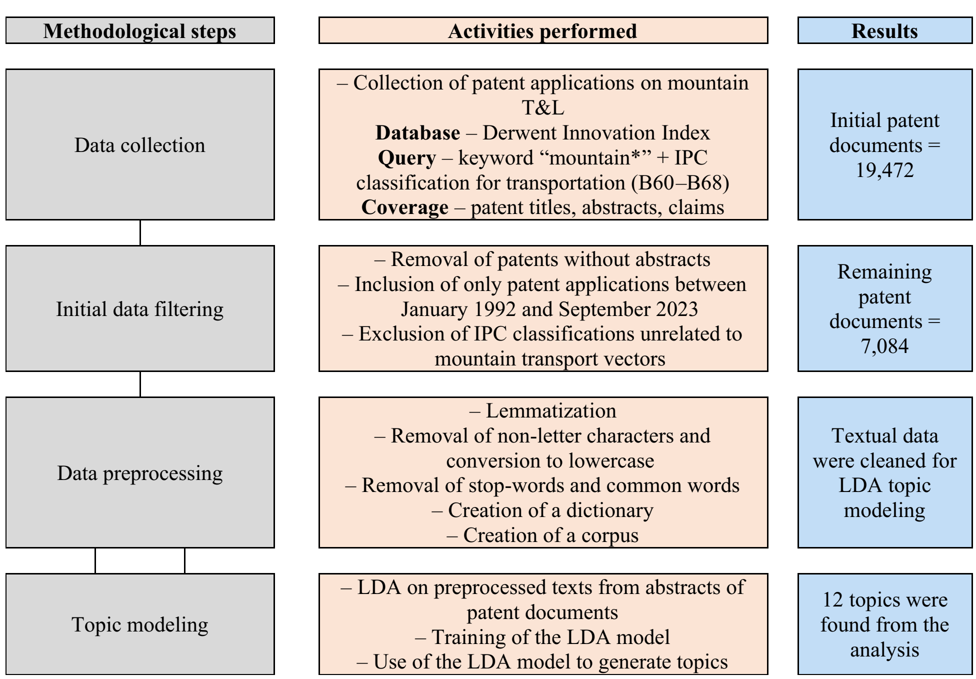

Fig. 2. Summary of the methodological procedures.

3.2. Data preprocessing and topic modeling

Text mining is valuable for detecting topics, clustering documents, and summarizing unstructured data (Hashimi, Hafez, & Mathkour, 2015). In this study, we used topic modeling to accurately categorize technological areas related to mountain T&L based on patent documents. The model used for topic modeling was LDA, which helped to ensure reliable and valid thematic classification (Blei et al., 2003). The main challenge of performing LDA on textual data is appropriate processing of the data to ensure high-quality results by eliminating noisy texts (Maier et al., 2021). The process involves tokenization, elimination of high-frequency stop-words, and removal of custom stop-words that appear frequently in our patents but without a specific meaning (e.g., *claims*, *mountain*, *provided*, *end*, *first*, *one*, *two*, *second*, *c*, *solved*, *copyright*, *also*, *least*, *side*, *like*, *fig*, *use*, *thereby*, *means*, *problem*, *comprising*, *side*, *part*, *portion*, *solved*, *said*, and *solution*). In addition, all characters are converted to lowercase, and numbers and special characters, such as punctuation marks, are removed. Lemmatization is also applied to determine the precise part of speech of the word and to convey its intended meaning in a sentence (Savin, Ott, & Konop, 2022).

The relevant topics were extracted from the patent abstracts without relying on preexisting knowledge or inputs to avoid bias (Maier et al., 2021). To this end, we used the Gensim software package in Python (Řehůřek & Sojka, 2010). Furthermore, we preprocessed the patent abstracts using Python libraries, including Pandas, Openpyxl, Nltk, and Spacy.

One of the main challenges in topic modeling is that the topics generated may be inconsistent or difficult to interpret (Goedecke, 2017; Maier et al., 2021). Additionally, the optimal number of topics for a given corpus is left up to the user to decide on. To address these challenges, we changed the number of topics from 2 to 15 and assessed their resulting coherence scores (Ghaffari et al., 2023). The number of topics that provided the highest coherence values is twelve, with a score of 0.544 (see Fig. 3), which aligns with previous studies (e.g., Ghaffari et al., 2023). This rigorous approach allowed us to capture the nuanced topic structures inherent in the patent documents, in order to come up with an in-depth assessment of the technological domains in mountain T&L.

4. Results and discussion

4.1. Temporal distribution of patent applications

As shown in Fig. 4, the analysis indicated a clear upward trend in the number of patent applications related to mountain T&L, reaching a record high of 1139 in 2020, with growth rates of 0.35 % in 1999 to 60.65 % in 1997.

The surge in patent applications can be attributed to three main factors. The first is the rising need for transportation in mountain regions. Following the 1992 EU conference on mountain development, there has been a growing demand from mountaineers and tourists for more diverse, high-quality, and convenient travel options (Carroll-Foster & Li Pun, 1993). This has boosted innovation in T&L technology and services. Second, organizations are increasingly recognizing the pivotal role of patents in enhancing their market value and are relying heavily on patents as crucial elements of their business strategies (Agostini et al., 2019). Third, the enhancement of digital technologies brings remarkable solutions to T&L challenges in mountain areas, such as intelligent vehicle control systems, autonomous vehicles, and electric vehicles, resulting in heightened R&D efforts (Barreto, Amaral, & Pereira, 2017).

As a side note, the decrease in the number of patent applications in 2023 is because patent applications are published 18 months after the earliest priority date (Ernst, 1999). However, to ensure that we would not miss out on the latest advancements, we conducted our search up to 2023 and included all the available patent applications in the database.

4.2. Distribution of patent applications by country

The geographical distribution of patent applications for mountain T&L from 1992 to 2023 (Fig. 5) shows China in the leading position (with 53 % of the total), followed by Japan at 14 % and South Korea at 8 %. The United States, Germany, and other countries (e.g., Canada, Austria, Russia, and France) contribute to the remaining percentage. These results align with the current trend in patent applications. According to the 2022 report of the European Patent Office (EPO, 2022), there has been a decline in the number of patent applications from US and European companies, while there has been consistent growth in the number of patent applications from companies in China and South Korea. More specifically, in 2022, China filed more patent and utility model applications than the US and Japan combined (WIPO, 2023).

Additionally, we investigated the dominance of different countries in patent applications over time. Table 1 indicates the number of applications filed, the corresponding percentages for each period, and the cumulative percentages. In the initial period (1992–2001), Japan emerged as the predominant contributor, accounting for 33.37 % of the patents filed, followed by China at 21.92 %. However, a notable shift occurred in the subsequent periods, with China progressively asserting dominance and reaching an impressive 67.88 % of total patents filed by 2012–2023. The US, after years of relative stability in patent applications, is experiencing a decrease, from 9.34 % in the first period to 5.62

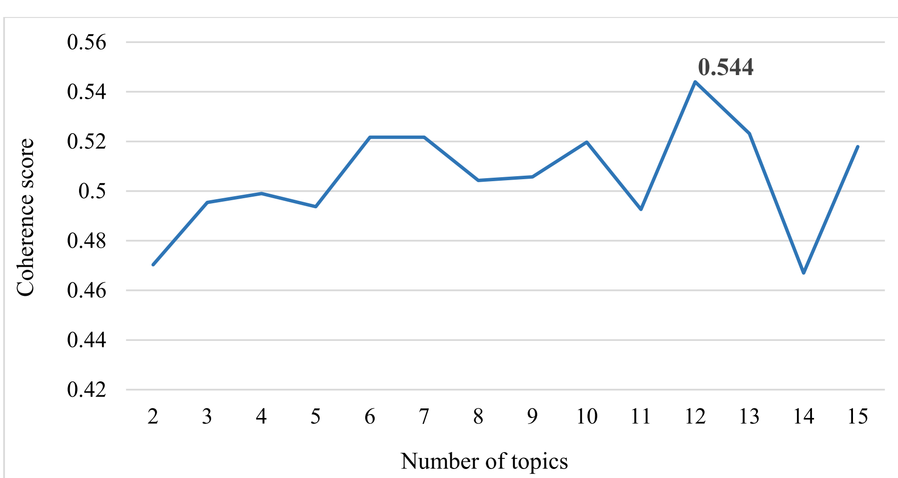

Fig. 3. Topics and their corresponding coherence scores.

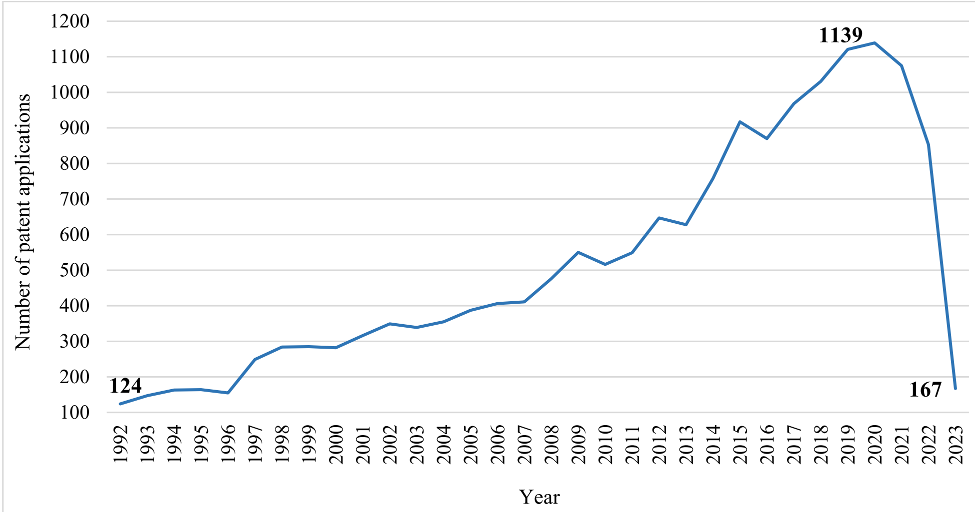

Fig. 4. Annual number of patent applications related to mountain T&L (1992–2023)

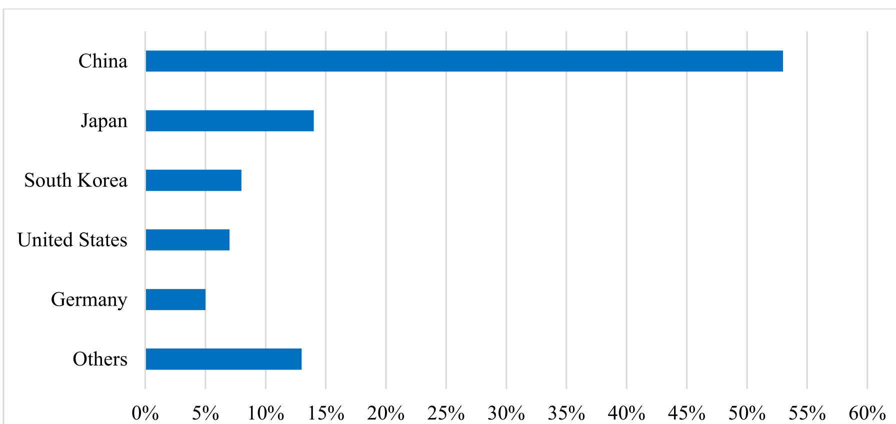

Fig. 5. Share of patent applications related to mountain T&L by country (1992–2023).

Table 1
Temporal changes in dominance in filing of mountain T&L patents by country.

1992–2001				2002–2011				2012–2023			
Country	# of applications filed	%	Cum. %	Country	# of applications filed	%	Cum. %	Country	# of applications filed	%	Cum. %
JP	268	33.37	33.37	CN	521	29.64	29.64	CN	3070	67.88	67.88
CN	176	21.92	55.29	JP	349	19.85	49.49	JP	353	7.80	75.68
DE	77	9.59	64.88	KR	178	10.13	59.61	KR	347	7.67	83.35
US	75	9.34	74.22	US	173	9.84	69.45	US	254	5.62	88.97
EP	71	8.84	83.06	EP	151	8.59	78.04	DE	150	3.32	92.28
FR	28	3.49	86.55	DE	133	7.57	85.61	EP	128	2.83	95.11
CA	26	3.24	89.79	CA	49	2.79	88.40	TW	29	0.64	95.76
KR	14	1.74	91.53	TW	40	2.28	90.67	FR	24	0.53	96.29

% in the last. Interestingly, Germany and South Korea exhibited noteworthy variations in their positions, reflecting dynamic changes in global innovation patterns.

4.3. Top patent applicants

Moving to the analysis of the organizations that are investing most heavily in the development of mountain T&L technologies, Table 2 again shows Asian dominance. Interestingly, Japan's strategy mainly builds on private companies such as Toppan Printing Co. Ltd., Rengo Co. Ltd., Dainippon Printing Co. Ltd., Honda Motor Co. Ltd., and Yoshino Kogyosho Co. Ltd., while in China, the innovation landscape is driven by universities such as South China Agricultural University and Northwest A&F University. These trends not only reflect the technological capabilities of these organizations but also the different strategic approaches to innovation between Japan, which leans heavily on major corporate players, and China, which mainly builds on public funding (Băzăvan, 2019; Yoshikawa, Tsui-Auch, & McGuire, 2007).

On the other hand, there is only one European company (i.e., Innova Patent GmbH) and no American institution in the top 20. The absence of US organizations among the top patent applicants in this field is particularly striking, considering the country's historical strength in

Table 2
List of top applicants for mountain T&L patents.

Applicant	Type	Country	# of applications filed	Average family size
Toppan Printing Co. Ltd.	Company	Japan	196	2.24
Innova Patent GmbH	Company	Austria	184	18.58
South China Agricultural University	University	China	105	1.50
Rengo Co. Ltd.	Company	Japan	87	2.13
Dainippon Printing Co. Ltd.	Company	Japan	87	1.81
Northwest A&F University	University	China	68	1.00
Honda Motor Co. Ltd.	Company	Japan	57	4.80
Yoshino Kogyosho Co. Ltd.	Company	Japan	48	11.03
Kao Corp.	Company	Japan	46	9.32
Toyota Motor Corp.	Company	Japan	39	6.57
Toyo Seikan Kaisha Ltd.	Company	Japan	39	5.12
Nissan Motor	Company	Japan	39	9.32
Hyundai Motor Co. Ltd.	Company	South Korea	38	3.29
Jujo Paper Co. Ltd.	Company	Japan	35	6.95
Korea Railroad Research Institute	Government	South Korea	34	1.74
SIG Technology AG	Company	New Zealand	32	14.58
Bridgestone Corp.	Company	Japan	32	8.59
Nippon Steel Corp.	Company	Japan	29	2.22
Mazda Motor	Company	Japan	29	6.75
Mitsubishi Electric Corp.	Company	Japan	28	4.42

technological innovation (Fink, Khan, & Zhou, 2016). Similarly, Europe's modest representation suggests a potential area for growth and investment, highlighting the importance of policies aimed at fostering R&D efforts in this domain (Del Bo & Florio, 2012).

To conclude, the *average family size* metric provides information on the patenting strategies employed by various applicants. A larger family size, as seen with Innova Patent GmbH (18.58) and SIG Technology AG (14.58), suggests an aggressive approach to IP protection on an international scale. These applicants tend to file related patents across multiple jurisdictions, thereby significantly broadening the scope and protection of their innovations (Neuhäusler & Frietsch, 2013). Conversely, entities such as Chinese universities, with a smaller family size, for instance, South China Agricultural University (1.5) and Northwest A&F University (1), appear to concentrate their patenting efforts more locally. This may reflect a strategy focused on protecting innovations within specific areas or a preference for a more selective patent-filing approach (Gilardoni, 2007).

4.4. Patent applications distribution by IPC class

The dataset's IPC codes highlight that most (approximately 43 %) of the patent applications are related to *vehicles in general* (B60) (Fig. 6). The second most common category is *land vehicles for traveling other than on rail* (B62), which consists of 36 % of the applications. *Railway transport* (B61) accounts for 11 %, and *aircraft and aviation*, for less than 10 % (B64).

4.5. Technology areas and their future relevance

The content analysis was performed after the 7084 patent applications were distributed to one of the 12 technological areas (i.e., topics) identified based on the LDA topic modeling. Each topic was named and described by considering the corresponding list of the most relevant keywords (Table 3 and Fig. 7) and by reviewing the assigned patents (see Table 3 for some examples), which resulted in the following topics: *mechanical power transmission*, *tire design*, *cableway systems*, *seat and suspension control systems*, *steering systems*, *mountain bike parts and accessories*, *aerial vehicles*, *intelligent vehicle control systems*, *vehicle body structure*, *electrical systems and electric vehicles*, *bicycle frame design*, and *safety devices*.

To assess the future relevance and developmental stage of each technological domain, we employed two key metrics: the count of citing patents and the citations-to-total-patent-applications ratio (Squicciarini, Dernis, & Criscuolo, 2013). The results are summarized in Table 4 and described in the succeeding text.

The first technological area focuses on *mechanical power transmission*, which involves innovative approaches to transmit power efficiently. Patents in this category highlight developments such as belt-driven mechanisms, self-propelled tillers with light caterpillar bands, multi-functional four-drive machines, and balance shaft mountains in skidding trailers. These innovations are crucial for vehicles used in mountainous terrains; they can enhance efficiency and reliability in environments where several challenges could disrupt daily work activities and operations, and where the loads differ from those in flat areas (Maclaurin,

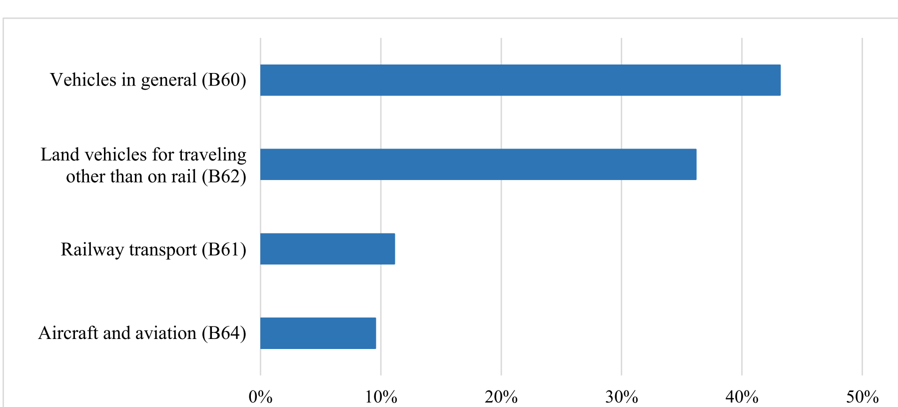

Fig. 6. Distribution of patent applications related to mountain T&L by IPC class

Table 3
Technology categories and exemplary patent documents.

Topics	Keywords/terms	Exemplary patents in the category Title
Topic 1: Mechanical power transmission	wheel, driving, shaft, gear, device, transmission, mechanism, walking, vehicle, connected	- A moving chassis driven by belt - Light caterpillar band self-propelled tiller - A multifunctional four-drive agricultural machine - Belt drive reversing mechanism - A simple skidding trailer with balance shaft mountain
Topic 2: Tire design	brake, tire, layer, tyre, pattern, tread, surface, rubber, block, pressure	- A mountain bike tyre tread pattern structure - A block pattern tire - Tread pattern for pneumatic winter tyres - Mountain cross-country tyre - Pneumatic radial tire
Topic 3: Cableway systems	rail, unit, guide, cable, station, track, along, device, lever, position	- Installation for moving individuals from a mountain station into a valley station - Cable railway system - Aerial cableway system operating method - At least one bearing transport cable between valley and peak station mobile aerial cableway system - Cableway system having transport devices that can be coupled to a conveying cable with increased conveying capacity
Topic 4: Seat and suspension control systems	tube, rear, seat, frame, member, front, suspension, spring, position, shock	- System and method for adjusting spring rate of a coil spring in a bike suspension - Rear suspension system for two-wheeled vehicles, particularly bicycles - A shock mitigation seat and shock monitoring system - The seat for vehicles - Emergency lock mechanism for vehicular seat
Topic 5: Steering systems	front, steering, pedal, mechanism, cylinder, rear, frame, body, adjusting, hydraulic	- The wheel connection structure - An ultra-low half-hanging vehicle shaft steering device - Hill hillside tractor four-wheel steering system and steering control method - Four-wheel steering system and steering control method of hilly mountain tractor - Rotated component around the transverse connecting auxiliary power for vehicle electric steering device
Topic 6: Mountain bike parts and accessories	connecting, connected, pipe, model, plate, utility, inner, outer, fixing, hole	- Adjustable cushion for mountain bike - A telescopic handle of mountain bike - A mountain bike with mud baffle - A light, high-strength of mountain bike front fork - Frame structure of mountain bike
Topic 7: Aerial vehicles	unmanned, aerial, device, vehicle, invention, system, machine, wing, aircraft, platform	- Unmanned aerial vehicle of farm insecticide - The monitoring forest fire and the suppression system using the drone. - Drone and dispersed identification system including the drone. - A fire-extinguishing device for forest fire extinguishing - Medium-sized cargo unmanned helicopter system
Topic 8: Intelligent vehicle control systems	vehicle, control, device, module, system, information, signal, data, driving, method	- Intelligent driving control method and device, vehicle, electronic device, storage medium - Method and apparatus for estimating a vehicle maneuvering state and method and apparatus for controlling a vehicle running characteristic - Robotic driving system - Vehicle mountain H_2S monitoring system - Disaster risk avoiding method and system, device and vehicle
Topic 9: Vehicle body structure	frame, plate, vehicle, body, supporting, connected, bottom, main, bracket, beam	- A detachable mudguard device - Vehicle front structure - Rear vehicle body structure - Back top beam structure of automobile - Vehicle-mounted adjustable climbing ladder
Topic 10: Electrical systems and electric vehicles	power, electric, motor, battery, energy, vehicle, control, engine, system, storage	- Control of drive components in a hybrid electric vehicle to the mountain holding - Electric vehicle having dual source power - Cooling system for electric vehicle and hybrid electric vehicle - Mountain intelligent electric vehicle with continuous climbing and double anti-fake - System and method for controlling the ascent of an electric vehicle driving
Topic 11: Bicycle frame design	bicycle, element, invention, bike, handlebar, saddle, relates, handle, support, present	- Bicycle handle-bar grip - An improved bicycle saddle - Flexy knock down bike - Ergo grip mountain bar - Side-by-side flexible twin bicycles
Topic 12: Safety devices	direction, formed, surface, vehicle, body, member, section, shape, outer, inner	- Buffer attached to shock absorber in vehicle wheel - The folding method of an airbag and an airbag - The crash box for the vehicles. - The center-pillar structure of 2 door vehicles - Airbag for collision safety system of motor vehicle

2018). For instance, in mountain forestry, robust power transmission systems allow navigation of steep and uneven slopes while carrying heavy freights of timber, reducing the risk of mechanical failure and ensuring continuous movement. In mining operations, they enable maintenance of high torque and stability while moving minerals across rugged terrain, preventing breakdowns. Remote mountain construction

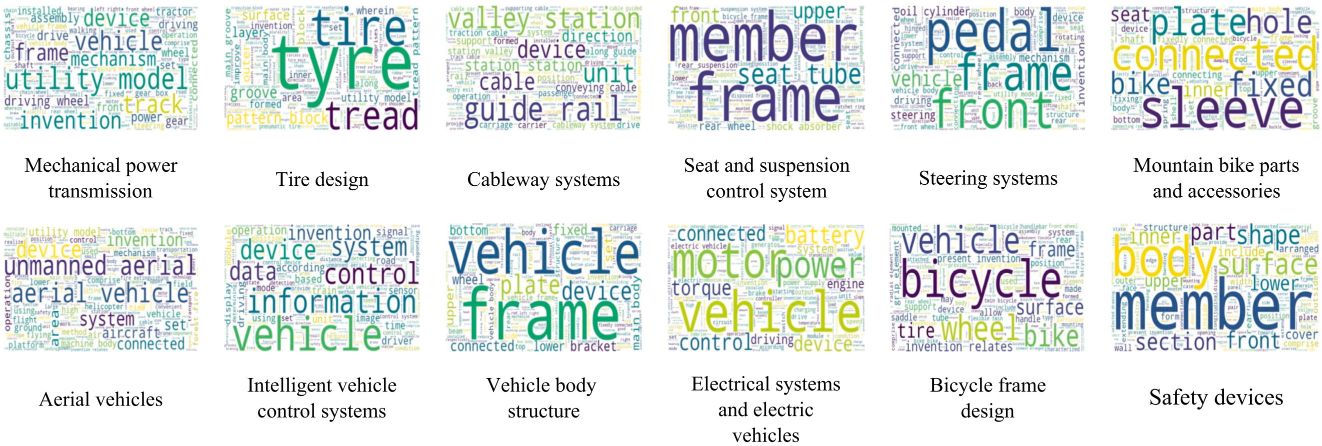

Fig. 7. Word cloud for topics under mountain T&L.

Table 4
Topic metrics.

Technological areas in transportation	# of patent applications	Share of patents (%)	Count of citing patents	Ratio of citations to total # of patents applications
Mechanical power transmission	1143	16.13	2037	1.78
Tire design	170	2.40	467	2.75
Cableway systems	328	4.63	1029	3.14
Seat and suspension control systems	400	5.6	2555	6.38
Steering systems	271	3.83	895	3.30
Mountain bike parts and accessories	590	8.33	350	0.59
Aerial vehicles	632	8.92	1449	2.29
Intelligent vehicle control systems	896	12.65	4642	5.18
Vehicle body structure	768	10.84	643	0.84
Electrical systems and electric vehicles	322	4.55	1218	3.78
Bicycle frame design	378	5.34	1708	4.52
Safety devices	1186	16.74	4366	3.68

sites benefit from these systems as they allow heavy machinery to function smoothly and haul construction materials in harsh conditions, minimizing downtime and costly repairs. Furthermore, these advancements enable the development of compact and lightweight machinery that is easier to transport and maneuver in difficult mountainous terrain. They also reduce fuel consumption and emissions by optimizing mechanical efficiency, which is vital in remote areas with limited resources. Overall, these innovations make vehicles more durable, efficient, and capable of handling the unique challenges of rugged landscapes. Our analysis indicates that this area ranks second among 12 categories, holding 16.13 % of total patent shares. However, it has a lower citations-to-total-patent-applications ratio (1.78), suggesting that it is in a mature phase and may soon approach saturation. This is probably driven by the need to automate the mechanical power transmission design process using AI techniques based on existing knowledge bases (Saric, Muminovic, Colic, & Rahimic, 2017).

The second area of technology pertains to *tire design*, including aspects such as block and tread tire patterns, pneumatic winter tires, mountain cross-country tires, and pneumatic radial tires. These tire designs are essential for vehicles operating in mountainous regions, including all-terrain and emergency response ones (Bosch, Hamersma, & Els, 2016; Dressel & Sadauckas, 2020). The primary objective of the tire design patents is to provide the necessary traction and stability on rugged and slippery surfaces (e.g., snow-covered roads, muddy trails, and mountain passes), while maintaining low resistance, ensuring comfort, reducing the risk of punctures, and achieving excellent grip. For instance, emergency response teams rely on these specialized tires to reach remote and inaccessible areas quickly during natural disasters or medical emergencies. Additionally, the tourism industry benefits from safer transportation for activities such as off-road excursions. Enhanced tire designs also play a critical role in heavy machinery used for mountainous construction and logging, ensuring that they maintain traction and operational efficiency while moving materials and navigating uneven terrains. Similarly, specialized tire designs improve the reliability and efficiency of the transport of goods through mountainous regions, ensuring timely deliveries and reducing the risk of accidents. Furthermore, these innovations help mitigate soil erosion and damage to sensitive mountain ecosystems by providing better grip and control, thereby reducing the environmental impact of vehicles. While scholars (e.g., Ghaffari et al., 2023) have emphasized the potential of airless and intelligent tires in the tire industry's future, our study presents a different perspective. We found that the design of tires for mountain terrains represents a minimal patent applications share of only 2.40 %, with a citations-to-total-patent-applications ratio of 2.75. This finding underscores the relatively limited relevance of tires specifically developed for mountainous areas compared to those used on other terrains.

The third technological area focuses on *cableway systems*, which improve motor drive mechanisms and operational techniques and encompass aspects such as transport cable bearings, carrier roller guides, and rail cables running along the path. Cableway systems offer safe, reliable, efficient, and high-performance conveyance for people and goods from mountain to valley stations, where traditional roadways are impractical, thereby enhancing accessibility and economic development in isolated regions (Ferrarese, Loner, & Pulina, 2021; Tiessler, Ricci, & Bogenberger, 2020). Specifically, in remote villages, these systems facilitate the movement of goods and people, ensuring that essential services and economic activities can thrive despite challenging terrain. For ski resorts, they offer a seamless experience by efficiently transporting skiers and snowboarders to the tops of slopes. They also play a vital role in disaster management, providing a swift and efficient means of evacuating people from dangerous areas and delivering supplies to regions cut off by landslides or heavy snowfall. Our analysis shows that cable systems have impacted innovation in mountain T&L with 4.63 % patent applications share. This category boasts a remarkable 1029 citations of patent applications and a citations-to-total-patent-applications ratio of 3.14, making it a notable driver of progress in this field.

The fourth technological area is related to *seat and suspension control systems*. This category includes innovative methods of adjusting suspension and shock absorbers in vehicles and bikes, as well as of improving the functionality and ergonomics of vehicular seating. These innovations are particularly important for vehicles used in off-road and mountainous terrains, including specialized transport vehicles. They enhance stability and thus, improve performance in extreme conditions and on uneven and rough surfaces, such as rocky paths and steep inclines. In commercial off-road vehicles, improved suspension and seating enhance driver comfort and safety during long hours of operation in rugged environments, leading to increased productivity and reduced risk of injury. Additionally, these systems are crucial for public transportation in mountainous regions, as they improve passenger experience by minimizing the impact of the terrain. This area has emerged as a frontrunner, with a relevant 5.65 % patent applications share; and its significant citations-to-total-patent-applications ratio (6.38) indicates its pivotal role in shaping future mountain T&L advancements.

The fifth area concerns *steering systems*, which emphasizes innovations in the design of components responsible for transmitting steering wheel movement to control the vehicle's direction. The patents in this category focus on improving steering mechanisms for enhanced performance and adaptability, particularly, for navigating tight turns and steep inclines, and for improving maneuverability and safety. Key components, such as axial rods, tie rod ends, drag links, and wheel-end bearings, have been developed, with particular attention to their application in vehicles operating in mountainous and off-road conditions, including tractors, cross-country motorcycles, and construction vehicles. For instance, in agricultural applications, sophisticated steering systems enable precise control of tractors and harvesters on uneven terrain, enhancing efficiency and crop yield while facilitating the transport of produce from fields to storage or processing facilities. In construction projects on steep slopes or rugged terrains, advanced steering systems help machinery maintain stability and precision, reducing the risk of accidents and improving operational efficiency, as well as ensuring the smooth movement of construction materials and equipment to and from sites. They also enable vehicles to navigate challenging routes safely and effectively, thereby supporting the reliable movement of goods and materials and ensuring timely deliveries. For mountain rescue operations, modern steering systems are crucial for quickly and safely reaching remote locations, ensuring assistance during emergencies. Additionally, for recreational vehicles such as ATVs and off-road buggies, improved steering systems provide a better and safer experience for users exploring challenging trails and mountainous regions. To conclude, these innovations benefit snowplows and other winter maintenance vehicles by providing precise control and stability on icy and snow-covered roads. Our analysis shows that steering systems play a significant role in driving innovation and, thus, in shaping the future of mountain T&L, with their 3.83 % patent applications share and commendable citations-to-total-patent-applications ratio of 3.30.

The sixth technological area focuses on *mountain bike parts and accessories*, which are designed to enhance rider experience and performance across mountain terrains. These innovations encompass a range of components, such as a damping front fork to minimize vibrations, a telescopic handle for adjustable positioning, a bumper for impact protection, and a low heat-generating polyurethane roller for smoother rides, which are crucial for ensuring mountain bike durability and performance in challenging conditions. For instance, advanced components, such as adjustable handles and impact-resistant bumpers, enhance safety and comfort for riders tackling steep descents. Enhanced bike parts contribute to a safer and more enjoyable riding experience, promoting the use of mountain bikes as a primary means of transportation in mountainous regions (Jahre et al., 2019; Lovejoy & Handy, 2012). These parts are also essential for adventure tourism, enabling bike rental services to offer reliable and high-performance equipment to tourists that not only enhances the tourist experience but also supports local economies in mountainous regions by boosting the popularity of mountain biking as a sport and recreational activity (Buning, Cole, & Lamont, 2019; Buning & Lamont, 2021). Mountain bike parts and accessories hold a remarkable 8.33 % patent applications share and play a crucial role in shaping the mountain T&L landscape due to their unique focus. However, their lower citations-to-total-patent-applications ratio (0.59) indicates that they receive less attention for further innovation and growth and are in the saturation phase.

The seventh technological area encompasses *aerial vehicles*, which have various applications, including agricultural practices, environmental monitoring, firefighting, cargo transport, and emergency response. For instance, drones equipped with sensors can survey vast areas that conventional means of transport cannot reach, providing valuable data for environmental conservation, disaster management, and wildlife protection by enabling the tracking and monitoring of endangered species in remote habitats. In agriculture, UAVs assist in precision farming by applying pesticides and fertilizers with high accuracy to crops on steep slopes, thereby ensuring efficient use of resources and reducing the need for ground transportation. In firefighting, drones quickly assess wildfire spread and direct firefighting efforts, significantly improving response times and allowing access to difficult-to-reach locations that are challenging with traditional methods. For search and rescue operations, aerial vehicles help locate missing persons in isolated areas by providing real-time information to ground teams. Additionally, drones are used in infrastructure inspection, such as in monitoring the condition of mountain roads, bridges, and pipelines, ensuring their timely maintenance and preventing accidents. Finally, medium-sized cargo unmanned helicopter systems highlight developments in UAVs for cargo transport, facilitating efficient deliveries in rugged and difficult terrains. This category accounts for 8.92 % of patent applications share and 1449 patent citations, with a citations-to-total-patent-applications ratio of 2.29. Thus, aerial vehicles are poised to impact the future of mountain T&L by facilitating efficient and innovative solutions across various applications.

The eighth area concerns *intelligent vehicle control systems*, which have revolutionized the driving experience in mountain areas. These systems are vital for enhancing vehicle safety and efficiency in mountainous regions where driving conditions can be unpredictable and hazardous (Iyer, 2021; Omeiza, Webb, Jirotka, & Kunze, 2021). For example, autonomous driving technologies and robotic driving systems help vehicles navigate narrow, winding mountain roads with precision, detecting obstacles and, thus, reducing the risk of accidents and ensuring safer travel. Moreover, intelligent driving control systems present crucial information tailored to the driver's preferences and driving conditions, fostering situational awareness. These systems also assist in optimizing fuel efficiency by adapting driving patterns to the terrain, which is crucial for long journeys in remote areas with limited refueling options. Similarly, some inventions in this area aim to monitor the environment, such as the H2S monitoring system, which automatically assesses and broadcasts real-time alerts based on H2S levels to minimize vehicle emissions in sensitive mountain ecosystems. Intelligent technologies also support freight transport in mountainous regions by optimizing route planning and vehicle performance, ensuring timely and safe delivery of goods. For example, smart logistics vehicles can automatically select the safest and most efficient routes, even in adverse weather conditions. In the sphere of public transportation, intelligent systems improve the reliability and safety of bus and shuttle services in mountainous areas by providing real-time assistance with speed and braking adjustments based on road conditions, potentially making them more appealing to residents and tourists. Intelligent vehicle control systems have emerged as a critical factor in the advancement of mountain T&L technology, accounting for a noteworthy 12.65 % patent applications share in this field. Moreover, with an impressive 5.18 citations-to-total-patent-applications ratio, this category plays a significant role in shaping the future of the T&L industry.

The ninth technological area focuses on *vehicle body structure* innovations aimed at improving impact resistance, aerodynamics, structural integrity, load-bearing capabilities, and overall vehicle durability. These innovations ensure that vehicles can withstand harsh environments, such as landslides, falling rocks, and heavy snowfall. Reinforced body structures also improve the vehicle's ability to carry heavy loads, which is crucial for transporting goods, people, and equipment to remote mountain areas. In emergency response situations, vehicles with advanced body structures can navigate debris-strewn paths and provide reliable transport for rescue operations. They also enhance the off-road capabilities of recreational vehicles, allowing adventurers to move through rugged terrains with confidence. Furthermore, these innovations contribute to the longevity of vehicles, reducing maintenance costs and downtime, with potential benefits for fleet operators in remote and harsh environments. However, despite this area's significant patent applications share (10.84 %), it has a lower citations-to-total-patent-applications ratio (0.84). This indicates that innovations in vehicle body structures are not actively referenced, suggesting a degree of saturation and limited future interest compared to other technological fields.

The tenth technological area is related to *electrical systems and electric vehicles*, highlighting the evolution of automotive electrical systems and the growing field of electric vehicles. These innovations are pivotal for promoting sustainable and resilient transportation in mountainous regions, where traditional fuel supply can be challenging. A significant advantage of electric vehicles in these areas is their ability to leverage local renewable energy sources, such as hydroelectric power, which are typically abundant in mountains (Enel, 2023; Soha et al., 2017). In terms of application scenarios, electric vehicles equipped with advanced electrical systems can handle steep inclines and uneven terrains with improved torque and power management, ensuring efficient movement of goods and people in these demanding conditions. In tourism, electric vehicles provide a silent and pollution-free option for guided tours, preserving the natural beauty and tranquility of mountainous areas. For residents of remote mountain villages, electric vehicles offer a reliable and low-maintenance transportation and commuting solution, improving access to essential services and reducing dependency on fuel deliveries. Electrical systems and electric vehicles have a notable impact on mountain T&L, representing 4.55 % of patent applications share. Moreover, with a 3.78 citations-to-total-patent-applications ratio, this category plays a significant role in advancing sustainable mobility solutions for challenging terrains.

The eleventh technological area focuses on *bicycle frame design*, which includes advancements such as ergonomic handlebar grips for improved rider control, and ergo grip mountain bars for better user comfort and efficiency. Additionally, the concept of side-by-side flexible twin bicycles showcases the diversity of design possibilities in this field. These innovations are vital for improving the durability and stability of bicycles on rugged trails, ensuring that they can withstand the stresses of extreme terrains and be used habitually as an eco-friendly mode of transportation. Patents in this category also support the development of specialized bicycles, providing lightweight, reliable, and high-performance equipment suited to the unique challenges of mountainous areas and that can also reduce the physical strain on the rider. Advanced frame designs enable individuals to use bicycles for routine transportation needs, such as commuting to work, running errands, and accessing local amenities (Chen & Lee, 2017; Heinen, Van Wee, & Maat, 2010). This promotes sustainability, reduces reliance on motor vehicles, and benefits local economies by encouraging cycling as a viable transportation option (Si, Shi, Wu, Chen, & Zhao, 2019; Sun, Feng, Kemperman, & Spahn, 2020). Additionally, specific designs enable individuals with disabilities to move around mountainous areas with specially adapted bikes that meet their needs. For example, frames with adjustable features can accommodate different physical requirements, promoting inclusivity and mobility in mountainous regions. Furthermore, these innovations bolster the growing trend of using e-bikes, integrating electric assistive technologies with robust and lightweight frame designs for enhanced performance on challenging terrains. *E*-bikes with advanced frames are particularly useful for commuting in hilly urban areas and for long-distance touring, providing an eco-friendly and efficient mode of transportation. Bicycle frame design holds a share of 5.34 %; and with a high citations-to-total-patent-applications ratio of 4.52, this category evidently plays a significant role in driving innovation in mountain T&L and, thus, in shaping the future of this field.

The last technological area focuses on *safety devices*, which are crucial for enhancing vehicle safety in challenging mountain environments, where steep inclines, sharp turns, and unstable surfaces increase accident risks. These innovations highlight the interdisciplinary nature of safety, encompassing aspects of structural design, materials used, and advanced technologies to mitigate risks and enhance the overall safety profile of vehicles. For instance, in vehicles that transport goods or passengers on rugged, uneven paths, buffer attachments to shock absorbers decrease impact forces during sudden drops or accidents on mountain roads, enhancing stability and significantly reducing the risk of rollovers. Similarly, crash boxes dissipate impact energy during collisions, minimizing damage and maintaining operational integrity. This ensures that vehicles, such as construction machinery and transportation trucks, can continue operating even in the event of minor impacts with rocks, trees, or similar obstacles, thereby preventing delays. Additionally, reinforced side-impact beams provide extra protection during side collisions, which are common on narrow mountain roads, thus maintaining the structural integrity of the vehicle's passenger compartment and ensuring occupant safety. Taken together, these innovations play a pivotal role in reducing accidents, minimizing injuries, and ensuring that vehicles operate efficiently in challenging mountain environments. Our analysis indicates that this category has a significant patent applications share of 16.74 % and a citations-to-total-patent-applications ratio of 3.68, underscoring its critical importance and ongoing development in the mountain T&L field.

Figure 8 presents an intuitive view of the 12 distinct technological areas and the related patenting activities from 1992 to 2023, thus helping in the identification of R&D trends (Nagaoka, Motohashi, & Goto, 2010; Ponta, Puliga, & Manzini, 2021). Over the years, certain technological areas have emerged as hot domains of interest for innovation, with a surge in patent filings. These include intelligent vehicle control systems, safety devices, aerial vehicles, electrical systems and electric vehicles, and steering systems. On the other hand, the number of patent applications for mechanical power transmission, vehicle body structures, and mountain bike parts and accessories hardly changed from 2012 to 2023. This outcome further reinforces our previous findings from our citation analysis, suggesting that these areas have reached their technological saturation point.

4.6. Country-specific trends

We also analyzed the technological advancements in the top five countries in terms of patent applications (Tables A1–A5 in the Online Appendix). This approach allowed us to identify the most relevant technological areas for each country, providing a clearer picture of the country-specific dynamics and highlighting potential opportunities for future development (Grimaldi & Cricelli, 2020; Kalıp, Erzurumlu, & Gün, 2022). In particular, in China, the focus is on mechanical power transmission (27.85 % patent applications share), with a limited citations-to-total-patent-applications ratio (1.72), suggesting that this field is mature and mostly driven by incremental innovation. On the contrary, seat and suspension control systems, while accounting for only 0.56 % of patent applications share, have a high citations-to-total-

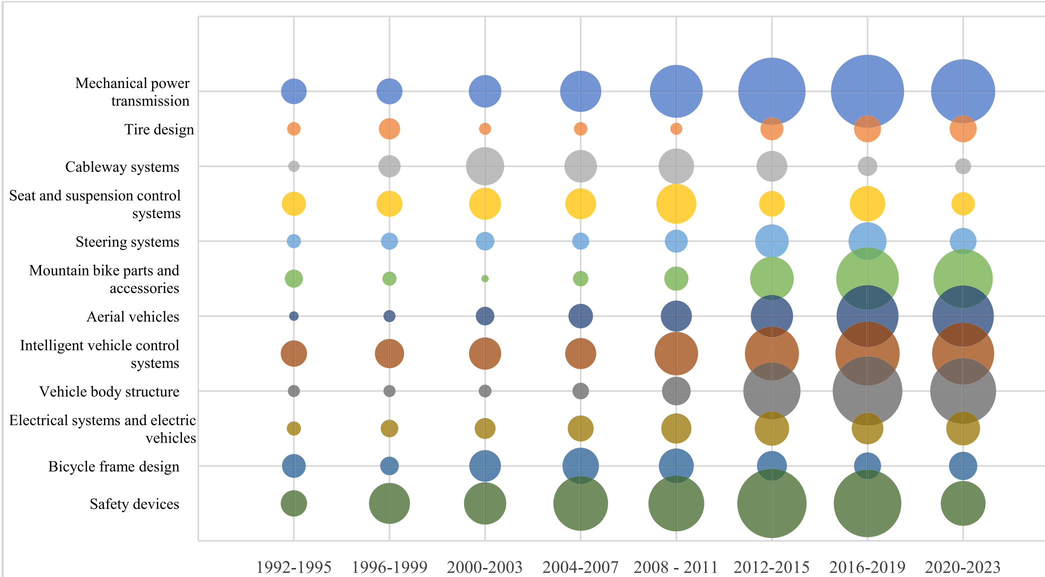

Fig. 8. Temporal trends of the 12 technological subcategories (the bubble size indicates the number of patent applications related to mountain T&L)

patent-applications ratio (4.48), indicating a strong potential for future development. Intermediate areas such as intelligent vehicle control systems (with 10.06 % of patent applications share and a 2.51 citations-to-total-patent-applications ratio) and aerial vehicles (with 13.38 % of patent applications share and a 2.17 citations-to-total-patent-applications ratio) appear to be characterized by moderate innovation activities. Both mountain bike parts and accessories and vehicle body structures have significant patent applications shares (14.63 % and 18.95 %, respectively) but very low citations-to-total-patent-applications ratios (0.50 and 0.84, respectively), pointing to potential saturation.

In Japan, two areas are characterized by substantial innovation potential: intelligent vehicle control systems and tire design. The first encompasses 15.36 % of patent applications share, with a citations-to-total-patent-applications ratio of 7.56, indicating significant growth. Similarly, tire design, although accounting only for 2.68 % of patent applications share, has a citations-to-total-patent-applications ratio of 7.42, suggesting that this smaller yet highly innovative field is poised for considerable development. These areas are followed by several other technologies with citations-to-total-patent-applications ratios between 3 and 6, thus indicating growth prospects: electrical systems and electric vehicles (5.67 % patent applications share and 5.51 citations-to-total-patent-applications ratio), mechanical power transmission (1.65 % patent applications share and 4.63 citations-to-total-patent-applications ratio), seat and suspension control systems (6.29 % patent applications share and 3.93 citations-to-total-patent-applications ratio), and aerial vehicles (1.24 % patent applications share and 4.67 citations-to-total-patent-applications ratio). Conversely, mountain bike parts and accessories (0.52 % patent applications share and 0.20 citations-to-total-patent-applications ratio) and vehicle body structures (1.13 % patent applications share and 0.91 citations-to-total-patent-applications ratio) show signs of saturation.

In South Korea, the patent landscape highlights two areas of moderate innovation potential: aerial vehicles, which have a 9.09 % patent applications share and a 2.31 citations-to-total-patent-applications ratio, and seat and suspension control systems, which, despite having only a 2.41 % patent applications share, have a citations-to-total-patent-applications ratio of 2.23. Several other domains show modest or incremental growth prospects. These include electrical systems and electric vehicles (5.01 % patent applications share and 1.89 citations-to-total-patent-applications ratio), mountain bike parts and accessories (1.48 % patent applications share and 1.75 citations-to-total-patent-applications ratio), cableway systems (9.28 % patent applications share and 1.60 citations-to-total-patent-applications ratio), and tire design (0.93 % patent applications share and 1.60 citations-to-total-patent-applications ratio). Conversely, the following areas indicate potential saturation or limited innovation activity—safety devices, which, despite having the largest patent applications share (34.69 %), have a low citations-to-total-patent-applications ratio of 0.92; and vehicle body structures (3.15 % patent applications share and 0.59 citations-to-total-patent-applications ratio) and steering systems (1.86 % patent applications share and 0.50 citations-to-total-patent-applications ratio), which appear to be established, with limited room for advancement.

In the United States, the transportation technology patent landscape generally indicates a growth trend, with many domains showing strong or substantial innovation potential. Among them, intelligent vehicle control systems (16.33 % patent applications share and 19.29 citation-to-total-patent-applications ratio) and seat and suspension control systems (21.71 % patent applications share and 16.40 citations-to-total-patent-applications ratio) were particularly notable. Other technologies also exhibit strong growth trends, including cableway systems (6.18 % patent applications share and 10.68 citations-to-total-patent-applications ratio), steering systems (4.78 % patent applications share and 13.33 citations-to-total-patent-applications ratio), electrical systems and electric vehicles (3.59 % patent applications share and 12.39 citations-to-total-patent-applications ratio), bicycle frame design (15.94 % patent applications share and 12.39 citations-to-total-patent-applications ratio), mountain bike parts and accessories (1.00 % patent applications share and 8.40 citations-to-total-patent-applications ratio), and aerial vehicles (1.99 % patent applications share and 7.90 citations-to-total-patent-applications ratio). Notably, however, the number of patents in these fields is relatively low, potentially reflecting a still limited overall interest.

In Germany, the patent landscape likewise generally indicates a growth trend, with numerous technologies demonstrating strong innovation potential. Intelligent vehicle control systems (23.33 % patent applications share and 6.57 citations-to-total-patent-applications ratio) and electrical systems and electric vehicles (11.39 % patent applications share and 8.27 citations-to-total-patent-applications ratio) are particularly prominent. Other relevant areas include tire design (3.06 % patent applications share and 5.00 citations-to-total-patent-applications ratio), aerial vehicles (3.33 % patent applications share and 3.92 citations-to-total-patent-applications ratio), seat and suspension control systems (9.44 % patent applications share and 3.32 citations-to-total-patent-applications ratio), steering systems (5.56 % patent applications share and 3.30 citations-to-total-patent-applications ratio), bicycle frame design (15.83 % patent applications share and 3.16 citations-to-total-patent-applications ratio), and mechanical power transmission (1.94 % patent applications share and 3.14 citations-to-total-patent-applications ratio). Despite these trends, we should acknowledge that the number of patents in some fields remains relatively low, suggesting still limited efforts. To conclude, vehicle body structures (1.39 % patent applications share and 1.40 citations-to-total-patent-applications ratio) and mountain bike parts and accessories (1.67 % patent applications share and 2.00 citations-to-total-patent-applications ratio) display lower levels of innovative activity, potentially pointing toward only incremental advancements.

Overall, these analyses show that Japan, the US, and Germany exhibit strong alignment with the global trends displayed in Table 4, focusing on intelligent vehicle control systems, safety devices, and electric vehicles. These countries appear well-positioned to drive future advancements in transportation technologies, although they are still characterized by relatively modest numbers of patents. In contrast, China and South Korea show only partial alignment with global trends. China holds the highest number of patents in almost all the technological areas, despite a significant focus on traditional technologies, such as mechanical power transmission. It is also gradually shifting toward more innovative fields, such as seat and suspension control systems, reflecting an evolving innovation landscape and a potential for future alignment with global trends. On the other hand, South Korea demonstrates more modest innovation activities and lower citations-to-total-patent-applications ratios, notwithstanding its investments in intelligent systems. This suggests its slower pace of growth compared to the other leading countries. Similar dynamics appear when considering the aggregate metrics (Table A6 in the Online Appendix). Japan, the US, and Germany stand out with higher citations-to-total-patent-applications ratios—5.14, 12.93, and 4.37, respectively—while China and South Korea have lower ratios of 1.50 and 1.30, respectively.

5. Key takeaways

Understanding the technological landscape is essential for making informed decisions in various domains, including in mountain T&L systems. To this end, patents are rich sources of technical data, aiding in determining the strategic direction of R&D investments and planning (Baglieri & Cesaroni, 2013; Hao, Liang, et al., 2024a; Hao, Wen, et al., 2024b; Tao et al., 2024). The examination of such documents in this study provided valuable insights into the latest advancements and trends in transportation vectors specifically designed for mountain regions. In particular, our investigation identified the following key aspects:

- The analysis revealed a clear upward trend in patent applications, reaching a record high of 1139 in 2020. This surge reflected the increasing innovation in T&L technologies, driven by the growing demand for diverse and convenient travel options in mountain regions. Moreover, it underscored the significance of IP rights in fostering competitiveness in the mountain T&L sector.
- This study showed that the innovation landscape is mainly driven by Asian organizations, especially Chinese, Japanese, and South Korean organizations. The different approaches of China and Japan are particularly noteworthy, as the former relies heavily on public institutions (i.e., universities) and the latter is driven by private companies. This distinction marks an interesting aspect of study for innovation researchers, indicating the importance of delving into the impacts of different approaches—state-driven versus market-driven—on the speed and character of technological development (e.g., Kamikawa & Brummer, 2024; Yang & Wang, 2024).
- LDA grouped the patent data into 12 clusters, each of which represents specialized areas within mountain T&L vectors. This approach offered a comprehensive view of technological advancements in the field and enabled comprehension of the innovation landscape therein.
- Considering forward citation metrics (Squicciarini et al., 2013), this study identified emerging technologies in mountain T&L vectors, such as seat and suspension control systems, intelligent vehicle control systems, electrical systems and electric vehicles, bicycle frame design, and safety devices. These areas are deemed significant for the future of mountain T&L vectors. On the other hand, the fields of vehicle body structures, mountain bike parts and accessories, and mechanical power transmission are becoming saturated or obsolete, as evidenced by the decreasing citations of patent applications in these areas.

6. Conclusions

6.1. Contributions to the literature

According to the findings and the considerations reported in the previous sections, our analysis is valuable to the academic literature in several ways. First, we present the first comprehensive overview of technological advancements and innovation dynamics in the field of mountain T&L. This facilitates the consolidation of existing knowledge while aiding scholars in pinpointing areas where further investigations can be conducted (e.g., Peppel, Ringbeck, & Spinler, 2022; Rajak, Chatterjee, & Upadhyay, 2024).

Second, by performing a patent analysis, we were able to examine real-world trends and draw an accurate picture of the actual development state in mountain T&L, dispelling potential hype (Albino et al., 2014; Ardito et al., 2022). This approach also allowed us to explore the connections between technology domains, revealing synergies and cross-cutting themes, as well as identifying the key players driving innovation in mountain T&L. In contrast, previous research often relied on systematic/bibliometric literature reviews or conceptual elaborations, which can be characterized by a certain degree of speculation and, at times, might lack ground-based evidence (e.g., Culot, Podrecca, & Nassimbeni, 2024).

Third, this study adopted a balanced perspective by considering a wide range of technologies within the unique context of mountain T&L, whereas previous contributions often appeared either too specific or too generic. Some of them focused narrowly on individual innovations (e.g., UAVs for mountain rescue – Silvagni et al., 2017; mountain bikes – Buning et al., 2019) or single-application fields (e.g., mountain agriculture – Flury, Huber, & Tasser, 2012; recreational mountain activities – Yuan & Wang, 2018), thereby missing the broader picture. Others adopted a general view (e.g., considered the entire topic of vehicle tires – Ghaffari et al., 2023) without providing context-related insights.

Fourth, many prior studies concentrated on improving existing mountain T&L infrastructure (e.g., Kelley et al., 2013; Pernkopf & Gronalt, 2021), often overlooking the potential of recent developments and lacking a predictive assessment crucial for strategic planning. We considered both established and cutting-edge technologies while also presenting likely future trends, offering valuable foresight into emerging trajectories.

Finally, by leveraging topic modeling, we gained a deeper knowledge of technological interdependencies. This enhances our understanding of the complex landscape of mountain T&L by providing a more detailed and comprehensive view of the field. Compared to traditional patent analysis methods (e.g., relying solely on descriptive statistics), topic modeling offers a more nuanced and effective means of analyzing unexplored domains and identifying aspects that would otherwise be difficult or even impossible to detect (Ghaffari et al., 2023; Momeni & Rost, 2016; Park et al., 2021). From this perspective, we evidenced the benefits of adopting innovative and data-driven analytical approaches over conventional procedures, which are still widely used in patent-based research.

6.2. Contributions to practice

From a practical point of view, at least two significant implications emerge. First, by showing that the number of patent applications related to mountain T&L is growing, we provide managers with crucial information concerning technological competitiveness and business opportunities. The increasing trend in patenting activity should be recognized as a clear sign of rising expectations and opportunities in mountain T&L; this is indicative of a robust and expanding market that offers high potential for investment and innovation (e.g., Ardito et al., 2022). By staying attuned to these developments, companies can strategically allocate resources to R&D, form partnerships with innovative organizations, and position themselves as leaders in the burgeoning field of mountain T&L. Furthermore, the growing patenting activity in the field highlights opportunities to explore new product lines and address specific challenges that are unique to mountainous regions.

Second, this study's projection of future patterns in mountain T&L helps identify critical technological areas that require further attention and investment, while pointing out domains moving toward saturation and decline. Acknowledging and understanding these emerging trends is essential for making informed decisions. From this perspective, Chinese organizations, which are leading in mountain T&L research, can leverage these data to identify the most promising technologies and maintain their competitive edge. On the other hand, companies in Europe, Japan, and the US can use these insights as guides to enhancing their positions in the global mountain T&L landscape and bridging the innovation gap.

6.3. Contributions to policy

This study also presents several policy contributions. First, the analyses highlight a broad spectrum of technologies being developed to tackle the unique challenges of mountain T&L. For instance, electric vehicles can enhance transportation efficiency while reducing environmental impact, thereby preserving the fragile ecosystems of mountainous areas. Drones can revolutionize last-mile delivery by reaching remote and difficult terrains, ensuring that essential goods and medical supplies are delivered promptly. Promoting the adoption of these technologies can enhance the connectivity, efficiency, and sustainability of T&L systems in mountainous regions, which could ultimately foster economic growth and improve the quality of life of local communities. From this perspective, policymakers could use our findings to guide the selection and integration of relevant technologies into mountain development plans. This can be achieved by creating supportive regulatory frameworks and investing in the necessary infrastructure (e.g., Makino, Manuelli, & Hook, 2019; Ying, Ke, Zhu, & He, 2023).

Second, by presenting information on the likely future directions of technological advancements in mountain T&L, we provide policymakers and funding agencies with valuable insights for making strategic decisions on which research fields and technologies to support. By directing resources toward the most promising areas, they can facilitate technology transfer, stimulate economic growth, and drive social change (Zhang, Shi, Gao, & Feng, 2023).

Third, despite Europe's extensive mountain areas (Walsh & Giguet-Covex, 2019), the participation of European organizations in the R&D landscape for mountain T&L remains limited. To address this gap, it is crucial to implement targeted incentive schemes and provide robust financial support for R&D in innovative technologies. Policymakers could introduce tax breaks for companies investing in mountain T&L research. Additionally, grants for collaborative projects between industry and academia could foster partnerships that drive technological advancements. Increasing funding for education and training programs focused on mountain T&L would also ensure a skilled workforce capable of sustaining innovation in this sector.

Finally, the significant differences between the actors driving technological advancements in mountain T&L (universities vs. companies) highlight the strong potential for industry–academia collaboration. By fostering these synergies, both sides can benefit: universities can effectively commercialize their innovations, and companies can balance immediate market demands with long-term foundational research, ensuring future prospects. From this perspective, in contexts such as China, where academic institutions play a pivotal role in innovation dynamics, it is necessary to develop policies that support technology transfer from research centers and universities to private firms, as well as encourage the formation of university spin-offs and public–private ventures (Ardito et al., 2022). Conversely, in regions where companies primarily drive development, such as in Japan, creating clusters that link businesses, research entities, and government bodies can stimulate joint research efforts (Mazur, Barmuta, Demin, Tikhomirov, & Bykovskiy, 2016).

6.4. Limitations and future research

This paper has some limitations that can be addressed in future research. First, although the use of patent applications is a well-established method of systematically and quantifiably measuring innovation on a large scale and is thus useful for tracking the evolution of specific technologies and comparing the innovation efforts of different actors and contexts (Agostini et al., 2019; Su et al., 2023), it presents some disadvantages. Specifically, patent data do not capture all innovations, as some may be ineligible for patenting or may be more effectively safeguarded through other methods. Patent analysis particularly tends to overlook innovations in industries where patenting is less common or less effective as a means of IP protection (Ardito, Petruzzelli, Panniello, & Garavelli, 2018b). Furthermore, the complexity and cost of the patent application process may discourage individuals and small enterprises from filing them, which could lead to a greater representation of larger organizations with more resources (Athreye, Fassio, & Roper, 2021). Future research could incorporate additional secondary data, such as industrial and funded projects, or collect primary information through interviews with technology providers, policymakers, and users (e.g., Cowls, Tsamados, Taddeo, & Floridi, 2023). Combining these methods with patent analysis could provide a more comprehensive understanding of innovation dynamics and overcome some of the limitations associated with relying solely on patent data.

Second, although LDA is a robust and acknowledged technique (e.g., Kang et al., 2021; Momeni & Rost, 2016), it also has downsides. Specifically, LDA results can be influenced by parameter choices, necessitating careful tuning to ensure meaningful outcomes. Interpreting the topics can also be complex, often necessitating domain expertise. Additionally, although this study used LDA to generate topics from patent abstracts, it may have overlooked important information in other parts of the patent documents, such as claims, specifications, or drawings. Future research could benefit from using more advanced topic modeling methods and including all sections of patent documents to capture the complexity and evolution of the topics. Moreover, complementing LDA with other analytical approaches, such as qualitative content analysis or network analysis, can help validate and enrich the findings.

Third, we used forward citation analysis to evaluate the future relevance of the topics, thus neglecting aspects such as the patent age, patent office, or patent examiner. Further studies could use more robust and nuanced indicators or resort to forecasting models, such as Verhulst and Gompertz curves.

Finally, we focused on the technological aspects of mountain T&L without considering their social, environmental, and economic implications. Future research could extend the analysis by combining different data sources, such as scientific publications, news articles, and social media posts, to gain a broader and deeper understanding of the field and its implications.

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CRediT authorship contribution statement

Mehari Beyene Teshome: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Matteo Podrecca:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Guido Orzes:** Writing – review & editing, Supervision, Funding acquisition, Project administration.

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.

Appendix A. Supplementary data

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