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Entry

Road Markings and Signs in Road Safety

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Definition: Due to the dynamic nature and complexity of road traffic, road safety is one of the most demanding social challenges. Therefore, contemporary road safety strategies incorporate a multidisciplinary and comprehensive approaches to address this problem and improve the safety of each individual element, i.e., the human, vehicle, and road. Traffic control devices are an important part of road infrastructure, among which road markings and road signs play a significant role. In general, road markings and signs represent basic means of communication between the road authorities and road users and, as such, provide road users with necessary information about the rules, warnings, obligations, and other information related to the upcoming situations and road alignment. The aim of this entry is to briefly present the main functions and characteristics of road markings and signs, and their role in road safety. In addition, practical issues and future trends and directions regarding road markings and signs are discussed.

Keywords: road markings; road signs; road safety; traffic control devices; road infrastructure

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1. Introduction

Road safety is still one of the major issues worldwide, given that annually approximately 1.3 million people die in road crashes, with an additional 20 to 50 million people injured [1]. In general, the state of road safety is considered to be the result of the interaction between three main factors: human, vehicle, and road. Given the propensity for error, humans have long been considered a major perpetrator of road crashes, although external factors typically contribute to human error. Roadway characteristics, as well as the vehicles themselves, can provoke human error and thus be primary causes of crashes. Accordingly, current road safety strategies (such as the Safe System Approach) clearly differentiate factors that cause road crashes—human, environmental, vehicle-related, etc. and focus on a more holistic approach for resolving the problem. This kind of approach is aimed at taking actions that improve the roads and their environments, vehicle safety systems, law enforcement, and the behavior of road users. There are many ways to influence road users and human behavior, such as safe driving training, public campaigns, and additional education in schools, i.e., road safety education [2]. Furthermore, the effects are improved when several preventive measures are combined [3].

As one of the elements of road safety, the road consists of its entire infrastructure and surrounding environment. Therefore, traffic control devices, such as road markings, signs and signals, and other road safety elements, are an important part of road infrastructure.

Traffic control devices date back to the time of ancient civilizations, whereby roads were marked were in a primitive way, using trees or stones. The purpose of this practice was primarily navigational, and it can be said that trees and stones represented the first directional road signs. Technological progress, construction, the interconnectedness of evolving geographical areas, the need for faster transport, and the migration of people and goods led to the need to establish a legal framework for managing transportation networks. Moreover, the rise of international road transportation increased the need for rules that could be interculturally understandable.

Therefore, the first International Convention on Motor Traffic was held in Paris in 1909, and it addressed problems related to the construction of motor vehicles, international traffic, road signs, and lighting [4]. Among other things, the convention defined the basic shapes of road signs, e.g., danger signs were defined as equilateral triangles with the top facing upwards, mandatory signs as circles, and notice signs as rectangles. The Paris Convention was supplemented by two new conventions related to road and motor traffic (the International Convention relating to Road Traffic and the International Convention relating to Motor Traffic), the conclusions of which were adopted in Paris in 1926. However, the conclusions mentioned did not deal exhaustively with the issue of road signs and lighting, which is why a convention on the unification of road signals was held in Geneva in 1931. In 1949, the United Nations Economic and Social Council concluded that the current conventions from 1926 and 1931 were obsolete and organized a new conference in Geneva the same year. The outcome of the conference was the Convention on Road Traffic and the Protocol on Traffic Signs and Signals.

Several other conventions followed, but the most important was the one held in Vienna in 1968, when the Geneva Convention was revised and significantly expanded. The Vienna Convention [5], officially called the Convention on Traffic Signs and Signals, is a multilateral treaty aimed at increasing road safety and standardizing international road traffic, which is still the basis for regulations in most countries, especially European ones. The convention unified colors, shapes, and basic dimensions of road signs and defined the use of symbols instead of words to make the signs more understandable to people from different countries, and cultural and linguistic origins, and to illiterate people. In addition, the Vienna Convention defined some new specially shaped signs, such as the octagonal obligatory stop sign in place of the previous round sign with the delineated triangle.

Except road signs, the Vienna Convention also included and defined road markings. The first documented use of road markings dates to 1911 when the center line was painted on Trenton River Road in Wayne County, Michigan (USA) [6]. The originator of the idea was Edward N. Hines, chairman of the Wayne County Road Committee, who got the idea after seeing milk leaking from a milk truck on the road. Shortly after, center lines were painted on rural and state roads in Michigan, Oregon, and California. In Oregon, in April 1917, a yellow center line was painted on the Columbia River Highway, representing the first application of yellow markings. In Europe, the first road markings were applied in Great Britain in 1918, and as in the US, their use quickly spread through Europe; for example, in 1925, the roads in Berlin were already marked with white center and edge lines.

Relatively soon after their first application, it was found that during nighttime, road markings were neither visible nor effective. The solution to this problem was presented in the article Luminous Marking for Highways, which proposed the use of retroreflective glass beads in road markings [7]. Today, in addition to contrast, retroreflection is a basic qualitative characteristic of both road signs and markings.

The Vienna Convention was later updated with the Supplementing Agreement (1971) and Protocol on Road Markings (1973), and as such is used in 69 countries worldwide. However, the system based on the Vienna Convention is not the only system for signs and markings. In the United States, the system is based on the US Federal Highway Administration's Manual on Uniform Traffic Control Devices (MUTCD). The main difference between the MUTCD and Vienna Convention is related to road signs, i.e., their shape, colors, and the way the message is conveyed to the road user. For example, diamond-shaped yellow signs signify warnings, rectangular signs with a white background convey traffic regulations, while yellow circular signs warn of a railroad crossing, etc. Moreover, road signs in the MUTCD are often more text-oriented, though some signs do use pictograms as well. When comparing road marking standards, the main difference is that the MUTCD requires all center lines dividing opposing traffic on two-way roads to always be painted in yellow.

Today, the Vienna Convention and MUTCD are the two main systems and the basis for standards worldwide (Figure 1), e.g., Canadian and Australian systems are based on the MUTCD to a large extent, in Latin and Central America and in some Asian countries, the systems are based on a combination of the Vienna Convention and MUTCD, while in most African countries, European (the Vienna Convention) or the old British system is used. Regardless of the system, road markings and signs have to be properly designed and situated in order to provide timely and appropriate messages to road users in all weathers and traffic conditions, and thus positively affect overall road safety.

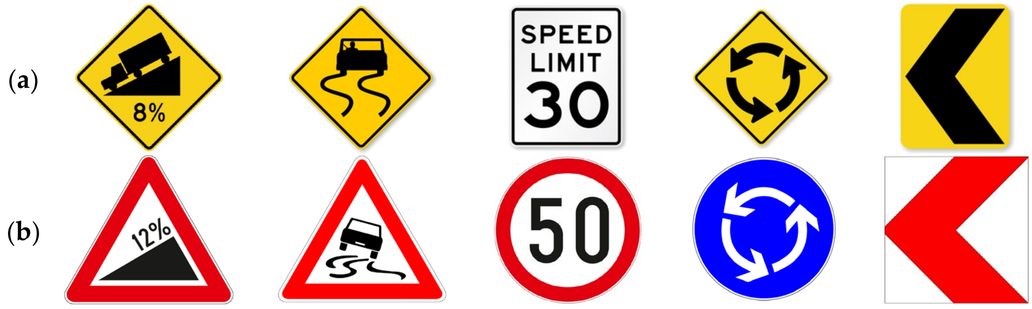

Figure 1. Comparison of road sign designs from (**a**) the United States (MUTCD system) and (**b**) Croatia (Vienna Convention-based system).

In the following chapters, the main functions and characteristics of road markings and signs, and their role in road safety are described, with an emphasis on conventional signaling. Moreover, practical issues and future trends and directions are discussed.

2. Functions and Main Characteristics

Road markings and road signs represent basic means of communication between road users and road authorities, and as such have several main functions. First, they have to manage and regulate traffic in a proper and safe manner by stating rules, obligations, and restrictions. Furthermore, they must help by guiding road users through the network and provide them with all the necessary information. To achieve these purposes, road markings and signs, as stated in the introduction, need to be designed and have a certain level of quality as to be properly detected, read, and comprehended by road users in a timely manner.

To fulfill their function, road markings and signs first need to be visible. During daytime, their visibility is achieved with the contrast between markings/signs (their shape and colors) and the environment. However, in comparison to daytime circumstances, during the night and in low-visibility conditions (dusk, dawn, inclement weather), there is a lack of ambient light in the environment, which reduces the contrast level and degrades the functioning of human visual system. All of this results in the road markings and signs becoming difficult to see. Therefore, they need to have retroreflective properties to be visible in such conditions. In other words, they must contain retroreflective materials, i.e., materials that redirect incident light (e.g., from vehicle headlights) back towards the source [8].

In the rest of this chapter, the basic properties and functional characteristics of permanent road markings and signs are presented.

2.1. Road Markings

Road markings can be classified based on different criteria (color, material, function, durability, thickness, retroreflectivity, etc.), but the main division is based on their function and the material they are made of. Usually, road markings are, according to their function, divided into three groups: longitudinal, transverse, and other road markings. Longitudinal road markings are used as the center and edge lines, and as guidelines at the intersections. They can be composed of solid, dashed, or double lines. Transverse road markings represent all road markings that are positioned perpendicularly or at a certain angle to the axis of the road. They include stop lines, pedestrian crossings, bicycle crossings, etc. Arrows, traffic routing fields, inscriptions on the pavement, markings that delineate traffic areas for special purposes, markings for parking spaces, markings of traffic reducing devices, etc. fall into the other road markings group.

Based on the material that road markings are made of, they can be divided into three groups: paint, plastic material, and tapes.

Paint is a thin layer material with a thickness of 300 to 600 μm after application. Its main advantage, compared to the other two materials, is price and ease of application. Because of this, it is a widely used material around the world. Even though it is the most used material for road markings, it is also the poorest quality material. The reason for this is its low density, which results in road markings wearing out relatively quickly and losing their contrast and retroreflective properties (loss of glass beads) [9]. Moreover, the durability of paint is the shortest compared with the other materials and it usually only lasts around 1 year.

Paints are composed of resin (today styrene-acrylic, acrylic-alkyd blends, and 100% acrylic are mainly used), pigments and fillers, and different additives [9]. They can be solvent-borne or water-borne. Solvent-borne paints are based on acrylic resins (rarely styrenic- or alkyd-acrylic blends), and after application, the solvent evaporates, which results in the formation of a dry film of paint. Due to environmental concerns related to volatile organic compounds (VOC), in some countries solvent-borne paints are slowly being replaced by water-borne paints or solventless road marking materials [10]. Water-borne paints were first commercialized in the 1980s and were very similar to solvent-borne paints, i.e., instead of solvent, the evaporation of water triggered the drying process. Moreover, they have a low VOC content. However, such paints had limited use due to their slow drying and the very slow development of washout resistance [9]. Recently, new progress in quick-set binders led to the development of more resistant water-borne paints, which can be applied with a film thickness of 900 μm or more, without significant slowing the drying time. They can be applied on a variety of road surfaces (including bituminous and concrete materials), generally adhere well to the existing markings regardless of their type, and have a service life of between one and 2 years in most cases.

Compared to paint, plastic materials represent a better solution. These are plural component systems that can be made from thermoplastic or cold plastic. Thermoplastic materials are composed of resin (solid hydrocarbon or alkyd) intermixed with pigments and fillers, and glass beads. The application of thermoplastic requires reheating of the dry raw material to about 200–220 °C and melting [9]. In cold plastics, monomers are mixed with pigments, fillers, and anti-skid materials, and then they are polymerized (by adding a small amount of initiator) on the road surface to form durable, hard, and well-adhering markings [9].

Regardless of the type, the thickness of road markings made from plastic materials is between 1–3 mm for non-profiled markings, and up to 6 mm for profiled and structured markings. Due to the larger thickness, they have a longer service life, which is usually between three to 6 years. As the material wears off, intermixed glass beads progressively become exposed to the traffic, which allows the high retroreflectivity to be maintained throughout the usable life. Moreover, due to their thickness, they provide better visibility in wet and rainy conditions, especially in the case of structured and profiled plastic markings. Such markings also produce vibrations and sounds when being passed over, thus providing a warning to drivers, which can significantly affect the frequency of crashes caused by the vehicle turning into the opposite lane or the vehicle leaving the road. In addition, similar to paints, both thermo and cold plastics can be applied in a thinner layer (spray plastic), which is usually used for the renewal of existing road markings.

Another material used for road markings is tape. Tapes are factory-made materials with embedded glass beads. These glass beads are equally distributed and optimally embedded, which leads to a high level of quality. For this reason, they have a high level of retroreflectivity and have a good level of visibility in all weather conditions. They can be produced and used as permanent or temporary road markings, and do not require expensive machines for application. However, their main disadvantage is their price, which can be a limiting factor in the use of this material.

Besides paint, plastic materials, and tapes, there are some alternatives, like epoxy and latex paints, urea, urethane, polyester, etc. Developed in the 1970s, epoxy paint is the most commonly used of these alternatives. Their main advantage is the possibility of use at low temperatures, because their chemical composition makes them less sensitive to temperature. Disadvantages that limit their usage include their poor resistance to UV radiation, which causes color and pigment changes, and high levels of volatile organic compounds (VOC), which presents a great risk for human health and environmental pollution [9].

2.2. Road Signs

In the past, road signs were made by painting a metal base, but these signs did not have the aforementioned retroreflective properties, and were soon replaced. In 1939, the company 3M developed the material "Scotchlite", which represented the first retroreflective material [11]. Since "Scotchlite" had glass beads on the surface of the material, it would lose its retroreflectivity relatively quickly over time due to dust, rain, and other weather conditions. A decade after the first use of "Scotchlite", 3M invented a new material, "Engineer grade—EG". The main difference between these two materials is that the glass beads in Engineer grade are embedded in the material and "shielded" from outside influences, which enables the material to have longer durability compared to "Scotchlite". Today, in Europe, this material is considered a class I material (the European and US system classifies retroreflective materials differently: Europe has three classes, while the USA has up to 11 types) and is made with both glass beads and micro-prisms as retroreflectors, since prisms produce higher retroreflection values. In general, class I micro-prismatic materials provide a retroreflectivity from 150 to 180 cd $\times$ lx^{-1} $\times$ m^{-2} for white, while the beaded variant provides a retroreflectivity of around 70 cd $\times$ lx^{-1} $\times$ m^{-2}. More than 30 years later, in 1971, a new material was developed with glass beads encapsulated into the material. This material is now known as "High Intensity grade—HI" and is classified (in Europe) as class II. As with class I, class II today is also produced with glass beads or micro-prisms. Beaded material can provide retroreflectivity of around 250 cd $\times$ lx^{-1} $\times$ m^{-2}, while prismatic material provides a retroreflectivity from 400–600 cd $\times$ lx^{-1} $\times$ m^{-2}. In 1988, a class III material was produced based only on prismatic retroreflection, due to the superiority of micro-prisms compared to glass beads in returning incident light to its source. For white, it can provide a retroreflectivity of around 800 cd $\times$ lx^{-1} $\times$ m^{-2}.

Except retroreflection power, i.e., the potential of the material to return as much input light as possible back to the source (drivers), retroreflective materials differ in the orientation of retroreflected light, their angularity, and durability. The orientation of retroreflected light determines the direction in which the retroreflected light will go, i.e., it determines the scattering of light returning to the source. To determine the angularity, it is important to consider two main factors that describe the light rays' paths. Firstly, the entrance angle is formed between the light ray "entering" the road sign and the vertical axis directed to the surface on which the sign is placed. It depends on the position of the road sign on the road—the smallest angle is when the sign is placed on the right side, and it increases for the left side or when the sign is positioned above the pavement. Secondly, the viewing angle is the angle formed between the entrance and the reflected light, and it depends on the type of vehicle (which determines the height of the driver's seat) and the input angle. In Europe, the relevant geometry for personal vehicles implies an entrance angle of 5° and a viewing angle of 0.33° (different geometries that differ in entrance and viewing angles, to "simulate" different sign positions and vehicle types, are also used). With the increase in either of these angles, the driver's "feel" of the signs' retroreflection decreases. Therefore, the angularity of the material means that the material can return light toward the source (driver), even if the entrance and viewing angles increase. The fourth characteristic of the materials is durability. This describes the period in which the material will meet the minimum prescribed quality requirements. Producers usually guarantee that class I materials will meet the minimum prescribed quality requirements for 7 years, 10 years for class II materials, and 10–12 years for class III materials.

After a road user detects a sign, they have to read and comprehend its message. Since road signs convey their message through shape, colors, and symbols or text, all their elements must be easily and quickly legible so that users can incorporate the information promptly. Factors that determine whether the road user will detect and comprehend road signs are numerous and include the road users themselves (age, gender, quality of the visual system, background, education, current psychophysical condition, etc.), environmental and visibility conditions (day/night, weather conditions, type and complexity of the environment, etc.), and road sign characteristics (position, retroreflective properties, design, the frequency of the presence of specific sign on the road, etc.). Studies indicate that drivers generally have a low awareness of road signs (usually under 50%), which implies that a big percentage of signs are overlooked by drivers [12]. Overall, ergonomically designed road signs ensure easier learnability and understanding of the message being conveyed [13].

Aside from their visibility and design, several other principles should be followed to ensure the detectability and readability of road signs. For example, road signs must be uniform, no matter what part or section of the road network they are located in, and each part or section of road with similar characteristics must be equipped with road signs in the same way. Furthermore, road signs need to have a level of detail that ensures their full effectiveness. It is necessary to ensure that the road network is well equipped along its entire length, so road signs must be set up continuously. Finally, road signs must retain the same appearance in terms of shape, size, and color in daytime and nighttime conditions.

When necessary, due to traffic safety or technical requirements, road signs can be made in whole or in part as variable signs (continuous and non-continuous). Given their function and price, they are mainly located in places with a higher traffic load to ensure the optimal level of road service, in places with increased risk of crashes in certain conditions, and in places where there is a need for a flexible traffic regime.

2.3. Road Markings and Signs within Contemporary Technologies

With the increasingly complex requirements that arise in the transport system comes the application of new technologies. In the last two decades, a significant effort has been focused on variable message signs (VMS), which are also known as changeable, electronic, or dynamic signs. These signs are electronic, are usually modular, and use LED technology to display different messages, standard signs, or customized signs and text messages (Figure 2). Given the restrictions, such as the need for electricity, VMS are most often used on motorways, in urban areas, or in front of tunnels and in parking lots. On the other hand, there are many advantages regarding the use of VMS. For example, they can be operated remotely, which is a useful feature in adaptive traffic control systems. Further, the symbol and text message on the sign can be changed according to real-time traffic demands, emergency notices, and working-zone info, etc. Although the initial costs of setting up the VMS are higher, they consume low amounts of power during their operation, i.e., lower costs.

Figure 2. Variable message signs (VMS) on a Croatian A1 motorway designed as electronic LED panels.

With the development of different vehicle technologies, new possibilities regarding road signs emerged, and signs began to be seen as a means of communication not only for human drivers, but also for automated vehicles. One such approach was developed and tested by the company 3M. The project presented specially designed QR codes that were installed on road signs and used a vehicle equipped with an IR light source and a camera that can read the QR code at a distance similar to the one at which a human driver can read a traditional road sign (Figure 3). The size of the code was approximately 65% that of the surface area of the sign and its design was optimized to enable far and near readings, and to ensure that critical information is conveyed to the vehicle even if the sign is partially obscured [14]. Other researchers proposed the use of RFID or radar technology for different purposes, such as warning drivers about weather conditions and hazardous road conditions ahead, additional information for advanced driver assistance systems (ADAS), and updating road sign inventories and the optimization of maintenance activities [15–20].

Figure 3. Example of visible and near-IR view of QR code (Source: [14]).

Regarding road markings, there are some proposals that involve using road paint that glows in the dark [21,22], like shown in Figure 4. The paint uses strontium aluminate pigments to create the glowing effect through the night (8–10 h); however, the strength of the glow is not constant during that period. A potential benefit of using this kind of paint is saving electricity (no need for an external light source at night) [23]. However, some further research is needed to evaluate the use and effects of such a material, e.g., its durability, possible light pollution, performance under different weather conditions, influence on road users' behavior, etc.

Figure 4. Luminescent road markings (Source: [24]).

3. Role of Road Markings and Signs in Road Safety

Since drivers primarily base their decision making on the environmental information collected visually [25], it is evident that road markings and signs play an important role, since they guide, warn, and inform drivers about the situation ahead, possible hazards, speed limits, and other regulations. Overall, the presence of road markings and signs has shown to have a positive impact on driver behavior (driving speed, the lateral position of the vehicle, etc.) [26]. However, their mere presence is not enough. For road markings and signs to be sufficiently visible in a timely manner, and thus provide the desired safety benefits, they have to be of adequate quality in all weather and traffic conditions.

Everything said above was, and still is, a motivation for many researchers to conduct studies that investigate the impact of road markings and signs on driver behavior, crash occurrence, and crash consequences, etc. In the following paragraphs, the main findings of such studies are presented.

3.1. Influence of Road Markings on Driver Behavior and Road Safety

Since road markings help to regulate traffic, particularly in terms of guiding road users and helping them to predict the traveling trajectory and boundaries of the road, their impact on road safety is substantial. Studies have shown that on roads without edge lane markings, drivers drive closer to the center line because the center line is located on the driver's side of the vehicle, and thus it provides them with a clear and convenient reference for maintaining a proper lateral position [27–29]. Moreover, the width of road markings also affects driver behavior, e.g., with the presence of wider road markings ($\geq$15 cm), drivers approach the edge of the road more closely, which reduces the risk of head-on crashes. However, it must be noted that this effect may increase the risk of run-off-road crashes in certain situations.

Furthermore, various forms and types of road markings were studied in terms of speed compliance and reduction, and their overall safety value. Researchers and practitioners studied a number of different perceptual road marking measures, such as transverse bars (flat or raised), dragon teeth, colored strips, medians, optical circles, and herringbone patterns, and highlighted their positive impact in terms of speed reduction and proper lateral movement in high-risk locations and situations, such as horizontal curves [30–35], intersection areas, and rural–urban transitions [36,37]. Furthermore, there are some indications that widening of longitudinal road markings could cause drivers to reduce their speed [38].

Moreover, road markings are especially appreciated by drivers in nighttime and low visibility conditions, in which the driver's field of view narrows and shortens. Studies have shown that the maximum detection distance of road markings increases as their retroreflectivity rises, although not in linear way [39,40]. Generally, road marking retroreflection is affected by several factors (e.g., quality, the embedding and density of the glass beads used, road marking material, age, winter maintenance activities, traffic volume, type and roughness of roadway, etc.), and according to the literature review, different studies demonstrate similar results, concluding that the minimum retroreflectivity (R_L) of road markings for drivers of all ages should be at least 100 mcd $\times$ lx^{-1} $\times$ m^{-2} [41].

However, the exact impact of road marking retroreflectivity on road safety is still not entirely clear when looking at the frequency and consequences of road crashes. Some studies did not find any significant correlation between the number of crashes and road marking retroreflectivity [42–45], while others concluded that road markings with a higher retroreflectivity are associated with lower crash numbers as they provide better visual guidance [46].

Overall, road markings affect both the lateral lane position of the vehicle and driving speed and, as such, are important road safety elements. Nevertheless, to fulfill their function and provide the desired safety benefits, they must be of adequate quality and properly maintained.

3.2. Influence of Road Signs on Driver Behavior and Road Safety

To fulfill their function, road signs must be visible and attract drivers' attention. Some early studies on road signs conclude that drivers' awareness of road signs differs depending on a number of factors, such as the type of sign, driver's experience, familiarity with the sign, time of the day, etc. [47–49]. Moreover, as stated in the introduction, research has shown that poorly designed and more complex signs with more information ultimately affect driver behavior [50,51]. In other words, the more information a road sign shows, the longer the driver's recognition time will be. However, a study from 1992 points out that the effectiveness of road signs should be assessed by their ability to alert the driver about the following hazard, and not in terms of the accuracy of the driver's recall of the sign [52]. Moreover, results from the same study indicate discrepancies between the driver's verbal recall and vehicle control that are not readily apparent from roadblock research. In a methodological review from 2000, a difference between the perception of those drivers who are actively searching for some information and those drivers who are not was noticed [53]. A strong contrast between the sign and the environment and the size of the sign stand out as important factors when drivers are actively searching for information. In contrast, the sign's content, in terms of the meaning that the message has to the driver, seems to play an important role. The authors of a study from 2021 stated that the better road users understood road signs, the less of risky behaviors were observed [54].

As road markings, road signs must comply with minimum retroreflectivity standards. In practice, many road signs fail to meet the minimum desired retroreflectivity standards due to cutbacks in public spending, creating an unsafe road environment for all road users [55,56]. Road signs can become invalid due to a combination of factors, such as sunlight, rain washing, erosion, etc. All these factors, or a combination of these factors, can cause road signs to become invalid and more difficult to read for the driver. Several studies investigated the relationship between invalid road signs and crash occurrence and indicated that if there is an additional invalid road sign per kilometer, the crash rate for material-damage only and fatalities and injuries increased by 25% and 34%, respectively [57–59].

Scientists dealing with road safety in developing countries have also recognized the importance of road signs. A study from Nigeria shows that the lack of appropriate road signs for guiding road users through the numerous black spots and their insufficient maintenance on the highways is a major cause of traffic accidents [60]. Similar conclusions are highlighted in a study from Cameroon that showed that inadequate road signs are one of the three main leading causes of traffic accidents, which was also confirmed by the road users' opinions gathered in a survey [61]. The conclusions are consistent with the ones from Ghana, which highlighted that poorly maintained infrastructure, including road signs, should be improved to reduce the number of road traffic accidents [62].

From all of the above, it can be concluded that road signs are an important element of safe roads, as they represent simple and cost-effective measures that can positively influence road safety and, thus, reduce the socio-economic consequences [56].

4. Practical Issues

In practice, there are several issues and situations that affect both road marking and sign functionality. One of the most common factors affecting their performance is the weather, which is why it is of great importance to analyze the geographic area in which the road is located. For example, if the road is in an area with a higher winter service activity, it is expected that this will affect the service life of the road marking, depending on the marking material [63]. In areas with a high traffic volume, road markings often become dirty or wear out quickly after application, while in rainy areas, a water layer can completely cover up road marking and thus eliminate visibility. Furthermore, road signs are often damaged in traffic accidents or are a target of vandalism, which can disturb their retroreflectivity and visibility [64]. Moreover, dirt or ice films often accumulate on the surface of road signs, or overgrown vegetation can conceal the sign. In addition, road signs can fade and/or their retroreflectivity can decrease [65] due to their age or the material quality, which can affect the understanding of the message of the sign.

Therefore, road marking and sign maintenance does not only mean replacing old and worn-out ones with new ones, but also taking care of the existing signs. All the above-mentioned circumstances lead to the conclusion that regular and optimized maintenance of road markings and signs has a direct impact on their functionality and effectiveness, and consequently on the safety of road traffic and overall costs. For road authorities, agencies, or maintenance services, it can be a challenging task to perform proper maintenance, because of the lack of infrastructure data or funding. For this reason, many of them develop infrastructure databases or use infrastructure management software as a support in the decision-making process. Furthermore, further investigations and modeling of the service life of road markings, and analyses of the features that could prolong it and enhance their performance, are required.

In certain circumstances, for example in countries popular with tourists, it can be a problem to understand road signs if they contain text terms or internationally incomprehensible symbols, or if different colors are used for road categories. In those cases, road users often have to lean on the environmental context or their experience to understand the message the sign communicates.

The most recent questions and challenges are related to the detectability and readability of road markings and signs by automated vehicles. Since lane keeping assistance (LKA), lane departure warning (LDW), traffic sign detection and recognition (TSDR), and other advanced driver assistance systems (ADAS) rely (at least to a certain extent) on road markings and signs, it is evident that adequate quality is not only necessary for human drivers but also for the aforementioned systems [66].

One of the first studies related to the impact of the quality of road markings on ADAS system operation was conducted in Sweden in 2010 [67]. As part of the study, the authors tested the influence of different types of pavement markings (profiled, flat, worn, new) in different weather conditions on the ability and quality of their detection and recognition by systems installed in vehicles (camera-based system). The conclusions of the conducted study indicated that to see and recognize signs in dry conditions, it is necessary to ensure a minimum of 85 mcd $\times$ lx^{-1} $\times$ m^{-2} of daytime visibility, while in wet, nighttime conditions, at least 20 mcd $\times$ lx^{-1} $\times$ m^{-2} is required. In a study from 2016, a vehicle equipped with a Mobileye camera was tested for marking detection and recognition at different simulated driving speeds. Moreover, the visibility of markings on the road was assessed in different conditions (dry/wet road) [68]. The results indicate that the optimal distance at which the vehicle can recognize the signs is from 7.6 m to 13.71 m at a speed of 56 km/h, and with an increase in driving speed (from 56 km/h to 112 km/h), the optimal distance remained approximately the same (from 7.6 m to 16.76 m). Furthermore, wider markings (15 cm wide) and markings with a higher retroreflection coefficient were better recognized at night than narrower markings (10 cm wide) or those with a lower retroreflection coefficient, regardless of the color with which they were made.

A study conducted in 2017 found that snow and fog can significantly affect the correct and timely detection and recognition of signs by vehicles, and that the retroreflection of signs plays an important role in detecting signs in nighttime conditions [69]. For example, the test vehicle detected markings whose retroreflection was less than or around 100 mcd $\times$ lx^{-1} $\times$ m^{-2}, which is usually considered the minimum value for humans, but at this value, the best quality of observation and recognition could not always be achieved.

An extensive study was conducted in Australia in 2020 with the aim of determining the minimum quality levels of markings that ensure the high-quality operation of ADAS systems in vehicles [70]. Ultimately, the key conclusions were that the contrast ratio between the longitudinal markings on the road and the surface in daytime conditions must be a minimum of 3 to 1, which is about 150 mcd $\times$ lx^{-1} $\times$ m^{-2}, while in nighttime conditions, this should be 10 to 1 for asphalt roads and 5 to 1 for concrete pavements. Furthermore, the nighttime visibility of pavement markings should be at least 100 mcd $\times$ lx^{-1} $\times$ m^{-2}.

The study also found that rain reduces the detection of signs by 32%, but also that wet conditions have different effects on vehicle guidance within the traffic lane. The appropriate width of road markings should be 150 mm for edge lines and 100 mm for dashed lines, according to the study. It was also pointed out that broken lines are more difficult to recognize for automated systems in vehicles compared to continuous lines.

There are relatively few studies that have analyzed the various factors related to the influence of road signs on the operation of ADAS systems. One such study was conducted in Australia in 2018 in which a series of tests were conducted in real traffic conditions and under various weather and visibility conditions [71]. Based on the tests conducted, it was determined that most of the problems are related to speed limit signs, given that most systems in vehicles detect these signs. Furthermore, it was found that the poor condition of signs (damaged signs, faded colors and symbols, the presence of graffiti and various stickers on the sign, etc.) also affects the accuracy of detection and recognition. In addition, the environment of the sign can also negatively affect the quality of detection and recognition in such a way that it covers the signs (e.g., tree branches, bushes, etc.) or generally affects its visibility. In addition to all the above, speed limit stickers on trucks and buses, and electronic signs that may remain undetected, are also a potential problem.

In 2021, a study was published that investigated the influence of weather conditions and the level of retroreflection of road signs on the quality of the sign detection and recognition in the vehicle [72]. In the study, it was determined that weather conditions and sign retroreflection have a statistically significant effect on the quality of detection and recognition through machine vision. However, the influence of retroreflection proved to be a more significant factor in relation to weather conditions. The age of the sign proved to be a significant factor, e.g., older signs were perceived and recognized more poorly, since the older the sign, the more deteriorated its visual appearance and its retroreflective properties.

Many different technologies and systems are currently used to communicate between vehicles and road infrastructure, and their presence on the road will significantly increase in the near future.

5. Future Directions

Although widely used, over the last decade, road markings and signs received a significant amount of research interest, focusing on different aspects of their development. An increase in road safety awareness and the implementation of contemporary road safety strategies aimed at improving road infrastructure in order to facilitate the needs of drivers, combined with evolving vehicle technologies, is promoting the use of new materials, techniques, and technologies.

Innovations and new technologies related to road markings and signs will, on one hand, focus on enhancing and developing new materials for various application and to improve their visibility and durability. The use of more durable, resistant materials with better performance should provide significant benefits in terms of detectability and readability by both human drivers and ADAS, and in the optimization of maintenance activities and costs [56,66,73]. Moreover, further improvements in the uniformity and standardization of road markings and signs are expected in the coming years. Such efforts should bring additional benefits in terms of detectability and readability, especially for ADAS.

Besides infrastructural development and improvement, an improvement in vehicles is also expected. For example, technological devices in vehicles for communication and signal detection (e.g., cameras, sensors) are improving [74].

Along with the aforementioned developments, so-called “smart road markings and signs”, i.e., markings and signs equipped with different technologies such as RFID, radar or QR, have potential in terms of improving infrastructure-to-vehicle communication (and vice versa). However, more tests are needed to evaluate their full potential and to determine the limitations and cost aspects of their implementation. In addition to “smart road markings and signs”, the development of digital maps, i.e., “digital twins” of physical road infrastructures, which, among other things, contain data regarding road markings and signs, is already in full swing.

No less important, research activities related to road markings and signs should be continued and expanded in line with developing trends. There are several directions for future research, for example, improving road marking and sign construction materials, enhancing the impact of road markings and signs on driver/rider behavior and different vehicle technologies, and optimizing their impact on road safety and the role of traffic control devices in future mobility solutions.

6. Conclusions

Road infrastructure is not the only factor that affects road safety; however, it is an area in which significant improvements are certainly possible. Road markings and signs are part of the road infrastructure. Since they are in the centerfield of vision of both human drivers and perceptual vehicle technologies, they represent a basic means of communication between the road authorities and road users and, as such, provide road users with necessary information about the rules, warnings, obligations, and other information related to upcoming situations and road alignment. Therefore, they represent the most cost-effective road safety solutions and measures.

Currently, both humans and vehicle technologies use vision as the key tool for gathering information from the surroundings, so it is necessary to ensure that all road infrastructure elements, i.e., primarily road markings and signs, have good visual properties. Although the literature contains mixed reports regarding the impact of road markings and sign quality on road safety, i.e., the frequency and severity of crashes, several studies confirmed that properly designed road markings and signs with an adequate level of quality positively impact all road users and vehicle technologies. Apart from their quality, road markings and signs should also be standardized and uniform so that road users of all ages (and modern vehicles) can comprehend their meaning and adjust their behavior accordingly.

Future research on the topic of road markings and signs is highly recommended, since a better understanding of their impact on drivers and vehicle technologies, and thus overall road safety, could provide important guidelines for policy makers, road authorities, researchers, and practitioners.

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