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MATERIAL INFLUENCE ON THE PERFORMANCE APPEARANCES OF PASSIVELY SAFE POLES

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Abstract

Roadside poles, including those used for lighting, traffic signs, and monitoring systems, play a critical role in traffic safety. Collisions between vehicles and such poles can cause severe injuries and vehicle damage. To mitigate these risks, the paper analyses the possibility of applying passively safe poles, as an alternative to the traditional poles. Unlike traditional rigid poles, which cannot absorb energy in the event of a vehicle impact, so it is transferred to the vehicle, passively safe poles can absorb energy and deform or break in a controlled manner, reducing vehicle deceleration and the risk of serious injuries to passengers. This paper examines how different pole materials (steel, aluminium, and composite) affect energy absorption, impact performance, and occupant safety. It also investigates the influence of environmental conditions on pole durability, with a focus on corrosion mechanisms, including atmospheric and stray current–induced corrosion. Various corrosion protection methods, such as coatings and sacrificial anodes, are analyzed along with monitoring techniques for assessing pole integrity. The results demonstrate the relationship between material properties, impact energy dissipation, and long-term structural reliability, providing a technical basis for material selection and design of roadside poles in diverse environmental conditions.

Keywords: road infrastructure, traffic safety, passively safe poles, energy absorption, corrosion, corrosion protection

1 Introduction

According to the World Health Organization (WHO), approximately 1.19 million people are killed each year in road traffic accidents worldwide, while an additional 20 to 50 million people sustain serious injuries [1]. Road traffic injuries therefore represent a major global public health and safety challenge. Analyses of road accidents that occurred in the European Union between 2012 and 2022 indicate that, in recent years, approximately 35% of all road fatalities resulted from single-vehicle crashes [2]. These crashes include collisions with fixed and non-fixed roadside objects and animals (excluding pedestrians and parked vehicles), as well as run-off-road and rollover accidents. A significant proportion of such events involves vehicle impact with fixed roadside objects, accounting for approximately 20% of all road fatalities [3]. These statistics clearly demonstrate the need to improve road safety not only through enhanced driver awareness and behavioral measures, but also through the implementation of safer road infrastructure. One effective infrastructure-based approach is the application of passively safe poles as supports for lighting, traffic signs, and monitoring systems, as an alternative to the traditional poles. Unlike traditional rigid poles, which cannot absorb energy in the event of a vehicle impact, so it is transferred to the vehicle, passively safe poles are designed so that they can absorb energy and deform or break in a controlled manner, reducing vehicle deceleration and the risk of serious injuries to passengers.

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The consequences of a vehicle impact on a rigid and passively safe pole, which can absorb energy, can be seen in figure 1.

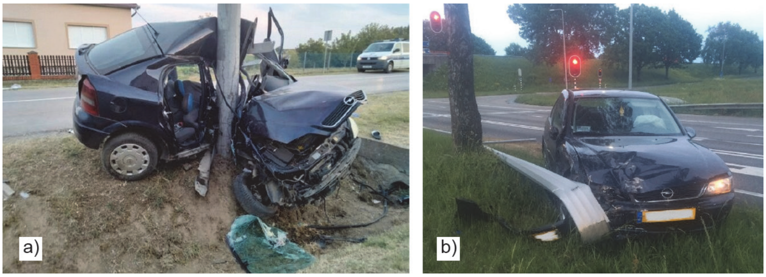

Figure 1 Consequences of vehicle impacts on different types of poles [4, 5]: a) rigid pole, b) passively safe pole

This paper presents the characteristics of passively safe poles with respect to the material from which they are most often manufactured: steel, aluminium, and composite poles. The analysis focuses on their energy absorption performance during vehicle impact, as well as their operational and service-life characteristics. Since roadside poles are continuously exposed to atmospheric conditions and environmental influences, they are susceptible to various corrosion processes. For this reason, particular emphasis is placed on the analysis of corrosion mechanisms. Furthermore, when poles are installed near railway infrastructure powered by direct current (DC) traction systems, they may be exposed to stray current corrosion. The mechanisms and effects of stray current-induced corrosion are discussed in detail in chapter 3.

2 Influence of material on pole behavior under vehicle impact

When a vehicle impacts a pole, the vehicle's kinetic energy is transferred to the pole structure. The energy generated during the collision depends on the mass and velocity of the vehicle and is expressed as [6]:

$$E_k = \frac{1}{2} m v^2 \tag{1}$$

where:
E_k – vehicle's kinetic energy [J]
m – vehicle mass [kg]
v – vehicle velocity [km/h].

Traditional poles are mostly rigid and cannot absorb the impact energy, so it is transferred to the vehicle and its occupants [7]. This results in an abrupt deceleration of the vehicle over a short distance, which has a detrimental effect on the occupants. In order to reduce the severe consequences of such accidents, the use of passively safe poles is recommended, especially in risk zones. Passively safe poles are designed so that in the event of a vehicle impact, they either absorb the energy and deform or detach at the base of the pole in a controlled manner. In order for poles to be considered passively safe, in EU countries they must be tested in accordance with EN12767:2019 [6]. The classification of poles with regard to passive safety according to this standard is carried out according to seven parameters:

- vehicle speed at the impact with a pole
- ability to absorb energy
- occupant safety level
- backfill type of foundation for the poles

- collapse mode of the pole
- direction class - direction of the vehicle in which it collides with the pole
- risk of roof indentation.

Considering the ability to absorb energy during vehicle impact, passively safe poles can be divided into three categories:
- HE (high energy absorbing) poles – designed to absorb large amounts of impact energy, resulting in rapid vehicle deceleration
- LE (low energy absorbing) poles – designed to absorb limited amounts of impact energy and enable gradual vehicle deceleration
- NE (non-energy absorbing) poles – poles that do not absorb impact energy but detach at the base, allowing the vehicle to continue moving at a reduced speed.

The behavior of passively safe poles is illustrated in figure 2.

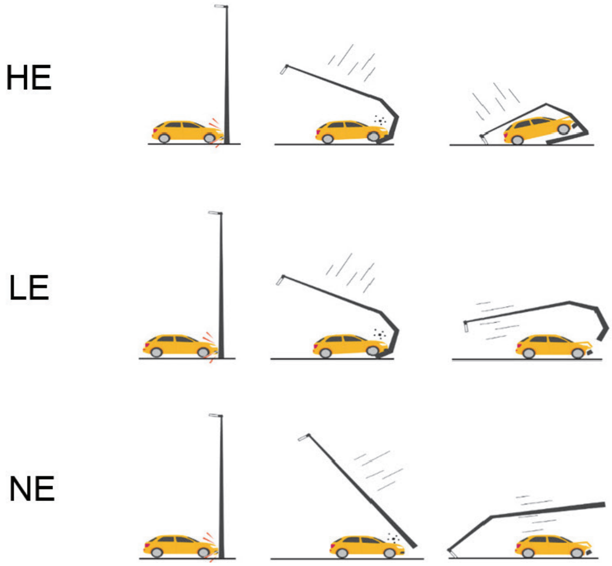

Figure 2 Behavior of passively safe poles during vehicle impact [8]

The material from which poles are made significantly influences its energy absorption capacity and its behavior during a vehicle impact. Materials with lower stiffness generally exhibit higher energy absorption. Reinforced concrete poles are characterized by high compressive strength, high stiffness, and significant mass [9]. In the event of a vehicle impact, nearly all the energy is transferred to the vehicle, leading to severe consequences for the occupants. Due to these characteristics, reinforced concrete poles are unfavorable from a passive safety perspective. Steel poles exhibit high tensile strength, considerable stiffness, relatively low mass, and good ductility. Traditional steel poles are rigid and somewhat safer than concrete poles; however, they can still pose a significant risk to vehicle occupants during collisions. Modern passively safe steel poles, such as ZIPpole designs, incorporate specialized structural features that enable high energy absorption and controlled vehicle deceleration [5]. In this way, they can achieve the HE classification according to [6]. ZIPpole poles are typically manufactured from thin-walled profiles connected by rivets (figure 3), which fail upon vehicle impact, allowing deformation of the thin-walled profile and energy absorption.

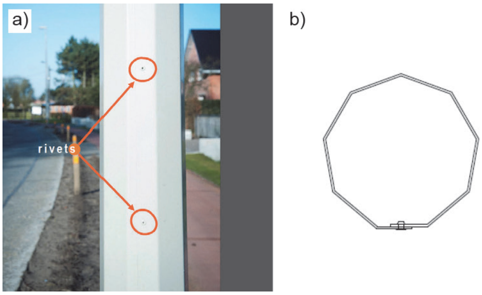

Figure 3 ZIPpole [5]: a) rivets, b) cross-section of ZIP pole

Aluminum is considered a passively safe material due to its elasticity [10]. Aluminum poles have lower strength, higher ductility, and lower weight compared to steel poles. Upon vehicle impact, aluminum poles tend to bend or deform, gradually decelerating the vehicle and reducing impact severity. They are commonly used for LE and NE pole categories. Compared to other materials, composite poles exhibit high strength, low mass, and the highest energy absorption capacity during vehicle impacts, thereby reducing the intensity of the initial collision experienced by occupants and minimizing vehicle damage [11]. They are commonly used for LE and HE pole categories. Numerous traffic accident cases have shown that lightweight composite poles often remain standing after a collision, reducing the risk of secondary accidents, such as subsequent vehicle impacts. An additional advantage of composite poles is their insulating properties; even if a pole carrying electrical voltage falls, it does not pose an electric shock hazard to pedestrians. The influence of pole material on occupant safety can be evaluated by analyzing G-forces and ASI (Acceleration Severity Index) values experienced during a collision. The ASI value represents a calculated measure of vehicle deceleration experienced by occupants during impact. It effectively quantifies collision severity and ranges from 1.4 (lowest safety level) to 0.6 (highest safety level) [12].

Previous studies have compared measured G-forces for impacts at 37 km/h involving concrete, steel, and aluminum poles [13]. The results indicate that collisions with concrete poles generate the highest G-forces, while traditional steel poles produce slightly lower but still significant forces on vehicle occupants. Aluminum poles, due to their deformation characteristics, generally result in lower G-forces, highlighting their effectiveness in mitigating impact severity [13]. Tests have also shown that collisions with conventional steel poles lead to significant vehicle deceleration, high deceleration forces, and considerable vehicle damage. In contrast, aluminum poles absorb energy more gradually, reducing both injury severity and vehicle damage [14]. In study [15], which analyzed the behavior of composite and aluminum lighting poles under vehicle impact, ASI values for composite poles were found to be nearly three times lower than those for aluminum poles and exhibited a more uniform response profile (figure 4). This suggests that vehicles decelerate more gradually during collisions with composite poles, thereby improving occupant safety and reducing vehicle damage compared to aluminum poles.

Analyses indicate that the choice of pole material has a significant impact on traffic safety. Reinforced concrete and traditional steel poles provide high structural stability but perform poorly in vehicle impacts. In contrast, passively safe steel poles allow controlled deformation and improved safety performance. Passively safe aluminum poles demonstrate even better behavior by enabling more gradual vehicle deceleration, thereby reducing the impact on occupants. Composite poles represent the most expensive but also the safest solution in the event of vehicle collisions.

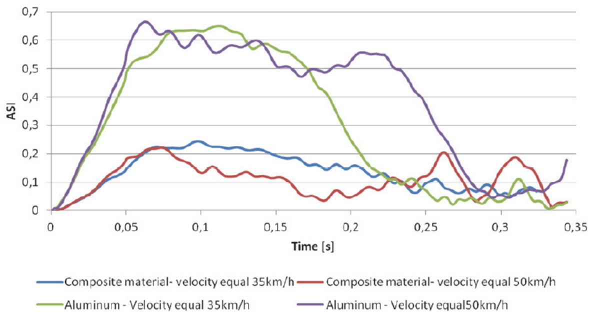

Figure 4 ASI values for composite and aluminum poles during vehicle impact [15]

3 Analysis of corrosion processes on poles

This chapter analyzes the impact of corrosion on various types of poles according to the materials from which they are made. It also examines corrosion caused by stray currents, which can have detrimental effects on steel poles located near railway tracks powered by direct current (DC) traction systems.

3.1 Corrosion caused by aggressive environment

Corrosion processes that occur on poles depend on various parameters, starting with the materials from which the poles are made and their locations. If steel poles are in a maritime environment, corrosion will be very aggressive. According to [16], corrosion in maritime environments accounts for almost 30% of all degradation in constructions. An analysis of corrosion on several steel poles is presented in [17], where the authors concluded that corrosion begins just below ground level, with the critical zone being approximately the first 20 cm below ground level. In the early stage, corrosion appears uniformly around the pole circumference. Harmful corrosion degradation at the pole base is shown in figure 5.

Figure 5 Corrosion degradation on poles base [18]

If corrosion processes on steel poles are not prevented in time, the resulting degradation can directly affect the mechanical properties of the pole. Corrosion may weaken the structure, causing the pole to behave differently during a vehicle impact than originally designed [19]. Furthermore, fallen poles can obstruct traffic, damage vehicles, or injure pedestrians. Unlike steel poles, aluminium poles exhibit significantly higher resistance to corrosion. This resistance is due to the formation of a thin, passive oxide layer that forms spontaneously on the surface when exposed to air [20].

This oxide film acts as a protective barrier, preventing further oxidation and shielding the underlying material. However, despite their inherent corrosion resistance, additional protection is recommended when aluminium poles are installed in aggressive environments, such as marine conditions. Aluminium is particularly susceptible to galvanic corrosion when it comes into electrical contact with a more noble metal (e.g. copper or zinc) in the presence of moisture [20]. In such conditions, a galvanic cell is formed, and the less noble metal, aluminium in this case, acts as the anode and undergoes accelerated corrosion. In terms of material composition and corrosion performance, composite poles offer the most advantageous characteristics [19]. As these materials are not subject to electrochemical corrosion processes, they represent a highly suitable solution for use in aggressive and highly corrosive environments.

3.2 Stray current corrosion

If steel poles are located near urban rail systems that use DC current, they can be at risk of stray current corrosion. Stray current is a consequence of electrified railway systems where rails are used as return current conductors. Under normal conditions, the traction current flows from the vehicle to the source (power station) using the rails [21]. However, if the rails are not properly insulated (i.e., the rail-to-ground resistance is not high enough), current will flow from the rail into the ground. This current is known as stray current. Stray current may then flow through nearby metal structures, such as poles or buried pipelines, effectively using them as an alternative path back to the source. At the locations where stray current leaves these metal structures, harmful, localized stray current corrosion will occur [22]. Figure 6 shows stray current leaking from the rail and entering the sheet pile wall near the track.

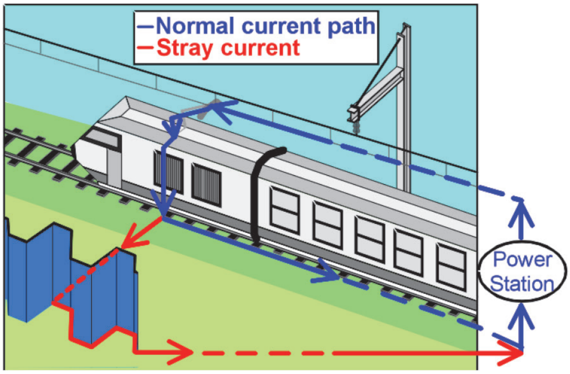

Figure 6 Origin and path of stray currents through a sheet pile wall [23]

Stray current does not only flow near railways or city power lines, but they can also spread through metallic structures to more remote locations. Until now, most cases of stray current corrosion have been observed on reinforcement steel and buried metal pipelines [24]. In [25], corrosion caused by stray currents was reported on reinforced concrete transmission line poles located near railway infrastructure. In some cases, complete failure of these elements occurred within just three years, despite their designed service life being 80 years. The primary cause of this accelerated degradation was severe reinforcement corrosion, which led to cracking and spalling of the concrete. Field measurements clearly confirmed the role of stray currents in such rapid deterioration.

3.3 Corrosion protection

To prevent corrosion on steel poles, various types of protective coatings are commonly used. However, if a coating is damaged, corrosion can initiate at that point, causing localized damage that may compromise the safety of the pole. The most widely applied corrosion protection methods are passive barriers, such as protective coatings, which prevent direct contact between the metal and the atmosphere. This category includes epoxy coatings, which are frequently used in practice [7]. Corrosion protection can also be active, most often involving the use of a sacrificial anode, a protective metal layer that corrodes preferentially to the steel being protected. Sacrificial anodes are typically made from highly electronegative metals, such as zinc or magnesium. The service life of this protection depends on the corrosive environment surrounding the protected element [26]. In [27] the effect of corrosion on several steel pole samples was analyzed. Sample A represented an unprotected steel pole, while the other samples had various corrosion protection methods applied: epoxy-coated steel pole (sample B), VEF polyglass steel pole (sample C), galvanized pole (sample D), epoxy-coated galvanized pole (sample E), and VEF polyglass galvanized pole (sample F). The samples were tested under different conditions to simulate varying levels of environmental corrosivity. The weight loss caused by corrosion on each sample during the tests is shown in figure 7, with the best results observed in sample E, which represents the epoxy-coated galvanized pole.

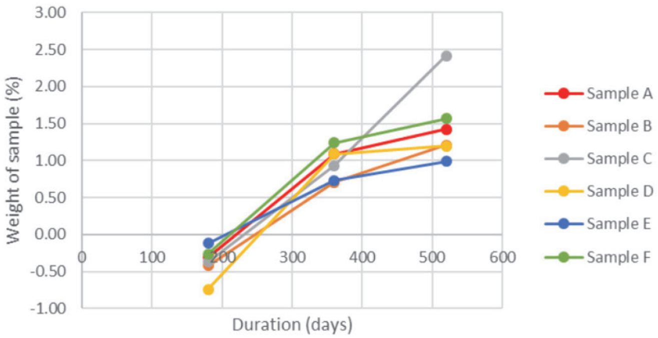

Figure 7 Percentage of weight loss during the testing [27]

The results of this research also showed that the effectiveness of anticorrosive protection varies depending on the corrosivity of the environment surrounding the sample. Therefore, to implement effective corrosion protection, it is essential to carefully analyze the conditions in which a structure will be installed. An analysis of the condition of all catenary poles in the tram infrastructure of the city of Zagreb was conducted in [28]. It was found that corrosion protection had been applied to all poles, however a significant reduction in coating thickness was observed at approximately 1 m above ground level. This led to the conclusion that thicker coatings should be used. The damage to the applied coatings was mainly caused by atmospheric conditions, which led to deterioration, as well as mechanical damage resulting from intentional or unintentional human actions. In addition to proper corrosion protection, it is crucial to continuously monitor the condition of poles through regular visual inspections, measurements of protective coating thickness, and corrosion monitoring. The most common corrosion monitoring methods include the use of corrosion coupons, which allow the measurement of mass loss over a given period to determine the corrosion rate, and electrical resistance-based methods. Electrical resistance measurements rely on the principle that corrosion reduces the cross-sectional area of a metal surface, causing mass loss and, consequently, an increase in electrical resistance [29]. Therefore, an increase in electrical resistance is directly correlated with mass loss, and the mass loss over time can be used to calculate the corrosion rate.

4 Conclusion

This paper demonstrates that the material of a roadside pole significantly affects both its impact performance and long-term durability. Traditional steel poles are considerably stiffer, generating higher deceleration forces and more severe impacts. However, modern passively safe steel designs, such as ZIPpole structures, provide improved energy absorption and controlled deceleration. It can be concluded that, in the case of steel poles, safety is not governed primarily by the material itself, but rather by the structural design of the pole. Aluminum poles deform under vehicle impact, gradually decelerating the vehicle, reducing G-forces on occupants, and minimizing vehicle damage. Composite poles offer the highest energy absorption capacity, with lower ASI values and more uniform deceleration profiles, thereby enhancing occupant safety and reducing vehicle damage. Environmental exposure also strongly influences pole performance. Steel poles are vulnerable to atmospheric and stray current corrosion, particularly at the base, which can compromise mechanical properties and energy absorption capacity. Aluminum forms a protective oxide layer but may require additional protection in aggressive environments, whereas composite poles are inherently corrosion-resistant and suitable for harsh conditions.

It can be concluded that careful material selection is crucial for ensuring reliable energy absorption, occupant safety, and long-term durability of passively safe roadside poles. However, to maintain optimal performance, it is equally important to implement effective corrosion protection and regular monitoring, using methods such as visual inspections, coating thickness measurements, corrosion coupons, and electrical resistance assessments, in order to preserve structural integrity.

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