Systematic Review
Climate Change Impacts on the Road Transport Infrastructure: A Systematic Review on Adaptation Measures

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Abstract: Road transport is one of the main contributors to increasing greenhouse gas (GHG) emissions, consequently aggravating global warming, but it is also one of the sectors that most suffer from climate change, which causes extreme weather events. Thus, strategies, also called adaptation measures, have been discussed to minimize the impacts of climate change on transport systems and their infrastructure; however, a knowledge gap is evident in the literature. Therefore, this article develops a systematic review with a bibliometric approach, still scarce in the literature, in renowned databases, focusing on studies developed on adaptation measures for road infrastructure. The results show that, since the development of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), an increasing amount of studies on the theme have been published in recognized journals such as Science of the Total Environment, Energy and Buildings and Urban Climate, analyzing climate threats such as intense precipitations and high temperatures that have led to biophysical impacts such as flooding and urban heat island. In addition, for each type of adverse weather condition, many impacts on road infrastructure can be listed, as well as ways to detect these impacts, and adaptation measures that can be used to minimize these problems.

Keywords: climate change; road infrastructure; adaptation; highway infrastructure; pavement

1. Introduction

The construction of transportation systems and infrastructure are responsible for several positive and negative impacts. The positive impacts are mainly related to creating many job positions, connecting isolated areas, improving logistics and transporting goods. All of these are essential for human development. On the other hand, they are responsible for negative impacts, such as exacerbated consumption of natural resources and increased emissions, especially greenhouse gas (GHG) emissions, which can severely affect and change the natural landscape.

Although transportation systems and their infrastructure are designed to withstand typical weather patterns, the impacts of current climate change and those arising in the short, medium, and long term can influence the infrastructure itself, the efficiency of transportation operations, and the ability of the infrastructure to withstand extreme events outside the “typical” range [1]. This indicates that infrastructures not only need to be reliable when submitted to standard load, but also be able to minimize the magnitude and duration of failures under exceptional conditions such as increased rainfall intensity, changes in precipitation patterns, and more extreme weather events [2,3].

Climate change creates several challenges for the transportation sector because this system is highly vulnerable to weather and climate conditions, and their impacts due to the
occurrence of extreme weather events, which influence infrastructure lifetime and transportation safety. This emphasizes the need to consider climate change in regular transport infrastructure projects, including the entire useful life of these assets [4–6]. However, transport agencies have limited financial resources for road maintenance and face demands for sustainable infrastructure [7]. The climate risk of a transportation infrastructure relies on a variety of factors, including its nature, location, design features, and construction practices.

Thus, decision-makers responsible for determining when and where infrastructure should be developed and/or improved are facing a new challenge with the emerging topic of climate change, which represents one of the greatest challenges currently threatening the planet [3,8–10]. Impacts of climate change on the transport network can both result in the loss of infrastructure assets and hamper the recovery and resilience of the entire sector, as transport infrastructure represents a substantial national investment [11,12].

In a study developed by Chinowsky, Price & Neumann [13], for example, it is indicated that maintaining the United States road network involves approximately $134 billion in government funds annually from federal, state, and local agencies. However, if climate change goes unchecked, annual maintenance costs for paved and unpaved roads will increase by $785 million by 2050. Thus, it becomes increasingly important to develop adaptation measures to reduce the impacts of climate change on transport infrastructure [4,14], which should be composed of well-structured actions that take into account the participation of all stakeholders in the decision-making process [15].

Adaptation can be defined as the process of adjusting the system to actual or expected climate change and their effects. These adjustments can be both structural, i.e., hard adaptations, and political, educational, and social in nature, i.e., soft adaptations. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities [9]. Adaptation measures should be linked to current and future risk reduction practices and management initiatives to increase transport resilience and reduce the impacts of extreme weather events [12,16]. In addition, these adaptation alternatives and solutions should be compatible with mitigation strategies (i.e., it needs to have synergy) in order to avoid dramatically increasing GHG emissions.

Therefore, this study aims to identify and analyze, through systematic review with bibliometric approaches, studies on the impacts of climate change on road transport infrastructure with a focus on the identification of adaptation measures—hard and soft adaptations—which includes direct searches in two of the main world databases, namely, Scopus and Web of Science. It is also worth mentioning that, for a coherent evaluation of studies, inclusion and qualification criteria (quality and applicability) were used.

The relevance of this study lies in dealing with a subject of worldwide concern that still lacks related research; this study gives special emphasis to the problems of funding for the study and implementation of adaptation measures, common mainly in developing countries. In addition, it should be highlighted that this study is aligned with the United Nations Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, especially with SDG 9 (“industry, innovation, and infrastructure—build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation”), SDG11 (“sustainable cities and communities—make cities and human settlements inclusive, safe, resilient and sustainable”), and SDG13 (“climate action—take urgent action to combat climate change and its impacts”) [17].

After this introductory section, the article is structured as follows: Section 2 presents the methodological procedure necessary to conduct the study; Section 3 presents results related to the bibliometric analysis of studies included in the research repository; Section 4 reflects on the need to consider the impacts of climate threats on road transport infrastructure, highlighting the main adaptation measures, found in the literature review. Finally, Section 5 contains the final considerations, which also include proposals for future research.
2. Materials and Methods

The production of knowledge, in recent years, has generated a magnitude of data and information at such high level that curating the most relevant content has been one of the greatest challenges for researchers and scholars [18]. Therefore, to obtain information about the state of the art on the impacts of climate change on road transport infrastructure with a focus on adaptation, a systematic review with a bibliometric approach was developed to identify and analyze relevant studies (quality, which refers to the importance of the study for the scientific community, and applicability, which refers to the alignment of the study with the theme under investigation) on the subject. To this end, the steps described below were adopted.

In the first step, the most relevant keywords for the efficient conduction of the research are defined, as well as the definition of the inclusion and qualification criteria, according to the summary presented in Table 1. It is noteworthy that the use of combinations between some keywords directly related to climate change and other keywords directly related to road transport was considered relevant. The choice of keywords and their combinations is considered a brainstorming process to choose the most relevant terms. Subsequently, a team of academics and transportation professionals refined these keywords to provide solid validity.

Table 1. Description of Search Strategies.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Databases</strong></td>
<td>Web of Science-TS = ('climate change' AND 'road infrastructure' AND 'adaptation') OR TS = ('climate change' AND 'highway infrastructure' AND 'adaptation') OR TS = ('climate change' AND 'pavement' AND 'adaptation')</td>
</tr>
<tr>
<td><strong>Topics</strong></td>
<td>Scopus-TITLE-ABS-KEY ('climate AND change' AND 'road AND infrastructure' AND 'adaptation') OR TITLE-ABS-KEY ('climate AND change' AND 'highway AND infrastructure' AND 'adaptation') OR TITLE-ABS-KEY ('climate AND change' AND 'pavement' AND 'adaptation')</td>
</tr>
<tr>
<td><strong>Search Method</strong></td>
<td>Direct Search</td>
</tr>
<tr>
<td><strong>Inclusion</strong></td>
<td>(I) Time of coverage: all years of the database (1945–2021), although a special focus has been given to the most current studies—the last ten years (2011–2022); (II) Source Relevance.</td>
</tr>
<tr>
<td><strong>Qualification</strong></td>
<td>(I) Does the study address the impacts of climate change on road infrastructure and/or the adaptation measures needed to minimize them? (II) Does the research present a well-founded literature review? (III) Does the study present technical innovation? (IV) Are contributions discussed? (V) Are limitations explicitly stated? and (VI) Are the results and conclusions consistent with the pre-established objectives?</td>
</tr>
<tr>
<td><strong>Search Date</strong></td>
<td>2 January 2022, at 7:00 p.m.</td>
</tr>
</tbody>
</table>

In the second step, direct research was carried out in two main databases: (i) Scopus; and (ii) Web of Science. We considered all their data sources/index. In addition, documentary research was carried out in important information bases of scientific institutions and initiatives that deal with the theme of climate change such as the Intergovernmental Panel on Climate Change (IPCC), the National Research Council, and the World Bank Group. Thus, the initial database consisted of 518 studies (246 studies from Web of Science, 268 from Scopus and four reports).

Step 3 shows the data processing, which consists of consolidating and organizing data to prepare technical information for the analysis of the impacts of climate change on the road transport infrastructure. As different databases can provide the same studies, the EndNote bibliographic manager software was used to organize data and remove duplicate content. At this stage, the final research repository was obtained, necessary for subsequent bibliometric and systematic analysis. This consolidated repository consists of 280 studies. The reason is that 238 studies were eliminated either because they were
duplicated (188 studies) or did not meet the inclusion and qualification filters (50 studies), as shown in Figure 1.

Finally, Step 4 shows the development of the research report, here expressed as an article, containing the knowledge produced from the research analyses. It is worth mentioning that, to carry out the bibliographic and systematic analysis, several other computer programs such as Excel were used to create simpler graphs such as the evolution of publications and citations per year, VosViewer to generate interconnection maps between keywords, Tableau for mapping publications by country under investigation, among others.

An important aspect still needs to be mentioned, while in the bibliometric analyses the growth of publications over the years and the journals that are most interested in the theme, for example, were obtained directly from the databases that make up the research, the systematic analyses come from the detailed investigation of each study. Thus, aspects such as countries under investigation, climate threats, and biophysical impacts investigated, among others, were obtained by filling in columns of the table created to analyze them. In addition, special attention is given to the adaptation measures (hard and soft adaptation) found in these studies.

3. Bibliometric Results

From the direct and documentary research, it was possible to verify that 280 publications were able to be included in the research repository; that is, they met inclusion and qualification criteria. These publications can be divided by document type, as shown in Figure 2. This analysis is important because studies published in important scientific journals, which use a blind review process, are generally more relevant than other publication sources. In addition, the more diverse the publication sources the greater the breadth of the topic and the opportunities for the study to be published. In them, there is great superiority of Articles, with 69% of publications, and a more intimate representation of Proceeding Papers, Books and Book Chapters.

Another important analysis is to verify how publications grow over the years, as this analysis is essential to assess the level of expansion on the subject, as well as new study opportunities. Thus, Figure 3 shows how the topic became more relevant from 2005 onwards and has been worked on until the present day, reaching a peak in 2020, when 41 publications on the topic were registered (about 15% of the total). It is also noteworthy that the issue grew rapidly after 2014, due to further consolidation of the impacts of climate change on the transportation sector with the publication of Fifth Assessment Report—AR5 [9]. Just to give an idea, from 2014 to 2022, 88% of studies were published. Comparing the two databases (Scopus and Web of Science), separately, it is also possible to
see the growth of publications from 2014, reaching its peak in 2020 in both databases, as well as the full repository results.

Figure 2. Publications by Document Type.

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Figure 3. Publications by Year.

It is also pertinent to evaluate studies by publication journal to identify which journals are most interested on the subject (as shown in Figure 4), as well as their Impact Factor (IF) (according to Table 2, which considers IF data for 2020 and the average of the last 5 years). This allows researchers to direct their efforts to journals that have a direct focus on the subject under study, avoiding undirected submissions and considerable time losses.

In Figure 4, it was observed that the journals that most address the subject are Sustainability, with 16 publications, Journal of Infrastructure Systems, with 10 publications, and Climatic Change, with 8 publications, which together correspond to about 12% of publications. It was also identified that the rest of publications are scattered in 189 sources that are interested on the subject. In addition, it was observed that by ordering the journals by IF, according to Table 2, it was possible to identify that the most relevant are: (i) Science of the Total Environment, (ii) Energy and Buildings, and (iii) Urban Climate, with an IF greater than 5.7 (which represents an excellent score).
It is also possible to determine the dispersion of citations of the most relevant studies in the database, as shown in Table 3. The reason is that many citations of a scientific publication through the years can prove to be an indicator of innovation (a new idea, method, discovery, etc.). In Figure 5, it is possible to identify how the citations of each of the 10 studies are distributed over the years. Thus, it was observed that the study by Sterr [19], which is the oldest study, has received citations to the present day, as well as the study of Charlesworth [20], which is the second oldest. Furthermore, it is worth noting the relevance of Akbari et al. [21], which in addition to being the most cited in the general context, has also received a higher percentage of citations, thus demonstrating its prominent position.

It is also important to evaluate the main keywords found in studies included in the research repository, as identified in the interconnection network between keywords shown in Figure 6, developed with the help of the VOSviewer Software (Centre for Science and Technology Studies, Leiden University, The Netherlands) that builds and visualizes bibliometric networks. This strategy allows researchers to more easily find studies directly related to the investigated subject, as well as identify new research directions, determining the factors, key dimensions, and main areas.
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The network represented in Figure 6 is composed of 2050 items, 46 clusters, and 36,139 links/connections, in which it is possible to identify the most used keywords (according to the size of the sphere under their representation), the interconnections between them (according to connections between spheres), and the period in which they were most used (according to the color of each sphere).
In Figure 6, it is possible to observe that the most recurrent keywords, as expected, are: ‘Climate Change’, ‘Adaptation’, ‘Climate Change Adaptation’, ‘Risk Assessment’, ‘Green Infrastructure’, and ‘Road Infrastructure’. In addition, it is important to highlight keywords related to the biophysical impacts of climate change such as ‘Floods’, ‘Erosion’, ‘Sea-level rise’, and ‘Coastal Erosion’.

It is also worth mentioning the presence of the keyword ‘Mitigation’. Although its main objective is to minimize the causes of climate change and not act to minimize its impacts, mitigation strategies can present significant synergies with adaptation strategies through an integrated approach enhancing responsiveness [25].

As this study focuses on ‘Adaptation’ or ‘Climate Change Adaptation’, special attention is paid to the network of links with these keywords, as exposed in Figure 7, which shows that: (i) the keyword ‘Adaptation’ presents 73 occurrences, 4 clusters and 723 links/connections with total size of 1117, having connections with interesting keywords such as: ‘Ecosystems’, ‘Green Infrastructure’, ‘Sensitivity Analysis’, and ‘Pavements’; and (ii) the keyword ‘Climate Change Adaptation’ has 44 occurrences, 1 cluster and 463 links/connections with total size of 615, being connected to keywords such as ‘Highway Planning’, ‘Risk Assessment’, and ‘Urban Heat Island’.

![Figure 7. Interconnection network between connections with the keyword ‘Adaptation’.](image)

4. Systematic Results

Currently, although most studies have been focused on climate change and the road sector in the general context, mainly listing mitigation strategies, an increasing number of studies have been designed to assess and document the impacts of climate change on the road transport infrastructure, providing guidance on the types of potential impacts and possible strategies for adapting to these impacts. The reason is that, whatever the warming scenarios and however successful mitigation efforts are, the impact of climate change and their economic, environmental, and social costs will increase in the coming decades [26,28]. From Figure 8, studies focusing on adaptation represent 18.41% of the total studies on climate change and road transport infrastructure and about 2.42% of studies on climate change and critical infrastructure.

It is noteworthy that not all studies included in the database are focused on road transport, many of them (about 54%) deal with critical infrastructure in general and bring some reflections on the sector, as can be seen in Figure 9. In this figure, it can be observed that only 46% (130 studies) of the database present road transport as the central axis of discussion, highlighting again the scarcity of relevant studies on the subject.
It should also be verified whether studies included in the database are literature reviews or case studies, as shown in Figure 10. This strategy is relevant because these two types of studies have different goals. While the first must identify critical points (literature gaps) to expand/deepen the state of the art on the subject, the second seeks to develop methodologies and apply them to analyze a current phenomenon in its real context and the variables that influence it. In Figure 10, it was identified that the largest number of publications (about 86%) carry out case studies to investigate problems in different regions at the most varied jurisdiction levels. It is also important to highlight that, although some literature review studies have similar objectives to those of this article, it is believed that, different from the others, the present research is innovative and enriching for providing bibliometric analysis and systematic literature reviews, representing a considerable differential for researchers seeking information on the subject.

Another interesting analysis is to find out which regions have been the focus of research, especially case studies, on the subject. It is important to note that this activity differs from the analysis of the authors’ educational institutions because researchers may investigate problems in regions different from their origins due to the greater occurrence of events of the magnitude under analysis or the availability of data to conduct deeper analysis in a particular location. Thus, Figure 11 presents a map of the most investigated countries in the research repository, developed in Tableau Software (Seattle, WA, USA).
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From Figure 11, it can be observed that the most recurrent countries are the United States, with 15% of total publications; Canada, with 9%; and the United Kingdom, with 8% of publications. That is, the three countries, all with a developed economy, account for 32% of publications. It is also noteworthy that the growing research on the impacts of climate change on critical infrastructure in several countries with developing economies (about 16% of the total) includes countries: (i) in Africa such as South Africa, Mozambique, Ethiopia, and Senegal; (ii) in Asia such as Bangladesh, Indonesia, Iran, and Israel; and (iii) South America, such as Colombia, Peru and Chile—although no publication has been registered in Brazil, a country of continental dimensions that suffers from the impacts of several climatic threats. It is worth noting that, although some technical reports on Brazil have been considered, none of them make a critical analysis of the problems for road transport infrastructure.
Schweikert et al. [29] for example, highlight that climate change figure as a critical threat to future development, especially in countries where poverty is widespread and key assets are underdeveloped even for current needs. Thus, the analysis of the best adaptation strategies must consider the costs of adaptation itself and the opportunity costs for each country. It is also noteworthy that special attention has been paid to biophysical impacts (mainly flooding and erosion) located in coastal regions (which are lowland areas on the coastal regions seas and oceans with two distinctions: human systems and natural systems), which have increasingly suffered from rising sea levels and more frequent episodes of severe precipitation and wind.

It should also be observed that for the construction of maps presented in Figure 11, the federal scope was considered, that is, if the study was developed to evaluate the impacts of climate change in the city of New York (e.g., Zahmatkesh et al. [30]) or Adelaide (e.g., Razzaghmanesh, Beecham & Salemi [31]), it was counted as being developed to analyze the United States and Australia, respectively, for example. Thus, Figure 12 seeks to determine which are the jurisdiction levels (local, municipal/city, state, federal, regional, continental) in which studies are carried out. It is emphasized that, due to the specific and far-reaching nature of impacts on climate change, adaptation measures need to be taken at all levels, from local to regional and national [9]. Thus, it could be observed that, although the federal level presents higher proportion of studies with 24%, there is a certain balance among scopes, including strong participation of state, municipal, and local levels. Still on this subject, it is noteworthy that countries with continental dimensions such as the United States and Canada usually conduct analyses in specific cities or even in neighborhoods and communities (local analyses).

![Figure 12. Division of studies according to jurisdiction levels.](image)

Subsequently, it is necessary to understand which are the main climatic threats (agents and weather conditions) that most affect the sustainability of long-term infrastructure. The reason is that diverse types of threats require different ways of detecting them as well as different adaptation measures to minimize them. Thus, in Figure 13, it was observed that most studies (about 27.8%) investigate episodes of intense precipitation, followed by high temperature with 13.1% and increased sea levels, with 10.8%. It was also observed that a large number of studies (30.3%) that deal with threats in a general way, addressed more than 3 weather extremes. Many of these studies are literature reviews; however, even case studies consider the interrelationship between different threats to analyze the impacts of climate change on a specific region. It is important to highlight a gap in literature that consists in the majority consideration of impacts of threats of immediate effect, e.g., intense precipitation over a short period of time at the expense of threats of prolonged effect, e.g., light precipitation over a long period of time.
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Figure 13. Division of studies by type of climate threat/weather extremes under investigation.

In addition to the analysis of climate threats, another crucial point is the identification of the main biophysical impacts under investigation. The reason is that climate change can intensify several types of impacts, the most common being Flood, with 39.8% of publications; Urban Heat Island, with 11.9%; and Erosion, with 6.4%, as identified in Figure 14. These components of the biophysical system have different effects on road transport infrastructure and should therefore be treated separately. Therefore, analyzing each of these biophysical impacts is especially important for highway planning, operation, and maintenance due to the longevity of the infrastructure and the possible human and economic losses derived from that these impacts [32].

Figure 14. Division of studies by type of biophysical impact under investigation.
Figure 14 shows the high amount of studies that have analyzed more than two biophysical impacts, corresponding to a total of 28% of studies. In addition, another aspect that needs to be mentioned is the scarcity of studies on fires, common in several regions with tropical climates, such as Brazil. This impact, however, is more difficult to evaluate since it can be caused either by a natural cause or by human action.

As a complement to the above, the information presented in the previous figures can also be correlated. This strategy is important to indicate, for example, which climate threats lead to certain biophysical impacts, as presented in Figure 15. This figure shows that intense precipitation can lead to different biophysical impacts such as floods, inundation, erosion, and landslides. In addition, high temperatures also deserve attention, which have strong impact on urban heat islands, erosion, and drought conditions, and increased sea levels, which cause coastal impacts such as erosion, floods, and inundations.

![Diagram](Image)

Figure 15. Correlation between climate threat and biophysical impact.

To develop context-appropriate adaptation measures, first, it is necessary to identify where the most intense climate threats and biophysical impacts are located. Deciding
the most appropriate allocation of these resources to potential projects represents one of the most essential functions of infrastructure planners [13]. According to IPCC [9], analyses of Climate Risk Assessment should consider three components: climate threat, exposure, and vulnerability (sensitivity and adaptive capacity). This analysis should consider tools to support decision makers using observational and/or experimental data and scenario simulation models to quantify the impacts of extreme events and incremental climate change and identify hot spots in the road network in any geographic location worldwide [32,33]. However, through the literature review, it was found that 28% of studies make no mention of the best strategies to identify threats and impacts, considering only adaptation measures without any identification of the history of implementation of climate models for future analysis. The remaining 72% of studies apply various forms of Climate Risk Assessment, as shown by type of threat in Table 3. An important aspect needs to be considered, which is that, although the Risk Identification Methods have been separated by threat type, many of them can serve to identify other threats as well as their corresponding biophysical impacts.

Another point worth mentioning is the identification of the main impacts that climate threats can cause on the distinct types of critical road infrastructure, as also discussed in Table 3. During this review, it was found that most studies, about 77%, have analyzed the infrastructure as a whole; that is, they do not analyze roads (paving, for example), special structures (bridges, viaducts, etc.), or current structures (drainage systems, for example) separately. The explanation is that, in many cases, the availability of data on elements supporting roads, especially about drainage, is even more scarce. Thus, it is believed that this gap in literature needs to be better addressed in the future because each of these infrastructures has characteristics that can make it more vulnerable to certain biophysical threats and impacts. For example, bridges are highly vulnerable to corrosion intensified by flooding, while drainage systems can be compromised by road erosion.

It is important to understand that the impacts of climate change on road infrastructure in terms of maintenance, repairs, and connectivity loss can be minimized and even avoided by implementing proactive adaptation measures that are crucial to protecting current and future infrastructure investments and the economic, social, and other functions they perform [29,34], as examples listed in Table 3 (Hard adaptation) and Table 4 (Soft adaptation), obtained through our literature review.

It is worth noting that hard adaptation consists of structural modifications such as protecting road corridors with engineered structures and redesigning or relocating road facilities, and soft adaptation encompasses policies, land use allocations, education, and social involvement [35]. Furthermore, while different hard adaptations can be implemented for each type of threat and corresponding biophysical impact, e.g., pavement irrigation is suitable in the context of high temperatures and permeable pavement is suitable in the context of intense precipitation, soft adaptation can be applied to general contexts that encompass all the major climate threats and their respective impacts.

It is emphasized that these adaptation measures (whether hard or soft adaptation) offer a feasible and potential way to prepare the transportation system for the impacts of climate change and help make it more resilient, flexible, and operational under adverse conditions if properly implemented [28]. However, in assessing any solution, any negative impacts on investment, public access and facilities should be taken into consideration. In addition, actions can be time-sensitive and collaboration between authorized agencies is particularly important for risk assessment and evaluation of solution feasibility [36].

With a thorough reading of the studies included in our database, it is believed that decision-makers should develop a climate change adaptation policy and an implementation strategy document, i.e., an Adaptation Plan, making allowances for the impacts on assets, systems, operations, and resources. This Adaptation Plan should articulate the need for adaptation and the interests of stakeholders, including (i) consideration of adaptation needs in all new or ongoing projects, (ii) detailing the various operations and maintenance actions to increase system resilience to more frequent and/or severe weather events, and (iii)
developing a system-wide risk analysis of existing assets [7]. In addition, special attention should be paid to Emergency Management Systems, which when effective, are of vital importance in minimizing potential damages resulting from a given disaster [33].

Lin et al. [37] pointed out that adaptation measures that integrate technological, nature-based, and social solutions can provide various co-benefits to address complex socio-ecological issues in cities by increasing resilience to potential impacts. Thus, there is a need for the creation of integrated climate solutions to strengthen urban climate resilience and outline ways to overcome the range of challenges that hinder integration. Although some solutions may have an immediate tangible effect, others may only be effective once enabling solutions to come into force (e.g., developing adaptive pathways that allow current issues to be considered while planning for future changes; maintaining flexibility in planning to allow for changes in solutions over time, and creating solutions with many co-benefits that address current issues but do not create poor adaptations for future changes).

It is also noteworthy that while road investment decisions often emphasize increasing the quantity and quality of infrastructure through a focus on construction and basic cost-benefit analysis approaches, it is necessary to identify the gaps in infrastructure investment, particularly in developing countries, as a result of extreme weather events, which are often due to a lack of technical capacity and institutional structure to support successful projects [38]. Thus, a robust organizational structure should be developed, including proper data collection and handling, identifying the best global practices in climate change adaptation and incorporating the tacit knowledge of transportation experts to expand climate change knowledge to raise awareness and bring the climate agenda to all levels of business [3].

Table 3. Aspects related to the impacts of climate change on road infrastructure—hard adaptation.

<table>
<thead>
<tr>
<th>Agents and Weather Condition</th>
<th>Possible Impacts to Road Infrastructure</th>
<th>Risk Identification Methods</th>
<th>Hard Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature: High temperatures and heat waves; Daily temperature variation</td>
<td>Impacts on concrete pavement construction practices, including thermal expansion at bridge joints [1]. Pavements are vulnerable to reduced life with climate-change-induced temperature rise [39]. Higher temperatures reduce asphalt-layer stiffness and strength [40]. Concerns about pavement integrity, for example, relatively large deflections, transverse cracks, reduced asphalt pavement deformation rate, and permanent set [5,41]. Changes in landscape/biodiversity [1].</td>
<td>Use of Geographic Information System (GIS) models to identify problem areas, based on performance criteria, considering two main factors: solar irradiance and pavement materials [42,43]. Use of unmanned aerial vehicle systems, sensors and photogrammetric processing techniques that allowed timely and highly detailed three-dimensional surface reconstructions [27]. A hybrid bottom-up/top-down approach can be used to quantify the impact of changing pavement seasons and temperatures on pavement life with incremental temperature rise [39]. The Long-Term Pavement Performance Model (LTPP) can be used to determine asphalt pavement surface temperatures in order to assess the relative impact on the appropriate Superpave Performance Grade for more durable and resilient pavement construction [44].</td>
<td>Pavement irrigation is an emergency response to heat waves [43]. Use of hard bitumen to withstand heat in summer, flexible and solvent-workable bitumen in winter, soil moisture control and maintenance planning [45]. Use of cool pavements (they have lower surface temperature and are an important solution to mitigate the effects of sensible heat flow) [21,46]. Use of vegetation around highways (providing shade, releasing water vapor into the atmosphere and maintaining air quality) [21,46]. Asphalt materials with stronger binders can allow easy adaptation of pavement materials so that no change in the behavior of the bituminous pavement occurs [5].</td>
</tr>
<tr>
<td>Temperature: Thawing/Thawing permafrost</td>
<td>Landfill instability caused by thawing [27]. Plastic deformation (sinking) of roads, bridge foundations (collapse), pipelines, and pavement layers [47]. Severe compromises of ice road infrastructure [48].</td>
<td>Use of unmanned aerial vehicle systems, sensors and photogrammetric processing techniques that allowed timely and highly detailed three-dimensional surface reconstructions [27].</td>
<td>Addition of gravel and coarse embankment to stabilize the road embankment [27]. Replace winter ice roads (built on vast fields of ice and snow instead of asphalt, concrete or crushed stones, etc.) with land roads [48].</td>
</tr>
</tbody>
</table>
Table 3. Cont.

<table>
<thead>
<tr>
<th>Agents and Weather Condition</th>
<th>Possible Impacts to Road Infrastructure</th>
<th>Risk Identification Methods</th>
<th>Hard Adaptation</th>
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</thead>
</table>
| **Temperature: Freezing/Thawing** | Occurrence of differential freezing (slippery conditions form on the surface of isolated sections of pavement, while adjacent conventional sections of pavement maintain dry surface conditions) [49].  
  Premature deterioration of pavement structures, resulting in increased cracked area [50].  
  Avalanches and rockslides result in road blockages, interrupting access, and cause infrastructure damage [51].  
  Occurrences of slush flows with impact on infrastructure, through entrain varying quantities of mineralogical material, topsoil and trees due to intense snowmelt [52].  
  Deterioration of porous asphalt resulting in raveling, pothole damage and material loss at the longitudinal joints [53]. | Application of pavement design methods to identify problem areas and determine the granular layer thickness that avoids most situations of differential freezing [49].  
  Application of meteorological statistics from regions affected, with data from National Center for Atmospheric Research (NCAR) and Arctic Climate Impact Assessment (ACIA) as well as NOAA-CIRES, Climate Diagnostics Center [52].  
  Use of the Road Weather Information System (RWIS) for continuous monitoring and early warning of slippage on road pavements based on road surface temperature, strength (dry, wet or salt), dew point and precipitation [53]. | Road infrastructure with large thicknesses of crushed granular material, so that ice penetration never goes deep enough to cause elevation (and therefore allow further thaw) of the subgrade without compromising infrastructure [5].  
  Modification of the asphalt mix design or increasing pavement thickness [54]. |
| **Precipitation: Intense Precipitation** | Decreased pavement life due to premature damage to materials and structure [7,7].  
  Overloading drainage systems, causing backups and flooding of roads [1,5].  
  Mass movements of soil and rocks (slides) that damage roads [1,55].  
  Impacts on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels [1,55].  
  Foundation damage of bridges and culverts due to abrasion [45].  
  Scour of piers/abutment foundations [55].  
  Possibility of delayed effect failure that occurs when no immediate damage is induced at the time of the flood, but deterioration is accelerated afterwards [7]. | Use of GIS to identify the area at risk of flooding, overlaying the flood-sensitive areas with the road network area, using the flood sensitivity data [56].  
  Determining the influence of landscape patterns (ie: composition and configuration) of the impermeable surface on flood risk points [57].  
  Data-driven spatio-statistical approach to quantify and map flood probability [58].  
  Integrated framework that couples simulations of flooding and transport to calculate the impacts of disruption [32]. | Permeable paving, improved drainage or raising the level of the link that reduce flooding [32,59].  
  Increased road surface curvature for rapid surface water removal, maintenance frequency, base and subbase design, and material selection [45].  
  Regarding bridges and culverts, there is a need to estimate flooding, return period, design flow, cleaning above the high level of flooding, river and bank protection and corrosion protection [45].  
  Large-scale adoption of nature-based solutions and other types of green infrastructure that allow water infiltration and decrease flow peaks [60].  
  Install geotextiles and geogrids to prevent cracking [55].  
  Development of Flood Emergency Management Systems [33]. |
| **Precipitation: Low Precipitation-Drought Conditions** | Ground stability impacts (desiccation, shrinkage of clay materials) [55].  
  Problems of instability in the infrastructure [61].  
  Increased susceptibility to wildfires that directly threaten transport infrastructure [1].  
  Greater susceptibility to landslides in areas deforested by forest fires [1].  
  Loss of soil cover, allowing for easier erosion when rain occurs, allowing soil fines to reach drainage systems [5]. | Droughts are typically associated with aridity. Therefore, to track predicted urban sprawl in drought-prone areas, one can use a dataset from the Global Aridity Index from the Consortium for Spatial Information of the Consultative Group on International Agricultural Research [62]. | Large-scale adoption of green infrastructure (or eco-efficient infrastructure) represents long-standing principles of durability, flexibility and energy efficiency in infrastructure construction [61].  
  The use of new, more permeable paving materials with the potential for water storage can help reduce the severity of droughts [63].  
  Removal of prone materials [55]. |
### Table 3. Cont.

<table>
<thead>
<tr>
<th>Agents and Weather Condition</th>
<th>Possible Impacts to Road Infrastructure</th>
<th>Risk Identification Methods</th>
<th>Hard Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation: Changes in seasonal precipitation and river flow patterns</td>
<td>Increased risk of runoff flooding, landslides, slope failure and road damage if rainfall increases [1]. Major impacts on the infrastructure of river crossings [64], including the submersion of bridges during floods [45].</td>
<td>Infrastructure elements should be examined in conjunction with local-level flood risk maps to map all elements that are at climate risk [64].</td>
<td>The drainage capacity of single-span bridges should be re-examined against projected flood discharges to estimate the probability of flooding [64].</td>
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<tr>
<td>Rising sea levels added to high temperatures: increased water table and risk of flooding</td>
<td>Submergence of roads [36]. Premature road pavement failures [65]. Decreased pavement life when unbonded layers become saturated [66].</td>
<td>Hybrid bottom-up/top-down adaptation approaches have shown promise by initially investigating an asset’s response to incremental environmental change and then identifying the timing of critical effects for budget planning [65].</td>
<td>The flexible and gradual retrofit plan includes hot mix asphalt layers with prescribed thickness and application time, base layer rehabilitation options, and reassessment opportunities [65]. Relatively simple pavement structural modifications to asphalt concrete layers can increase their service life [66].</td>
</tr>
<tr>
<td>Sea level rise added to the storm: increased risk of coastal infrastructure inundation</td>
<td>Flooding of roads in coastal areas [5,45], and more frequent or severe flooding of underground tunnels and low-lying infrastructure [1]. Erosion of the road base and bridge supports bridge wear and reduces clearance under bridges [1,5]. Strong winds can blow debris, such as vegetation, onto roads, causing their disruption [3]. Loss of coastal wetlands and barrier shorelines and land subsidence [1]. Higher salinity can lead to asphalt detachment and attack of cement-treated bases [5].</td>
<td>Methodology for prioritizing the criticality of the road segment in coastal areas based on a location-based accessibility index, which measures the performance of the entire network before and after the interdiction of the transport network and quantifies the degree of network degradation [67].</td>
<td>Focus on the improvement of coastal systems to reduce the impact of sea level rise, such as protective structures, modification and elevation of infrastructures [36]. Relocation and realignment of roads, design changes, and replacement and adaptation of structures such as bridges and pavements to deal with rising sea levels [12,45]. Protection wall, realignment of road sections to higher areas and edge reinforcement [45].</td>
</tr>
<tr>
<td>Storms: most frequent strong cyclones</td>
<td>Road flooding and landfill flooding [45]. Erosion of road platforms or land adjacent to the road [5]. Blockage of drainage system due to accumulation of debris [5]. Reduction of ground cover along the road [5].</td>
<td>Use of GIS to identify the area at risk of flooding, overlaying the flood-sensitive areas with the road network area, using the flood sensitivity data [56].</td>
<td>Permeable paving and drainage facilities reduce flooding [59]. Pay particular attention to the design of drainage culverts, if these become unsuitable to carry flows from future rain runoff events, serious destructive damage can occur [5].</td>
</tr>
<tr>
<td>Forest fires near highways</td>
<td>Burning of asphalt [55]. Failure or melting of components [53]. Obstruction of drivers’ vision and encroachment on the road by wild animals [68,69].</td>
<td>Use of Geographic Information System (GIS) models in conjunction with other technologies, such as machine learning and artificial intelligence, to identify the problem and potential areas, based on the identification of biomes and vegetation that are at risk of fire, especially during periods driest of the year [69,70].</td>
<td>Use of technologies and solutions, such as water reservoirs, to control the advance of fires in forests and vegetated areas [70]. Installation of high-volume sprinkler systems [59]. Use of structures with fire-resistant materials, e.g., steel or concrete [55]. Use of fast communication and information technologies, such as the Internet of Vehicles (IoV) for information management and fire safety [71].</td>
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Table 4. Non-structural adaptation—Soft adaptation—in the face of climate change.

<table>
<thead>
<tr>
<th>Category</th>
<th>Soft Adaptation</th>
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<tr>
<td>Planning</td>
<td>Creation of dynamic adaptation approaches, avoiding the predominance of solutions that are locked into single pathways or irreversible courses of action [72,73].</td>
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<td></td>
<td>Incorporating adaptation clauses into national investment in transportation infrastructure [74].</td>
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<td></td>
<td>Transparency and coordination between different transport agencies [28].</td>
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<td></td>
<td>Development of climate-sensitive policies, legislation, and development plans that reference resilience to protect infrastructure from known and anticipated climate risks [75].</td>
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<td></td>
<td>Invest early in high-quality public infrastructure to ensure long-term climate resilience [28].</td>
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<td></td>
<td>Stakeholder participation, engagement and support—encouraging stakeholder involvement with climate adaptation needs and building resilience [14,73–75].</td>
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<td></td>
<td>Integrate climate change resilience into local government planning [28].</td>
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<td></td>
<td>Using the Infrastructure Planning Support System (IPSS), a climate adaptation modeling system, to model the cost of climate change adaptation options and road infrastructure [53].</td>
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<tr>
<td></td>
<td>Development of Emergency Management Systems [33].</td>
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<td></td>
<td>Land use planning [36,76].</td>
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<td></td>
<td>Identifying the location and functional strength of interdependencies between sectors [72].</td>
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<td></td>
<td>Quantitative assessment of the economic costs of the joint impacts of local and global climate change [46].</td>
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<td></td>
<td>Special attention to adaptation in critical evacuation routes [36].</td>
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<td>Improved integrated spatial planning in relation to road alignments to ensure that adjacent critical ecosystems [35].</td>
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<tr>
<td>Monitoring</td>
<td>Monitoring of highways, bridges and drainage systems [55].</td>
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<td></td>
<td>Periodic review of risk maps [35,76].</td>
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<td></td>
<td>Developing appropriate monitoring indicators to assess the effectiveness of adaptation measures [74].</td>
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<td>Improved weather forecasting capability and implement early warning systems [73].</td>
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<td></td>
<td>Reviewing the effectiveness of current quantitative data collection procedures for the impacts of extreme weather events and long-term climate change, with the aim of developing a cross-sectoral reporting mechanism [74].</td>
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<tr>
<td>Maintenance</td>
<td>Authorities should re-examine the security features of the relevant infrastructure and assess the risk related to their failure [64].</td>
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<td></td>
<td>Minimization of losses, increasing the efficiency and effectiveness of monitoring and maintenance of infrastructure in the fight against droughts [78].</td>
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<td></td>
<td>Enhancing adaptive capacity in scalable, modifiable, and widely diverse ways [72].</td>
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<tr>
<td>Corrective action</td>
<td>Prioritization of remedial works for sites assessed as most at risk of failure or service interruption [77].</td>
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<td>Increasing resilience in the asset renewal phase [73,77].</td>
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<td>Relocation, or even abandonment, of critical roads [36,79].</td>
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</table>

5. Conclusions

Given the urgency for studies that evaluate the impacts of climate change on critical infrastructure, this study aimed to investigate how climate threats and their corresponding biophysical impacts can impact the road infrastructure, giving special emphasis to Climate Risk Assessment and adaptation measures. To this end, a systematic literature review was conducted with a bibliometric approach that analyzed 280 qualified studies (quality and applicability) published on the topic in recent years.

The results indicate that the subject has grown over the years, especially since 2014, with the IPCC—Fifth Assessment Report Climate Change [9] publication, with articles being published in important journals such as *Science of the Total Environment, Energy and Buildings*, and *Urban Climate*. Special attention should also be given to intense research on the subject carried out in countries such as the United States, Canada, and the United Kingdom and growing research in countries with developing economies such as many countries in Africa, Asia and South America.

It is believed that although recent studies have shown several possible impacts on road transport infrastructure, there are many knowledge gaps in the international literature, such as studies that deal with the peculiarities of tropical climate countries like Brazil. At the national level, it is necessary to know and map the main threats in urban and rural regions to identify, propose and implement adaptation measures based in technical, economical and social feasibility studies, and scale of prioritization, considering the urgency to put into practice actions needed to adapt the road infrastructure.

Therefore, it is important to highlight that the cost of inaction to adaptation will increase under a changing climate. Thus, this study presents a list of adaptation measures identified in literature (including hard and soft categories), which can be considered in urban planning.
and subsidize the decision-making process. Therefore, this article is useful for policymakers, authorities, and academicians around the world by assessing the existing literature and case studies to broaden the knowledge of engineers, academicians, and authorities on the subject.

For future studies, it is important to have a deeper analysis of action strategies for adaptation, its costs and finance opportunities, of adequate governance, and to identify the main potential tools that can facilitate this process. Furthermore, it is important to identify some case studies in order to verify if some of these strategies are being implemented and to evaluate their real effectiveness. Finally, the synergy and possible trade-offs between climate change adaptation and mitigation strategies should also be evaluated.


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Conflicts of Interest: The authors declare no conflict of interest.

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