Environmental Aspects of Rail Transport

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The development of railways stands as a pivotal milestone in the history of transportation, transforming the world and revolutionising the movement of people and goods. From their humble beginnings as rudimentary track systems to the sophisticated and interconnected networks we witness today, railways have played a crucial role in fostering economic growth, promoting globalisation, and shaping modern societies. Railways have long been recognised as one of the most environmentally friendly means of mass transit, offering lower carbon emissions, energy efficiency, and reduced congestion compared to other transportation modes. However, there are still many challenges to overcome to provide continuous sustainability in the context of environmental impacts, especially related to wildlife and habitat protection.

railway transport ecology wildlife traffic safety

1. Noise Pollution

Noise pollution can be considered any disturbing or unwanted sound that affects the well-being and mental, emotional, and physical health of humans or other organisms. Among the symptoms of the effects of noise pollution on organisms, we can distinguish dissatisfaction, anxiety, and irritation. In addition, it can result in the development of conditions such as hypertension [1], sleep problems [2], incomplete functional capacity [3], or even hearing loss [4]. Generated noise also has a negative impact on wildlife; it can negatively affect the habitat of wild species and their behavioural behaviour. Controlling noise pollution is therefore one of the key aspects of making transportation sustainable [5].

One source of noise pollution is rail transport. This phenomenon is particularly troubling in highly urbanised areas where tracks are close to human settlements [6]. Noise levels above 55 dB (A) are considered noise pollution for humans [7]. At the same time, the sound emitted by rail vehicles can be higher, reaching values close to 100 dB(A) [8]. It is estimated that 22 million people are exposed to excessive noise in the European Union alone [9]. Rail noise pollution can be of the nature of an acoustic wave propagating through the air or vibrations emitted onto the ground during the passage of a train set [10]. The sources of noise pollution from rail transport can be described as complex, resulting from both the mode of operation, the construction of the rail vehicle, and the infrastructure. Among the causes that arise from the mode of operation is the use of a train horn in certain situations, such as when passing a level crossing. Noise sources related to the construction of the rail vehicle include the sound emitted in front of the vehicle's propulsion system, its equipment (HVAC), aerodynamic noise at high speeds, braking systems, and the noise emitted by rolling elements such as bearings or wheels [6][11]. The noise generated

by the latter is particularly related to the infrastructure of the rail vehicle. One phenomenon with a significant impact on noise pollution is wheel-rail contact [12].

This noise takes various forms. The main one that we can mention is the rolling noise that occurs on a straight track. It is characterised by emissions over a wide frequency range. It is the result of phenomena related to direct contact between the wheel and the rail and is influenced by the wear of both, including the formation of roughness and unevenness. Particularly annoying impulse noise is also generated due to discrete elements such as wheel flats and the passage through rail joints or turnouts [13]. Very high noise levels, especially in urban areas with small radius curves, are caused by the squealing when passing through them due to the increased contact between rail and wheel [12].

Also problematic is the transmission of low-frequency vibrations to the ground during the passage of a rail vehicle, known as ground-borne vibrations [14]. Negative effects include adverse health effects and the degradation of infrastructure in the immediate vicinity of the rail tracks. Studies have shown that, in some cases, vibrations caused by passing trains can increase heart rate during sleep by 3 beats per minute, which, in the long term, can affect cardiovascular function [15]. Evidence was also found of a negative effect of ground-borne vibrations on the body's regenerative capacity, which impairs the long-term stress response [16]. It has also been shown that ground-borne vibrations can negatively affect wildlife [7].

Reducing noise pollution is an important element in ensuring sustainable rail transport. In the European Union, the harmonisation of solutions to reduce noise emitted by rolling stock is realised by the technical specification for interoperability 'Rolling stock—Noise'. Strategies to reduce noise pollution can be divided into solutions to limit its generation at the source and to prevent its propagation (scheme shown in **Figure 1**) [14].

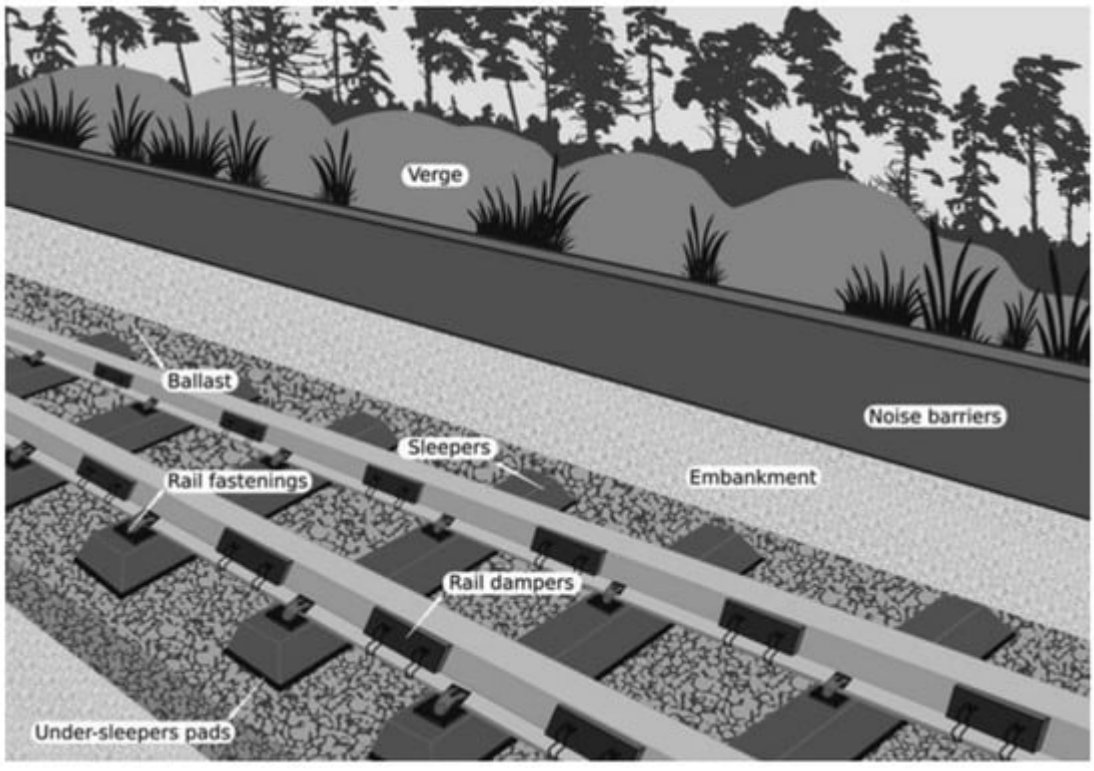

Figure 1. Schematic drawing of a railway showing some measures to minimise noise and vibration: rail fastenings; rail dampers; under-sleeper pads; and noise barriers (not at scale) [6].

The first approach requires technological and structural changes to the rolling stock and infrastructure. Rail vehicles can be upgraded with noise-reducing solutions. These include the installation of noise barriers in vehicle traction equipment, optimising wheel geometry, using appropriate suspension and dampers, and, in the case of high-speed trains, improving aerodynamics [17][18]. Another method is to change the materials used to make rail vehicle parts or modify their dynamic properties [19]. A particular type of design solution is the replacement of steel brake blocks with their composite counterparts. According to the TSI Rolling Stock Noise, the use of steel brake blocks will be banned from 2024 on lines defined as 'silent' [6]. Infrastructure solutions can include the modernization of railway tracks via the use of non-jointed rails, such as continuously welded rails that eliminate impulse noise associated with the passage of wheels through joints, the reduction in turnouts, and the use of damping sleepers [12][14]. An important aspect is the maintenance of the already upgraded infrastructure. The grinding of the rails alone can reduce the noise emitted by 3 dB [20]. Another solution is the use of automatic wheel flange and rail lubrication systems to reduce friction and noise, particularly when crossing curves [6]. The use of elastic pads on the sleeper was highly effective in reducing the vibrations transmitted to the ground, reducing them by 16 dB [21].

Noise propagation is reduced, among other things, by the use of trenches and embankments. Although these solutions require the occupation of a large strip of land, they are environmentally friendly and effective, achieving noise reductions of 25 dB. Noise barriers are also used; these structures can be made of soil, wood, concrete, or metal and can be an important tool to minimise the negative impact of sound on both people and wildlife, especially for species that are extremely sensitive to it. Green barriers, such as dense vegetation, can also be used and, in certain cases, provide an effective barrier against noise propagation [6][7].

Summarising the concerns of this subsection, many studies indicate that rail transportation can contribute to high levels of noise pollution, especially in areas near railroad tracks and stations. The continuous passage of trains, with the accompanying vibration and mechanical noise, can disturb human and wildlife behaviour. Despite legal regulations regarding noise restrictions and the implementation of damping technologies, the problem persists. To address noise pollution, several mitigation measures can be implemented. These include the use of noise barriers, sound insulation for buildings near railway tracks, and the development of low-noise train technologies. Furthermore, adopting quieter maintenance practices, implementing speed restrictions in areas sensitive to noise, and incorporating noise reduction strategies during the planning and design of the railway infrastructure can significantly contribute to minimising the impact of noise pollution.

2. Emissions

Atmospheric emissions from rail transport are considered to be lower than those from other modes of transport. Moreover, it is characterised by its high energy efficiency. For these reasons, the development of railways is eagerly being promoted as a sustainable transport solution [22][23]. However, this does not mean that this branch of

transport is completely environmentally neutral and is also characterised by the generation of harmful pollutants [24].

In the case of rail transport, we can divide emissions into direct and indirect. Direct emissions are associated with the operation of rolling stock, particularly those powered by traditional fossil fuels. They include greenhouse gases such as carbon dioxide (CO_2), hydrogen oxides (HC), and nitrogen oxides (NOx) resulting from the combustion process occurring in diesel vehicles. Additionally, airborne particulate matter (PM) is a pollution problem. PM refers to fine solid or liquid particles suspended in the air. It includes both fine particles (PM2.5) and coarse particles (PM10) [25][26]. PM emissions from rail transport can be due to diesel engine exhaust, brake wear, or abrasion of the track [27].

Indirect emissions in rail transport are related to ensuring the proper operation of infrastructure and rolling stock that are not produced directly by rail vehicles. Examples include the emission of greenhouse gases and particulate matter through power plants that provide energy to electrically powered rolling stock [28], harmful emissions from equipment used to maintain rail transport components, or pollution generated during the rolling stock production and maintenance process [29].

Various methods can be distinguished for reducing the atmospheric emissions of greenhouse gases from rail transport. The European Union has adopted emission standards for the NRMM (Non-Road Mobile Machinery) vehicle category, which includes rail vehicles. The standard provided limits for toxic compounds and PM mass emissions. As a result, rail vehicles were forced to be designed with better emission characteristics [30]. Another method is the transition from train sets consisting of diesel-powered units to those powered by more environmentally friendly energy sources. The primary method is the electrification of railway lines. By investing in a traction infrastructure capable of supplying electricity, the use of diesel units on electrified lines can be eliminated, directly contributing to reducing atmospheric emissions. To achieve total zero emissions, it is also necessary to modernise the sources of electricity that supply the catenary network, among other things, by replacing power plants fuelled by mine gases with plants that use renewable energy or nuclear power [28]. Another example of replacing rolling stock with more environmentally friendly vehicles is the use of hydrogen-powered units [31].

Another measure being taken to reduce the emissions of rail transport is to increase the energy efficiency of rolling stock, which is one of the most important ways to ensure the sustainability of rail transport [32]. This includes the use of lighter materials in trains, the implementation of braking systems that allow energy recovery, and the improvement of the aerodynamic properties of rail vehicles [33][34]. Ensuring adequate energy efficiency can be achieved not only via interventions in the design of the rail vehicle but also via appropriate planning of railway lines and train stops along the route. Studies have shown that, at higher maximum speeds, intercity and express trains have lower energy consumption per passenger-kilometre than suburban and regional trains. This is due to their different stopping cycles. Accelerating a train when it has reached a complete stop is highly energy-intensive, which, for trains that frequently stop in stations, results in increased overall energy consumption [32]. This shows that emission reductions in rail transport must take into account a wide range of factors and be limited not only to

on-site emission reductions but also to ensuring adequate energy efficiency as well as the provision of clean energy at the source, i.e., at power plants.

Although railway transport is known for its relatively low carbon emissions compared to other modes of transport, such as road or air transport, diesel-powered trains and outdated infrastructure can still contribute to emissions of greenhouse gases and air pollutants. Improving air quality near rail tracks is essential to safeguarding the health of both wildlife and humans. Therefore, implementing effective air quality monitoring, employing emission control technologies, and ensuring proper maintenance of locomotives and rolling stock are critical to minimising the direct impact of emissions on wildlife habitats and urban areas adjacent to rail tracks.

3. Direct Threats to Wildlife

Among the direct environmental threats posed by the unsustainable development of transportation networks are environmental fragmentation, leading to the loss of genetic diversity in the area, habitat loss, and increased animal mortality [35][36][37]. Many studies on that topic concern roads and highways [38][39] instead of railways. The issue remains the same, but the degree of impact differs [40]. Tracks cross wildlife habitats and animal migration routes [41] (often defined as so-called ecological corridors or habitat connectivity corridors), affecting the lives of wild animals in various ways.

The behavioural barrier effect [42][43], also known as the barrier effect or the fragmentation effect, refers to the impact of transportation infrastructure, such as railways, on wildlife populations and their movement patterns. Railroads can act as physical or psychological barriers that impede or disrupt the natural movement and behaviour of wildlife, leading to fragmentation, isolation, and potential negative consequences for ecological connectivity. This barrier can act on large ungulates, birds, reptiles, small mammals, and insects, such as bumblebees [35][43][44].

Railways can divide wildlife habitats, separating populations and fragmenting larger ecosystems [45]. The presence of railways can create isolated patches of habitat, limiting the movement of animals across their natural ranges. This fragmentation can have adverse effects on the ability of wildlife to find suitable resources, mates, and territories, leading to reduced genetic diversity and potentially increasing the risk of local extinction. One of the basic conditions for the preservation of biodiversity is to ensure the continuity and permeability of ecological corridors. Fragmentation caused by rails can impede gene flow among wildlife populations. Limited movement and reduced opportunities for interbreeding can lead to genetic isolation, inbreeding, and a decrease in genetic diversity. This can ultimately affect the long-term viability and adaptability of wildlife populations, making them more susceptible to environmental changes, diseases, and other threats to the balance of ecosystems [46][47].

In addition to genetic threats to biodiversity, railways can disrupt the natural movement patterns of wildlife, which may rely on certain corridors or migratory routes for foraging, breeding, and dispersal. Animals may be reluctant to cross railway lines due to the noise, vibrations, and perceived danger associated with trains. This disruption can result in altered migration patterns, reduced access to critical resources, and increased energy expenditure for wildlife as they seek alternative routes and stress levels. These changes in habitat use, resource selection, and

social dynamics can become a lasting behavioural modification [48] that can have cascading effects on the entire ecosystem, including changes in predator-prey dynamics and changes in the composition of the plant community.

This cascading effect is also related to increased mortality caused by collisions between wildlife and trains, which alter the size of animal populations in a particular territory. Animals, especially those with lower mobility or slower reaction times, such as reptiles, amphibians, and larger mammals, may be at higher risk of collisions with trains or other railway infrastructure. These collisions can result in injuries or deaths for wildlife populations, further exacerbating the impact of railways on their survival. According to research conducted in Montana in the United States, bear-train collisions were twice as frequent on a railway compared to a parallel road and were the second highest cause of mortality after poaching [49]. The significance of mortality correlates with many factors, such as the speed and size of trains, the lack of escape routes, the attraction of animals to the tracks (for example, the warmth of the tracks can attract reptiles seeking heat, and vegetation growing along the tracks may offer a food source for herbivores; litter and food scraps discarded by people on the train can attract bears (**Figure 2**) or wild boars; and the bodies of animals killed in collisions with the train can result in the presence of scavengers) [50].

Figure 2. A grizzly bear in Banff National Park, Canada, attracted by leftover food thrown from the train [51].

The frequency of collisions between wild animals and trains is influenced by the nature of the landscape, the number and concentration of animals in the area, the height of the railroad embankment in relation to the natural terrain, and seasons of increased animal migration. In addition, it depends on the volume of traffic, the speed of vehicles, the construction technique of the line, and the distance from human settlements [46][52]. A higher frequency of accidents occurs at night, especially at dusk and dawn, as well as in autumn and winter, which may be related to the fact that the population of ungulates increases in autumn, when they then form larger herds in which they migrate to winter feeding grounds [53]. Weather conditions also have an impact: the presence of thick snow cover (in Scandinavian countries and Canada) causes increased moose mortality during the winter months [54]. The blocking of tracks by moose, which use the tracks as a path in snowdrifts, is shown in **Figure 3**.

Figure 3. A moose deny to leave the railroad tracks near Caswell, Alaska [55].

Generally, collisions occur in grassland near forests in sparsely urbanised areas. Tourism-related expansion, climate change, and hunting are altering animal behavioural patterns and disrupting animal migration, which can result in increased animal disorientation combined with the unpredictability of their reactions (and a higher likelihood of collisions).

Except for strict collisions, there are also fatal accidents associated with electrocution, rail entrapment, and wire strikes [40]. Negative impacts of the railway infrastructure, specifically tubular poles that support the catenary, were observed in the form of creating pitfall traps for nesting birds and causing their deaths [56].

Another aspect is habitat alternation, related to construction and operation of railways. In addition to the zoning of land for the construction of the line, which involves clearing the forest and cutting down vegetation, the noise factor and traces of human presence are also important, as they disturb the ecosystem.

In the context of driving safety, which is part of the idea of sustainable transport development, attention should be paid to the risks to rolling stock, passengers, and cargo that accidents involving animals raise. Accidents with animals and the consequent measurable damage are especially experienced by passenger trains [57] due to the higher speed of travel and type of vehicle design (electric or diesel multiple units are more prone to collision damage than massive locomotives of freight trains). A collision involving large animals (e.g., deer, bears, elk, and elephants) can cause serious damage to a traction vehicle or locomotive, and a collision with a herd, in extreme cases, results in a train derailment. Among the vehicle components most susceptible to damage are body panels, headlights, windshield, suspension system, cooling, and fluid-containing systems. Furthermore, sudden braking

can injure passengers and destroy cargo, especially if it is fragile. However, in most incidents, the arrival of the trains is delayed and schedules are disrupted, which brings financial and image losses to the rail carriers.

Addressing the risk of train-wildlife collisions requires a comprehensive approach that includes identifying high-risk areas, implementing wildlife mitigation measures, imposing speed restrictions and warning systems, and providing public awareness and education. Conducting surveys and analysing collision data to identify locations where wildlife mortality is more prevalent can help prioritise mitigation efforts, such as constructing wildlife crossing structures, installing fencing along tracks, or implementing vegetation management strategies to reduce wildlife attraction, which can help minimise the risk of collisions. Additional enforcement of speed limits in wildlife-sensitive areas and the implementation of effective warning systems, such as sound devices or vibration systems for early detection of the presence of animals near railroad tracks, can provide additional safety measures for both animals and train operators. Methods to reduce the number of collisions and their effectiveness are described in detail in [58]. Among the many different approaches worth mentioning are innovative methods of informing about an approaching train in the zone of potential collision with wildlife based on rail vibrations studied in Canada [59] (**Figure 4**) and animal crossing projects studied in Sweden [60] (**Figure 5**) or Japan [61], combining infrastructural methods with acoustic deterrents.

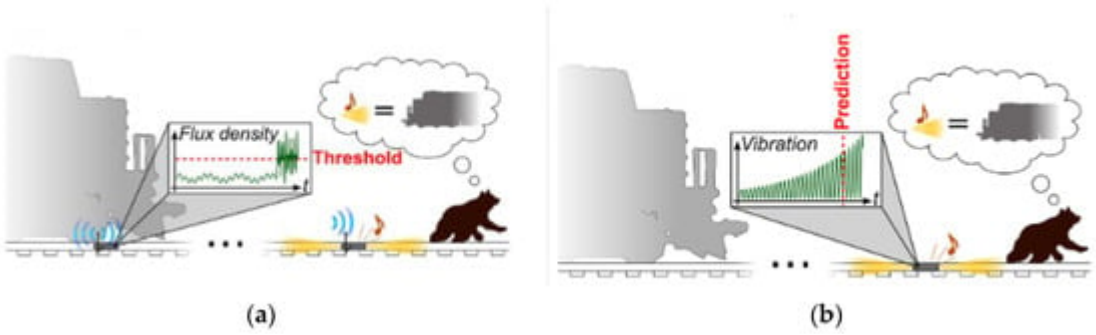

Figure 4. The idea of a wildlife alert system that is activated by trains tested on a freight railway within Banff National Park, Alberta, Canada and Yoho National Park, British Columbia, Canada, Yoho. (**a**) The passing relay relays triggers to a remote warning device using a sensing device to detect trains. (**b**) The approach detector combines integrated warning signals and vibrations in the train to find distant trains [59].

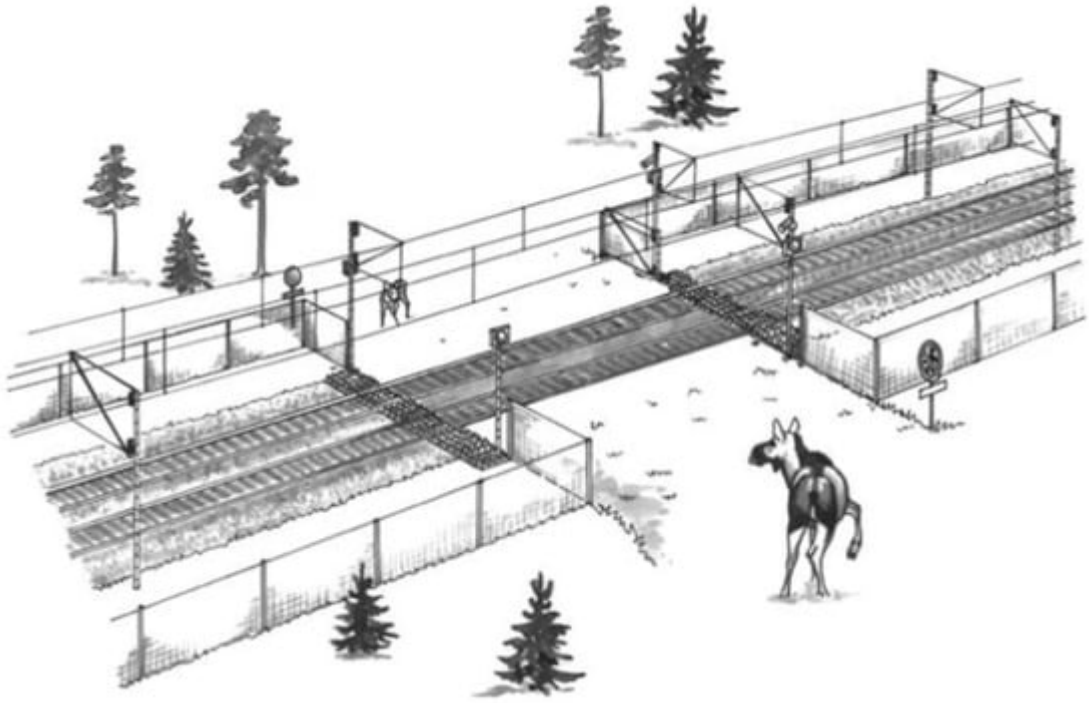

Figure 5. Schematic of an experimental animal crossing at track level, combining infrastructural methods and acoustic animal shooing systems triggered by the signal of an approaching train (investigated in Sweden) [60].

However, despite the use of various technical solutions (e.g., animal crossings, culverts, guide fences), the barrier effect, or the increased mortality of animals due to collision cannot be completely reduced [62]. Without a doubt, by implementing measures and adopting wildlife-friendly practices, it is possible to further mitigate the negative impact of railroads on the environment, protect wildlife populations while increasing the safety and reliability of rail traffic, and promote co-existence between transportation infrastructure and biodiversity conservation.

In discussing this subsection, it is worth observing how railway transport poses direct threats to wildlife populations. Collisions between trains and animals can result in injuries and fatalities, adversely affecting species populations and ecosystem dynamics. Larger mammals, such as deer, moose, and bears, are particularly susceptible to these collisions due to their size and slower movement patterns. The behavioural barrier effect, which leads to fragmentation of ecosystems and disruption of biodiversity, is difficult to minimise. In addition, the construction of railroad lines often causes habitat loss. The establishment of wildlife crossing structures, using animal deterrence systems and signals for early detection of the presence of animals on tracks in hotspot areas, can provide safe passages for animals to navigate across railway tracks, reducing the risk of collisions. These structures should be appropriately designed, considering the movement patterns and specific needs of the target species.

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