Sustainable Road Infrastructure

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The implementation of sustainability in road infrastructure has become dependent on providing measurements and guidance for including sustainable principles in road projects, resulting in a dozen voluntary certification and rating systems to evaluate the level of sustainability of road design, construction, and maintenance. The predominance of issues which analyse the life cycle assessment of road infrastructures in its both environmental and economic dimension as a way to mitigate their effects on climate change, including the reduction of resources and energy consumption, or of energy consumption and greenhouse gases emissions during the construction and operation stages, respectively.

sustainable road · sustainable highway · green road · green highway · rating systems · sustainability

1. Introduction

Road transport shows important advantages in comparison to other modes of transport, for example accessibility, adaptability to individual needs [1], the promotion of robust and sustainable regions [2]. Road transport also delivers economic benefits [3]. In consequence, a huge global road infrastructure network is operating nowadays, and it is expected to increase by 2050 [4], resulting in the main used transport mode in European countries [5] which includes strategic infrastructures in the economic [6][7] and social [6] development of countries.

Road infrastructure integrates all road categories as the main element [8], as well as a set of facilities, structures, signage and markings, and electrical systems, to guarantee safe and efficient traffic [9]. This infrastructure has significant environmental impacts during all its life cycle stages, i.e., construction, operation, and maintenance, including: consumption of natural resources (raw materials and energy), airborne emissions, acoustic pollution, ground and surface water contamination, habitat disturbance, land use or negative effects on plants [10], lighting disturbances [11], wildlife or animal movement [12], soil acidification produced by nitrogen oxide emissions, or chemical effects of road dust [11], among others. Besides, worldwide, the transport sector produces 32% of greenhouse gas (GHG) emissions, of which 75% are related to road transport [13], of which the largest portion is produced during the road operation phase due to vehicle exhaust fumes [14]. Besides, large quantities of natural resources are consumed during road construction and maintenance; in fact, roads consume about 60% of natural resources [15]. On the other hand, large amounts of waste are produced in road construction, leading to a significant negative environmental impacts and climate change effects [16]. In consequence, the construction, operation, and maintenance of roads have clear effects on climate change [16]; besides, road transport has also negative effects from a social point of view, for example because of the high mortality rate associated with traffic accidents worldwide [17].

To solve the problems described above, and according to the sustainability concept reported by Bruntland in 1987, environmental impact, social equity, and economic efficiency are dimensions that have to be prioritised by governments [18] for sustainable road development throughout all the stages of its life (planning, construction, maintenance, and disposal) [19], as a way to ensure economic growth and social development, as well as environmental safety [20]. As a result, the implementation of sustainability in road infrastructure has become dependent on providing measurements and guidance for including sustainable principles in road projects [21], resulting in a dozen voluntary certification and rating systems to evaluate the level of sustainability of road design, construction, and maintenance. These systems give a set of guidelines to achieve more sustainable road transportation to road transport infrastructure designers and managers [22]. Despite all of this, and taking into account the need both to implement measures to mitigate climate change and also to adapt to it, nowadays, it is necessary to implement new key milestones included in different agreements or planning in the concept of sustainable road infrastructure in Europe. This is the case of the 2030 Agenda for Sustainable Development, the European Circular Economy plan, and the European Green Deal.

The 17 Sustainable Development Goals (SDGs), which are part of the 2030 Agenda for Sustainable Development, include a total of 169 targets aimed at people, planet, prosperity, peace, and partnership [23]. In this framework, road transport can help deliver on some of the targets of the SDGs, including: SDG2 (zero hunger), on the basis of the key role of road transport in making sure that workers, equipment, products, and food get efficiently and quickly to people; SDG9 (industry, innovation and infrastructure), because of the importance of infrastructure in the connectivity between economies for trade in goods and services, and between the people who trade; SDG11 (sustainable cities and communities), in relation to the prominence of road infrastructure in mobility and logistics networks in cities; SDG13 (climate action) because of the importance of road transport in the decarbonization of the sector, from the energy source to the energy use, including the uses of resources in the construction and maintenance stages; and finally, SDG17 (partnerships and collaboration), in relation to the crucial and necessary public–private collaboration. On the other hand, the first European Circular Economy Action Plan, Closing the loop, in 2015, as well as the New Circular Economy Action Plan, For a cleaner and more competitive Europe, adopted by the European Commission in 2020, aim at the implementation of the 3 Rs principles (Reduce, Reuse, Recycling). These principles also influence infrastructure design [24], providing the idea of sustainability and green construction, and reducing environmental damage through the recycling and reuse of waste and reduced use of resources, materials, and energy [8], as well as finding ways to reduce the emission of greenhouse gases and other emissions released from fossil fuels [25]. Finally, the European Green Deal adopted a set of proposals for reducing net greenhouse gas emissions by at least 55% (compared to 1990 levels) by 2030. The European Green Deal emphasised important targets that are necessary in the transport sector in order to achieve a 90% reduction of greenhouse gas emission by 2050 [26].

As a result, the need to fulfil the cited new key milestones in terms of sustainability, as well as the severe effects of the increasing temperature, precipitation and storm events, and rising sea levels on road infrastructure, as a consequence of climate change [27][28][29][30][31], make it necessary to evolve towards the concept of resilience, which is defined as “the ability to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner” [32]; in fact, the ability of roads to be adapted to climate change is understood not only as part of mitigation, but also resilience. On the other hand, nowadays the concept of smart roads, referred to those that improve user, vehicle, and infrastructure connections, is achieving an important role for more efficient, safe, and sustainable roads; definitely when on the subject on resilient roads [33].

2. Sustainable Road Transport Systems

During the operational stage, traffic operation takes places in a complex system including road infrastructure, vehicles, vehicle operation, and weather conditions. In consequence, the improvement of traffic management and road safety are important roles in the sustainable road concept [34]. In fact, the sustainable road transport theme has been included in the keywords co-occurrence analysis in Cluster 1 (red), with the highest number of keywords. It includes a high number of keywords related with energy sources, fuels, electric vehicles, and also road systems, traffic, and transportation safety.

In consequence, even though road transport plays an important role in economic development and social integration, it also affects negatively to the environment and society [35]. Thus, road transportation activities and facilities have impacts on the economy (traffic congestion, mobility barriers, accident damage and costs), society (human health impacts and community interaction) and the environment (air and water pollution, non-renewable resources depletion) [36]. Besides, the classic approach to traffic design aims to increase the level of mobility, so it is important to plan transport infrastructure and cities without reducing the necessary traffic [37]. This is why the reduction of the emissions and energy use associated with the transport services is considered a strategic issue of energy policy [38].

As road transport, utilising a huge amount of fossil fuel is considered worldwide as a significant source of pollutant emissions [39], causing global warming and fossil fuel depletion. The total energy consumption, total number of fatalities, and greenhouse gases emissions are approaches to evaluate the development of sustainable road transport systems [40]. Therefore, countries must take more serious actions on CO_2 emission reduction and energy saving initiatives in this field [41]. In this sense, sustainable transport should contain a set of components to increase its efficiency with respect to environmental, social, and economic aspects [5]. Hence, the implementation of alternative transport fuels and vehicles is important in order to achieve energy saving and preserve air quality; thus, electric vehicles or eco-driving contribute significantly to sustainable road transport through cost reduction and environmental protection [42]. On the other hand, improvements to the rechargeable batteries of electric vehicles in their cycle life, in terms of their energy and power density, are important to increase electric energy storage to achieve a green road transportation system [43]. As a result, the vehicle electrification could provide GHG reduction potentials of 2–6% [44] of air pollution, and reduce noise, enabling pleasant and safer driving, and providing community welfare [45].

3. Materials for More Sustainable Pavements

The relevance of materials used in pavement have been highlighted in the analysis of themes and this topic is clearly identified in Cluster 2 (green) of the keywords co-occurrence analysis, including 54 keywords. It contains a huge number of keywords related to pavement, recycling, waste management and aggregates, identifying road sustainability through pavement design, the materials used, and waste recycling.

Other stages, such as materials production and road maintenance and rehabilitation, contribute substantially to GHG emissions as well, highlighting the importance of optimizing the management of these stages.

The construction, operation, and maintenance of pavements consume a huge amount of natural energy and material resources, inducing environmental impacts. In fact, asphalt, with an annual worldwide production of over 1 billion tons for paving operations, is one of the most extensively used materials in the road construction industry [46]. The scarcity and rising cost of aggregates have forced highway agencies to develop new engineering strategies in the pavement sector to reduce the costs of road pavements construction and maintenance and improve their environmental performance, by using solutions moving toward sustainable pavement practices [47]. The strategies developed include: the use of reclaimed asphalt pavement as an alternative pavement design for new construction, maintenance, and rehabilitation projects [48], as well as more recycled and environmentally friendly materials [49].

The use of reclaimed asphalt pavement as a recycled material in road construction is a valuable strategy to preserve natural energy and resources and to construct sustainable pavements [46][50]. In fact, in Europe, 47% of the available reclaimed asphalt pavement was utilised in warm or hot mix asphalt applications, and 22 million tons were utilised in other road construction applications stockpiles [51]. In USA, 71.8 million tons were accepted in 2011, 84% of which were utilised in road construction [52]. Because the recycled asphalt is not sustainable when degraded, whereas 100% hot mix asphalt performs the materials cycle by fully using the valuable materials in reclaimed asphalt in high quality road constructions [37], the reuse of hot recycling and construction waste results in good quality materials that can be used to construct sustainable and durable pavement structures [53].

On the other hand, reducing the virgin aggregate and binder content in warm and hot mix asphalt, reducing the emissions generated in mixture production and the energy consumed, and implementing preventive treatment are approaches to improving the sustainability of pavements [54]. To do that, some of the solutions mentioned in the literature are: long-lasting pavements [55]; industrial by-products and waste [56]; reclaimed asphalt pavement materials [57]; pavement preservation strategies [58]; and asphalt mixes requiring a lower manufacturing temperature [59].

Finally, alternative materials have been used for sustainable pavement, for example: stabilised quarry fines [60]; construction and demolition waste, fly ash, and jet grouting, as fillers [61]; fly ash as a stabiliser, which at 30% of total content improves the pavement resilience, although more than 30% reduces the pavement performance [48]; high pozzolanic mineral admixtures like silica fume could be used to make high quality pavement that is more economic, durable and environmentally friendly [62]; and rubber-modified asphalt improves the pavement performance in both low and high temperature conditions [63], providing a sustainable solution for the urban solid waste which is generated by waste tyres [64][65].

4. Tools for Roads Sustainability Assessment

With the increased concern about sustainability, several efforts have been made to develop assessment methods, indicators, assessment tools, and rating systems [66]. In fact, the sustainability assessment theme of Cluster 5 (purple) in the keywords co-occurrence analysis contains a large number of keywords related to life cycle assessment, environmental impact and costs.

One of the most commonly applied techniques to measure the impacts of roadway design along its service life [67] is a life cycle assessment (LCA). The estimator in this approach divides the service life of the pavement into the following stages: material production, construction, maintenance, rehabilitation, and end of life. As LCA is related with measuring only the environmental impacts, life cycle sustainability assessment (LCSA) is considered an appropriate approach to evaluate the pavement sustainability, embracing environmental life cycle assessment (E-LCA), social life cycle assessment (S-LCA) and life cycle cost analysis (C-LCA) [68]. The pavement C-LCA, published by the American Association of State Highway and Transportation Officials (AASHTO) in 1960, and the pavement E-LCA framework have been widely developed [69]; however, pavement S-LCA is still in an underdeveloped state, but its integration into pavement management is highly recommended [70].

On the other hand, given that the implementation of sustainability in road infrastructure has become focused on providing measurements and guidance for including sustainable principles in road projects [21], the use of a rating system to meet certain mandatory and minimum prerequisites could be a useful tool [71]. In this sense, a dozen voluntary certification and rating systems have been developed to evaluate the level of sustainability of road or roadway design, construction, and maintenance, including: CEEQUAL, Envision, BE2ST in-Highways, GreenRoads, GreenLITES, Invest, GreenPave, I_LAST, STARS, IS, and LEED ND [22]. Despite these systems being based on a set of best practices and showing a potential for supporting road projects managers in achieving environmentally sustainable, resilient, and smart transportation road infrastructures [21], new research is required to better develop these systems [66].

5. Adaptation of Road Infrastructure to Climate Change

Climate change may present both opportunities and risks for the management of the road infrastructure network [29][72]. Thus, changes in climate can lead to a decrease of the stress imposed on roads, however the effects on roads as a consequence of climate change have been reported in terms of the effects of high temperatures, daily temperature variation, heat waves increase, thawing and thawing permafrost and freezing, precipitation increase, low precipitation and drought conditions, changes in yearly precipitations, rising sea levels, river flow patterns, more frequent storm cyclones, and increasing forest fires [28]. Some of the effects reported include: reduction of pavement life [28][73], thermal expansion at bridge joints [74], rutting of flexible pavements [31][75], longitudinal and fatigue pavement cracking [76], effects on pavement roughness [77], changes in landscape/biodiversity [28], landfill instability caused by thawing [78], roads sinking and pipelines, pavement layers and bridge collapse [79], occurrence of differential freezing [80], avalanches and rockslides [81], ground stability impacts [82], loss of soil cover [83], increased susceptibility to wildfires, risk of runoff flooding, landslides, slope failure [28], erosion of road platforms and adjacent land [83], submergence of roads [84], saturation of unbonded layers (Knott et al., 2019), erosion of the road base and its structures [28], and higher salinity which affects asphalt and blockage of drainage systems [83], among others.

In consequence, preventive actions are necessary to protect and adapt road infrastructure against future impacts of climate effects and reduce maintenance costs [72]. Although Clusters 4 (yellow) and 6 (sky blue) in the keywords co-occurrence analysis include some keywords that could be related with effects of climate change, for example storms or drainage, the keyword adaptation has not been specifically identified among the most relevant themes. This means that the incorporation of the adaptation of road infrastructure to climate change is still an early stage in terms of sustainability.

6. Smart Road Infrastructure

The term “smart” is the acronym for Self-Monitoring Analysis and Reporting Technology and it is used to describe the availability of innovative technologies in different scopes. The smart road concept refers to road infrastructure that improves its operational capability to meet the major challenge of connecting users, vehicles, and infrastructure in an intelligent, efficient, safe, and sustainable manner, as well as improve the maintenance of roads [33]. This concept means the use of Information and Communications Technologies (ICT) in road infrastructure operation and maintenance, which can transfer data in real time to avoid accidents and delays, and allow damage detection of pavements, etc., but also the use of so-called intelligent materials [33].

The key functions of the smart road, in terms of the use of ICT, are [33]: self-awareness, information connection, self-adaptability, and energy harvesting. Thus, sources such as drones, sensors, cameras, satellite systems, among others, installed in different components of a road infrastructure are Big Data resources [85] and allow the sharing of information, connection, and cooperation. For example, they can be installed in pavement for temperature, moisture or structure damage detection and sub-grade/soil settlement and slope monitoring [86]; but they can also be used for traffic flow monitoring and management [33] to provide feedback to traffic managers, but also to users of vehicles to support their decision-making, as well as being connected to autonomous vehicles in the future to allow automatic adaptation to the circumstances of the traffic, weather, etc. On the other hand, road infrastructure can be seen as a suitable scenario for the use of clean energy, with the promotion of the use of electric vehicles [87][88], but also for its production thanks to the collection of solar, thermal, and mechanical energy from pavements, sub-grade, and other infrastructures [89]. Finally, intelligent materials are considered to be materials that are aware of their state and properties, monitored automatically and maintained proactively, with the objective of reducing carbon emissions and the consumption of resources or energy, namely, to be environmentally responsible. For example, materials sensitive to light and temperature have been developed to paint road pavements [33]; on the other hand, materials with the self-healing or self-restoring abilities have been developed for pavements thanks to the use of nano-particles, induction heating, and rejuvenation [90][91]. Induction heating also represents an active research field in safety design for the electric melting of ice and snow [92].

In short, smart roads can achieve greater resilience of the infrastructure. In consequence, this concept should be included in researching the sustainability of road infrastructure, both for the development and application of technologies to support it, and for the development of a framework of indicators to evaluate the implementation level as a tool to define strategies for planning. However, the contribution of the smart road infrastructure concept to sustainability is still in the early stages of development; in fact, the co-occurrence analysis of this research has only identified a few keywords clearly related with it, for example, intelligent artificial in Cluster 5 (purple), which has been identified with the theme of sustainability assessment and intelligent systems, intelligent vehicles, electric vehicles, or traffic control in Cluster 1 (red), related to sustainable transport.

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