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Review Article

Road Markings and Their Impact on Driver Behaviour and Road Safety: A Systematic Review of Current Findings

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As part of the traffic control plan, road markings form the traffic surface and provide visual guidance for road users. Since their first application to the present day, road markings have become a common element of road infrastructure and one of the basic low-cost safety measures. The aim of this paper is to provide a systematic review of the most significant academic activities to date regarding the influence of longitudinal and transverse road markings as well as road markings for hazard locations (curves, intersections, and rural-urban transitions) on driver's behaviour and overall road safety. The review includes a total of 71 studies from which are 52 peer-reviewed journal studies, 4 conference proceedings, and 15 professional reports. The studies are, based on their aim, divided into two categories: (1) studies on the impact of road markings on driver behaviour (36 studies) and (2) studies on the impact of road markings on road safety (35 studies).

1. Introduction

Road accidents are one of the leading causes of death in the world [1]. The statistics show that, in 2018 alone, 25,047 people were killed on EU roads [2]. Although road safety is improving in most European countries, the progress remains slow and misaligned with established targets. This slow progress is partially due to the dynamic and complex nature of road traffic, and safety performance depends on a number of interconnected factors related to the roadway environment, vehicle, and road users. Given the propensity for error, drivers have long been considered a major cause of road accidents, although external factors typically contribute to driver's error. Roadway characteristics, as well as the vehicle itself, can provoke driver's error and thus be the primary cause of the accident. Accordingly, current road safety strategies clearly distinguish between the factors that truly cause road accidents (be it road user, environmental, road-related, etc.) and focus on a multidisciplinary and comprehensive approach to addressing this problem. The aim of such an approach is simultaneous proactive action directed at improving the road infrastructure, superstructure, vehicle safety systems, legislation, and behaviour of road users.

One of the modern concepts related to road infrastructure is the concept of "self-explaining roads." First implemented in the Netherlands, the concept encourages drivers to naturally adopt a behaviour consistent with the road design [3]. The concept aims at conveying information about the upcoming situation to the drivers in an easy and intuitive way, using various measures, including the most cost-effective ones related to road markings and road signs [4–7].

Generally, as part of the traffic control plan, road markings delineate the traffic surface by using lines, text, and symbols to provide visual guidance information for road users [8]. The first use of road markings was documented in 1911 along the Trenton River Road in Michigan [9]. Since then, road markings have become an important and inseparable part of road infrastructure and one of the common safety elements around the world [10]. Their further development and expanded use in the mid-1960s prompted academic activities focused on a variety of issues such as impact of road markings on driver behaviour and road safety, visibility of road markings, road markings material selection, implementation of road marking, their environmental impact and acoustic properties, and monitoring and maintenance of road markings.

The aim of this paper is to provide a systematic review of the most significant academic research regarding the road markings as an important road safety element. For this purpose, we have analysed the studies related to the influence of longitudinal and transverse road markings as well as road markings for hazard locations (curves, intersections, and rural-urban transitions) on driver's behaviour and overall road safety.

2. Methodology

Based on the aim of this review, the identified studies have been categorized into two groups: (1) studies on the impact of road markings on driver behaviour and (2) studies on the impact of road markings on road safety.

The studies included in this review relate to at least one of the above groups and were published between 1980 and 2019 in an English language peer-reviewed journal, conference proceeding, or as a professional report. The literature has been searched by using the following keywords: "road markings," "pavement markings," "retroreflectivity of road markings," "road markings and road safety," "road markings and driver behaviour," and "visibility of road markings." The search was conducted on the following databases: Current Contents, Science Citation Index, Science Citation Index Expanded, Scopus, and Transportation Research Record. The authors also conducted a search based on keywords using Google services, since part of the studies is of a professional nature (reports) and not comprised in academic databases, but nevertheless contains valuable findings.

Each study containing the mentioned keywords has been examined for inclusion by at least two members of the research team, first based on the title and the abstract, followed by a full paper review. Disagreements were resolved based on a consensus reached between two reviewers.

After having reviewed the academic databases, articles, and professional reports, a total of 71 studies have been chosen to be part of this review. Literature selection process and categorization are presented in Figure 1.

3. Results

As mentioned in the Methodology section, based on their topic, the studies have been divided into two groups: (1) studies on the impact of road markings on driver behaviour (36 studies) and (2) studies on the impact of road markings on road safety (35 studies).

3.1. Studies on the Impact of Road Markings on Driver Behaviour. As road markings are located in the driver's central field of vision and mark the contours of the road, they have a significant impact on driver behaviour. Studies carried out to date have principally analysed the impact of road markings on driver behaviour in terms of maintaining the lateral position of the vehicle inside the lane and in terms of changing the driving speed in different road traffic situations (curves, transitions, intersections, etc.). From a total of 36 included studies, most of the studies, 19 in total, were conducted using a driving simulator, 13 were field studies, 3 were combined field and simulator research, while one was a meta-analysis. In order to provide a simpler overview, the studies have been further divided according to their research topic on studies related to the (1) impact of road markings width and configuration and (2) road markings as a measure for speed reduction and speed limit compliance. The first subsection analyses studies which investigated how road marking geometry, i.e., width and spacing between dashed lines, affects driving speed, lateral position of the vehicle, and driver's manoeuvres. On the other hand, in the second subsection studies which used different road markings as a perceptual measure for speed reduction and compliance, especially in hazard locations such as curves, intersections, and rural-urban transitions, will be presented.

3.1.1. Impact of Road Markings Width and Configuration. One of the first such studies was conducted in 1986, in which the authors examined the effectiveness of 10 temporary marking treatments on various measures of driver performance (speed and distance, erratic manoeuvres, and subjective comments and ratings of the treatments by the drivers) [11]. All the measures were tested in field experiment during dry weather and daytime, while the seven most effective ones have also been tested in night-time conditions. The study was conducted on a 9.7 km long test section of a 3.36 m wide two-lane and two-way roadway. The section included several horizontal curves, and the roadway was marked with a centre line and edge lines (outside the treatment zones). The treatments studied were placed on four horizontal curves. At these locations, the edge lines were interrupted 153 metres before the curve and were resumed 153 metres after the curve. The results of the study showed no significant differences among the treatments (both during the day and at night) in terms of impact on driver behaviour, that is, the speed and distance, or drivers' erratic manoeuvres.

A field study conducted in 1987 analysed the impact of different lengths of broken lines (0.31 m, 0.61 m, and 1.22 m) in work zones on driver behaviour [12]. The study was conducted on seven locations undergoing road works in the length from 772 to 2044 metres. All the locations included 3.66 m wide lanes, paved shoulders (l.22 to 3.05 m), yellow temporary centre line markings, and annual average daily traffic in the range from 2750 vehicles to 9600 vehicles. The results did not show a statistically significant difference among the tested lengths of road markings in terms of driving speed and the lateral position of the vehicle with respect to the centre line.

A similar field study was conducted in 1993 on a divided multilane facility, examining two temporary marking patterns: 0.61 m stripes with 11.59 m gaps and 1.22 m stripes with 10.98 m gaps [13]. Both patterns were compared with the full complement of markings (3.05 m stripes with 9.15 m gaps and edge lines). The authors used cameras to record the

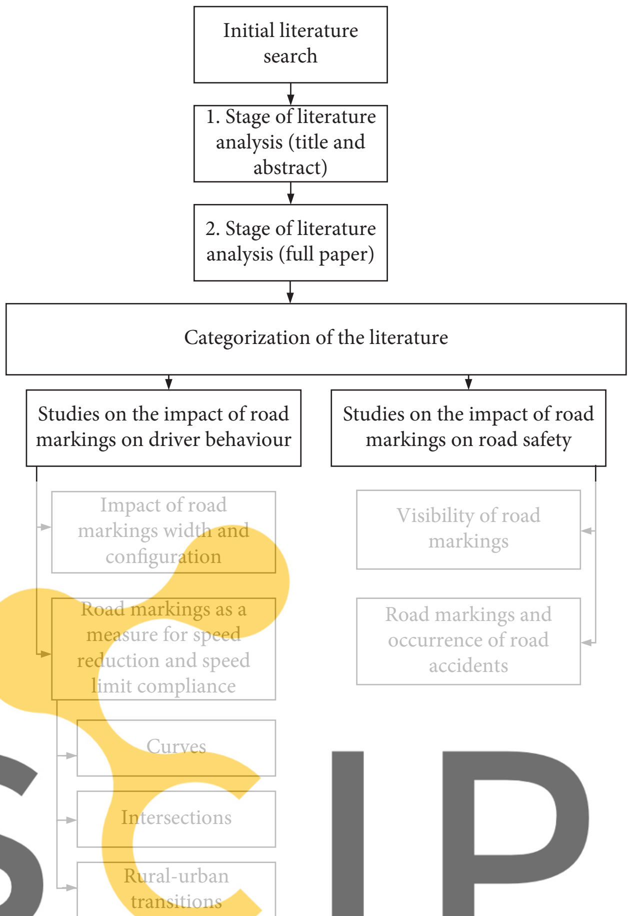

Figure 1: Literature selection process and categorization.

manoeuvres of each vehicle (a total of 436 vehicles) and to obtain the necessary measures of effectiveness (vehicle lateral position, speed within the test segment, number of edge line and lane line encroachments, and number of erratic manoeuvres) to evaluate driver performance related to the road marking patterns. For each examined measure, the results indicated that the drivers performed better (properly adjust the speed and lateral position and have less line encroachments) with the 3.05 m markings that included edge lines. The authors also noticed that the drivers generally performed better with the 1.22 m lane lines than with the 0.61 m lane lines, particularly under adverse weather conditions.

Lundkvist et al. analysed driver behaviour when driving on a straight road section (field study) marked with a 10 cm wide broken white edge line [14]. After that, the same road section was marked with 20 cm wide white marking placed closer to the edge of the road. The results of the study showed that, in the latter situation, the drivers changed the lateral position of the vehicle and their driving trajectory was closer to the edge of the road. This reduced the risk of a head-on collision as the distances between the passing vehicles increased.

The fact that the drivers change the position of the vehicle to be closer to the edge of the road when the road is marked with centre and/or edge lines was also recorded in a 2004 study [15]. Changes in the lateral position of the vehicle have been particularly noted on two-way roads, where it has been proven that the vehicles are systematically linearly moving away from the centre line. It starts when the vehicles are between 2.5 and 4 seconds apart and is increasing as they are coming closer. The study also reported an increase in driving speed on roads containing road markings compared to unmarked roads. This is due to an increase in the driver's sense of safety while driving on a road containing road markings, since they provide information on the road trajectory, thus allowing early identification of road areas that may constitute a hazard for road safety, such as curves, intersections, etc. However, an increase in driving speed has not been reported when edge lines were added on roads already containing the centre line and on roads where the centre line was replaced by edge lines.

Chang et al. studied the effects of longitudinal edge line road markings with varying deterioration levels and widths on driver behaviour and on their ability to maintain the lane position [16]. A sample of forty-eight licensed participants was tested in a driver simulation environment that replicated a two-lane rural highway. Every scenario was composed of multiple tiles that displayed appropriate roadway geometries and the surrounding daytime or night-time environment. Two different road marking widths (10 and 15 cm) and four different deterioration levels (0%, 25%, 50%, and 75%) were assessed in daytime and night-time conditions. The results suggested that the width of edge road markings has a statistically significant impact on drivers' lane deviation only in night-time conditions. In addition, during the simulation run, drivers were approaching the edge of the road and increasingly shifting away from the centre line as edge line deterioration worsened.

3.1.2. Road Markings as a Measure for Speed Reduction and Speed Limit Compliance. Several studies researched speed reduction measures related to road markings and their impact on driver behaviour. Maroney and Dewar (1988) conducted a field experiment aimed at evaluating the impact of transverse road markings on driving speed [17]. Transverse lines were painted apart at progressively diminishing distances to produce an alerting response and an illusion of vehicle acceleration. The data obtained during a 3.5-month period showed that the excessive speeding could be reduced by 40%. Daniels et al. presented the results of two evaluation studies (field and driving simulator) that analysed two additional types of road markings in order to support driver decisions regarding speed on 70 km/h roads in Belgium [18]. The first marking type was a white 0.5 m long line painted on the right side of the roadway close to the existing continuous edge line in the longitudinal direction and repeated every 50 m. The second type was a white number "7," marked close to the edge line like the first type and repeated every 50 m. Their impact on driver behaviour was evaluated in two ways: field study on four road segments and evaluation on a driving simulator. The results of the first part of the study did not show a significant impact of additional road markings on the driving speed. However, the evaluation on a driving simulator did report an impact of additional road markings on the lateral positioning of the vehicle.

Ding et al. carried out several driving simulator studies on this subject [19–21]. The studies were based on an analysis comprising vehicle operations and drivers' psychological and physical reactions. The results indicated that transverse speed reduction markings could significantly impact driver behaviour (speed and positioning) and that they could be implemented at downhill sections with roadway grades of 2%. On the other hand, longitudinal speed reduction markings could be placed in downhill sections with a roadway grade of 3%. Yotsutsuji et al. studied the effects of sequential transverse and lateral markings on perceived speed on a single-lane straight road using a driving simulator [22]. Different configurations of transverse markings with roadside poles were created by gradually decreasing the spacing between them. The results indicated that the perceived speed was higher than the actual vehicle speed.

Charlton et al. used a driving simulator to test the potential indicating speed limits with two types of road markings [23]. The first type was designed to provide visually distinct cues to indicate speed limits of 60, 80, and 100 km/h ("Attentional"), while the second type ("Perceptual") was designed to affect the drivers' perception of speed. The markings were compared to a standard undifferentiated set of markings. The participants were assigned to one of the four experimental groups (Attentional-Explicit, Attentional-Implicit, Perceptual-Explicit, and Perceptual-Implicit) or to a Control group. The Explicit groups were instructed on the meaning of road markings while the participants in the Implicit and Control groups did not receive any explanation. During the first run, the participants drove on five 10 km simulated roads containing three speed zones (60, 80, and 100 km/h). After approximately 3 days, the participants drove five more trials including roads they had not seen before, a trial that included a secondary task, and a trial where speed signs were removed with only markings present. The authors concluded that the association of road markings with specific speed limits may be a useful way to improve speed limit compliance and increase speed homogeneity.

Similar road marking measures were also used to alert drivers at curves, intersections, rural-urban transition road segments, and connectors. The risk of road accidents in the mentioned situations is high due to the changes in road geometry and trajectory, which requires adjusting driver behaviour.

(1) Curves. By conducting a field study in which the impact of edge markings on changes in the driving speed when going through curves was analysed, Shinar et al. found that perceptual measures and modifications may be an effective tool to affect the driver's behaviour in curves [24]. Agent and Creasy conducted a more extensive field research on driver behaviour when driving through curves [25]. The research comprised an impact assessment of raised pavement markers, transverse warning road markings, vibration markings, pillars, and chevrons. The results showed a significant decrease in the frequency of centre line encroachments or entering the lane intended for the opposite direction when using each of the above elements, but not a decrease in driving speed that was only observed when using chevrons.

Retting and Farmer conducted a field study on a suburban two-lane road in Northern Virginia involving a sharp left curve of about 90° [26]. By measuring speed, the authors determined a total decrease in the average driving speed by around 6% and 7% during daytime and night-time, respectively, due to the usage of an experimental marking that alerted drivers to the upcoming curve by means of text and an arrow.

Godley et al. conducted a systematic evaluation of the effectiveness of perceptual countermeasures to speeding [27]. Different treatments (narrower lane widths, inside hatching, centre line hatching, herringbone pattern, and reflector post positioning) were tested using a driving simulator. As for the impact of road marking measures, the report highlighted a significant reduction in speed, especially in case of full lane width and hatched median.

By using a driving simulator, Comte and Jamson tested four speed reduction measures for driving through curves, of which one involved transverse bars [28]. The results confirmed a significant potential of transverse bars for speed reduction. A similar study was conducted by Charlton in 2004 that compared the relative effectiveness of various types of warnings, including road markings, on driving speed at curves using a driving simulator [29]. A few years later, in 2007, Charlton again used driving simulator to test two types of curve treatments: warning signs and road markings [30]. Warning signs were placed before the curve in order to alert drivers and reduce the driving speed while approaching the curve. Road markings were designed to influence the speed and the drivers' lane position as they drove through curves. As for the road marking measures, the authors concluded that only rumble strips significantly reduce the speed, while herringbone road markings improve the drivers' lane positioning. Katz et al. evaluated peripheral transverse lines and their design [31]. They conducted a three-phase field study that included taking speed measures (1) before installation, (2) shortly after the installation, and (3) six months after the installation. The overall results showed that markings placed at 4 bars per second lead to a significant speed reduction, specifically when approaching curves. The same year, McGee and Hanscom published a report on the field evaluation of low-cost treatments for addressing identified or potential safety problems [32]. Several treatments had been studied, including basic different road markings solutions (rumble strips, optical speed bars, and curve advance markings). The report provided a description of each treatment with design features and showed some practical examples, suggesting when the treatment might be applicable as well as information on the safety effectiveness and costs of treatments.

Gates et al. evaluated the short- and long-term effectiveness of an experimental transverse bar road marking at a curve on a road in Milwaukee, based on a before-and-after analysis [33]. The experimental transverse marking treatment consisted of a series of white transverse bar markings installed by continuously decreasing the spacing between successive markings. The marking was installed in all lanes for each of the northbound and southbound directions of the curve. The overall findings confirmed that the treatment was effective in speed reduction when driving through curves. A lane-by-lane analysis showed that the marking treatment was most effective at reducing speed in the shoulder and middle lanes, while the speed in the median lane was relatively unaffected. Rosey et al., using driving simulator, tested four perceptual treatments (painted centre line, post delineators, rumble strips on both sides of the centre line, and sealed shoulders) to study their impact on driver behaviour on a rural road with different crest vertical curves [34]. The participants drove on a simulated straight rural road 3 km long with two crest vertical curves. The authors analysed four sections: the reference section (the first curve), the test section (the second curve), the pretest section (immediately before the second curve), and the posttest section (immediately after the second curve). The results showed that drivers drive more to the centre of their lane with rumble strips on both sides of the centre line and with sealed shoulders than with the typical centre line or other treatments.

Coutton-Jean et al. evaluated the role of edge lines when driving through curves by examining the driver behaviour in the face of unexpected gradual changes in road geometry using driving simulator [35]. The scenario consisted of a single-lane (3.80 m or 7.60 m wide) road with eight 90° curves with radii of curvature varying between 75 m and 500 m, separated by 500 m long straight-line segments. The authors used the model-based nature of the simulator to create unexpected online changes in road geometry. The changes were implemented through a gradual displacement of one or both edge lines while drivers steered around the delineated curve. The results showed that drivers consistently cut into and out of the curves. On the other hand, when the edge lines did not move, the drivers stabilized their lane position during the 20°–70° curve segments, adopting a position closer to the interior edge line for the narrower lane width and smaller radii of curvature. Generally, the displacement of the interior edge line (inward or outward) caused systematic changes in lane position, while the displacement of the exterior edge line did not affect driver behaviour.

A comparison of a simulator and a field test focused on the rural crest vertical curves was conducted in 2012 by Auberlet et al. [36]. A total of five treatments were tested on a driving simulator and two of them were applied on the field: rumble strips on both sides of the centre line and sealed shoulders. The results showed that the centre line rumble strips on the crest vertical curve affect the lateral positions, causing the participants to drive closer to the centre of the lane.

Montella et al. also conducted a driving simulator study to investigate driver behaviour when steering through curves on rural two-lane highways [37]. Different warning treatments were designed, aimed at alerting drivers on the presence of low radius curves and thus changing their behaviour, both while approaching the curve and when steering through it. The treatments consisted of advance warning signs and perceptual and delineation measures. Perceptual markings (dragon teeth, coloured strips, and medians) were found to have significant effects on driver behaviour, both in the approach tangent and inside the curve. The authors highlighted that the deceleration behaviour in the curve approach was significantly affected by the presence of treatments that helped the drivers to detect the curve earlier, providing more time to perform deceleration manoeuvres with lower rates. Using a driving simulator, Ariën et al. investigated the effect of transverse rumble strips and a backward pointing herringbone pattern on speed and lateral control when steering through and nearby curves [38]. Transverse rumble strips were found to be more effective in speed reduction, i.e., they generated an earlier and more stable speed reduction compared to the herringbone pattern. Transverse rumble strips were also more effective on the tangent which resulted in a better preparation of the drivers before the curve, while herringbone pattern reduced the driving speed along the curve. Overall, both treatments had a significant impact on the driving speed.

Calvi used driving simulator to study the effectiveness of three perceptual treatments (white peripheral transverse bars, red peripheral transverse bars, and optical speed bars) implemented along the approaching tangent to the crest vertical curve [39]. Their effectiveness was evaluated based on subjective measures consisting of the driver's static evaluation of the desired speed, risk perception, and markings comprehension and based on screenshot pictures that represented the simulated configurations of the treatments. The findings showed that the peripheral transverse bars, especially the red ones, provide the highest speed reduction (near to 6 km/h along the crest vertical curve), confirming their effectiveness in reducing the driving speed.

Using a driving simulator, Hussain et al. tested the impact of optical circles and herringbone patterns on driver behaviour while entering a curve on a two-lane rural road section [40]. The results showed that both treatments reduce driving speed before entering the curve, but the reduction was more gradual when optical circles were used. On the other hand, a herringbone pattern influenced the lateral position more than optical circles. Based on the results, the authors concluded that optical circles are an effective tool to reduce speed and increase drivers' attention and that a herringbone pattern could be used to reduce head-on collisions in curves.

(2) Intersections. In addition to evaluating the impact of road markings in curves, several studies investigated their impact on driver behaviour while approaching an intersection. Godley et al. used driving simulator to evaluate the impact of different treatments (transverse lines, peripheral transverse lines, a herringbone pattern, the Wundt illusion, and trees on the road edge) on driver behaviour while approaching an intersection [27]. The results showed a significant reduction in speed with all treatments. Thompson et al. conducted a field study to determine whether the transverse rumble strips are an effective warning device for drivers approaching rural

stop-controlled intersections [41]. For this purpose, the authors measured the driving speed on three locations along the approach to rural stop-controlled intersections, both before and after the installation of transverse rumble strips. Overall, transverse rumble strips generally produce small but statistically significant reductions in approach speeds. The amplitude of their impact during daytime and night-time and depending on different days of the week was not clearly determined. Using a driving simulator, Montella et al. investigated the effects of different perceptual treatments on several driving performances on major approaches to a rural intersection [42]. The method consisted of two runs on the test route. The authors used three different methods in the analysis: (a) cluster analysis of speed and lateral position data, (b) statistical tests of speed and lateral position data, and (c) categorical analysis of deceleration behaviour patterns. The results showed that the most effective treatments are the dragon teeth markings, the coloured intersection area, and the raised median island. These measures, in comparison with the base intersection, produced (1) a significant speed reduction starting from 250 m before the intersection in the range between 13 and 23 km/h, (2) a significant change in the deceleration behaviour with a reduction in the proportion of drivers which did not decelerate, and (3) a shift away from the intersection of the deceleration beginning. The same year, Zamora et al. presented their work which analysed the impact of five road marking patterns (transverse rectangular bars, peripheral square markings (staggered and nonstaggered), peripheral triangles, and width-increasing peripheral rectangular markings) on speed reduction while approaching key gateway intersections [43]. The study comprised a field study and a driving simulator part in which an optimal marking design was determined. The results showed that low-cost countermeasures encourage drivers to reduce speed as they approach intersections at urban gates. In addition, the peripheral square markings showed the best performance.

(3) Rural-Urban Transitions. In general, rural-urban transitions are a section of road that is continuous with and connects a road section with a high posted speed limit to a road section with a lower posted speed limit, and as such represent particularly risky locations in terms of safety.

The field study conducted by Lantieri et al. tested the effectiveness of different measures related to the gateway design [44]. The authors used before-after analysis of speed parameters and crash statistics as well as driver's eye movement in order to assess which components of the gateway were most looked at, how the gateway design could reduce distraction behaviour (gaze directed to nonrelevant driving targets), and how gaze behaviour was related to speed reductions. Twelve gateways located at the entrance and exit of 6 small towns on the Italian provincial route were analysed. Each design option consisted of a gateway preceded by 15 dragon's teeth markings (0.50 m × 1.50 m), extended town sign, curb, 4° chicane with raised island, and 3° gateway with "ghost" central island (defined only by a continuous boundary marking, without a curb). The results show that "ghost" central island affected speed reduction much less and that drivers had significantly shorter average fixation time compared to the raised island. In addition, dragon's teeth markings were looked on average for 152 ms, and although the drivers fixated more on curbs, authors highlight their positive effect.

Ding et al. explored the effects of longitudinal speed reduction markings on vehicle manoeuvring and drivers' operation performance on interchange connectors of different radii (50 m, 80 m, and 100 m) [21]. Using a driving simulator, the authors created two connectors of interest: one with and one without road marking measures. Based on the relative speed change, standard deviation of acceleration, and gas/brake pedal power, it was concluded that longitudinal speed reduction markings could reduce vehicle travel speed and limit drivers' willingness to increase speed in the entire connector. To further evaluate their impact, the connectors were divided into four even sections. The effects of the markings on driver behaviour were more significant in the second and the final sections of connectors. The measures also impacted drivers' adaptability in the first three quarters of a connector and their gas pedal operation in the entire connector when the radius was 50 m. On the other hand, the authors concluded that longitudinal road marking measures could only make drivers press brake pedal more frequently in the second section with 80 m and 100 m radius. In the second quarter section of a connector (from the first quartile point to the middle point), the markings had better effects on vehicle manoeuvring and drivers' operation performance.

Hussain et al. conducted a driving simulator study in order to investigate the impact of optical circles and bars on driver behaviour [45]. The measures were used to create perceptual effects and alert the drivers on road transitions between rural and urban areas where the speed limit reduces from 70 km/h to 50 km/h. The study results showed that the speed was reduced significantly for both road marking treatments, but they did not show a strong influence on standard deviation of acceleration/deceleration and lateral position of the vehicle. The results also suggested the optical circles with increasing size as the most effective solution.

Zhao et al. investigated how longitudinal speed reduction markings affect the vehicle operation and driver behaviour on direct connectors with different radii using a driving simulator [46]. The authors defined an analysis segment starting 500 m before the entering point of the connector and ending at the exiting point of the connector. In order to gain a more detailed overview of driver behaviour, the authors also divided this segment into a series of 50 m long subsections. The analytical results indicated that the longitudinal speed reduction markings may be effective at reducing speeds when the radius of the direct connector is 300 m.

The summary of the studies related to the impact of road markings on driver behaviour is presented in Table 1.

3.2. Studies on the Impact of Road Markings on Road Safety. As presented in the previous section, road markings affect driver behaviour which is why vast body of literature studied

Table 1: Summary of the studies related to the impact of road markings on driver behaviour.

Authors and year	Type of the study	Conditions	Analysis type	Variables
Road markings and driver behaviour: impact of road markings width and configuration				
Dudek et al. (1986) [11]	Field	Daytime and night-time	Comparison of the treatments	Driving speed, distance, lane encroachment, erratic manoeuvres, subjective comments, and rating of the treatment
Dudek et al. (1987) [12]	Field	Night-time	Comparison of the treatments	Driving speed, lateral position
Harkey et al. (1993) [13]	Field	Daytime and night-time	Comparison of the treatments	Vehicle manoeuvres, lateral position, driving speed, lane line encroachments
Lundkvist et al. (1990) [14]	Field	—	Comparison of the treatments	Driving speed and lateral position
Davidse et al. (2004) [15]	—	—	Meta-analysis	
Chang et al. (2019) [16]	Driving simulator	Daytime	Comparison of the treatments	Lateral position
Road markings and driver behaviour: road markings as a measure for speed reduction and speed limit compliance				
Maroney and Dewar (1988) [17]	Field	Daytime and night-time	Comparison of the treatments	Driving speed
Daniels et al. (2010) [18]	Field and driving simulator	Daytime	Comparison of the treatments	Driving speed
Ding et al. (2013) [19]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, vehicle manoeuvres
Ding et al. (2014) [20]	Driving simulator	Daytime	Comparison of the treatments	Driving speed
Ding et al. (2016) [21]	Driving simulator	Daytime	Comparison of the treatments	Driving speed
Yotsutsuji et al. (2015) [22]	Driving simulator	Daytime	Comparison of the treatments	Perceived, actual speed
Charlton et al. (2018) [23]	Driving simulator	Daytime	Comparison of the treatments	Driving speed
Road markings and driver behaviour: road markings as a measure for speed reduction in curves				
Shinar et al. (1980) [24]	Field	Daytime	Comparison of the treatments	Driving speed, perceived angle of the curve
Agent and Creasy (1986) [25]	Field	Daytime and night-time	Before-after analysis	Driving speed, lane encroachment
Retting and Farmer (1988) [26]	Field	Daytime and night-time	Before-after analysis	Driving speed
Godley et al. (1999) [27]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position, lateral variation, steering effort
Comte and Jamson (2000) [28]	Driving simulator	Daytime	Comparison of the treatments	Driver performance, workload, and acceptability of the treatment
Charlton (2004) [29]	Driving simulator	Daytime	Comparison of the treatments	Driving speed
Charlton (2007) [30]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position
Katz et al. (2006) [31]	Field	Daytime and night-time	Before-after analysis	Driving speed
McGee and Hanscom (2006) [32]	Field	—	Evaluation of different road marking measures	—
Gates et al. (2008) [33]	Field	Daytime and night-time	Before-after analysis	Driving speed
Rosey et al. (2008) [34]	Driving simulator	Daytime	Comparison of the treatments	Lateral position
Coutton-Jean, Mestre et al. (2009) [35]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position
Auberlet et al. (2012) [36]	Driving simulator and field	Daytime	Comparison of the treatments	Lateral position

Table 1: Continued.

Authors and year	Type of the study	Conditions	Analysis type	Variables
Montella et al. (2015) [37]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, driving behaviour (deceleration)
Ariën et al. (2017) [38]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position, acceleration/deceleration
Calvi (2019) [39]	Driving simulator	Daytime	Comparison of the treatments	Driving speed
Hussain et al. (2019) [40]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position
Road markings and driver behaviour: road markings as a measure for speed reduction at intersections				
Godley et al. (1999) [27]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position, lateral variation, steering effort
Thompson et al. (2006) [41]	Field	Daytime and night-time	Before-after analysis	Driving speed
Montella (2011) [42]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, deceleration, lateral position
Zamora et al. (2011) [43]	Field and driving simulator	—	Comparison of the treatments	Driving speed
Road markings and driver behaviour: road markings as a measure for speed reduction at rural-urban transitions				
Lantieri et al. (2015) [44]	Field	Daytime	Before-after analysis	Driving speed, crash data, eye movement
Ding et al. (2016) [21]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, manoeuvring
Hussain et al. (2018) [45]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, lateral position, acceleration/deceleration
Zhao et al. (2018) [46]	Driving simulator	Daytime	Comparison of the treatments	Driving speed, deceleration, control of the throttle

their overall influence on road safety. Such studies primarily investigated the general visibility or retroreflectivity of road markings as well as their presence on the occurrence of road accidents. In order to provide a simpler overview, the studies have been further divided according to their research topic on studies related to the general visibility of road markings and studies related to the impact of road markings on the occurrence of road accidents.

3.2.1. Visibility of Road Markings. Studies related to the general visibility of road markings were mainly focused on determining the maximum detection distance for road markings and the minimum levels of retroreflectivity required by drivers in dry and wet conditions, as well as other factors affecting road marking visibility.

One of the first such studies was conducted in 1999, in which authors (Zwahlen, Schnell, and Miescher) set up a field study in order to determine how various types of road marking arrows affect recognition distance [47]. Five arrow designs, at both full scale and half scale, were tested. Ten young subjects drove a vehicle equipped with a distance-measuring instrument and were asked to indicate what direction the arrow pointed to at the earliest point when they could correctly do so. The results showed that the elongated full-scale arrows provide significantly longer recognition distances than their standard full-scale counterparts. The design of the half-scale arrows did not affect recognition distances. On the other hand, the authors highlighted that successive pairs of half-scale standard arrows provide longer recognition distances than a single application of the full-scale standard arrow.

Other experimental field studies have shown that the maximum detection distance for road markings increases with an increase in their retroreflectivity, but disproportionately [48, 49]. According to the results of the experimental studies, road markings of retroreflectivity of 100 mcd/lx/m^2 are visible on average from 91.44 m away, while those of retroreflectivity of 300 mcd/lx/m^2 from 121.92 m away.

There are significantly more academic studies on the visibility of road markings that are focused on determining the minimum levels of retroreflectivity required by drivers in dry and wet conditions. Graham et al. published the results of a field study conducted to determine the subjective level of retroreflectivity required by older drivers when driving with low-beam headlamps [50]. A total of 65 participants aged from 20 to 89 years were interviewed, by assessing 24 road segments, with different values of road markings retroreflectivity for each segment. The results of the study showed that more than 85% of participants over 60 years old rated the retroreflectivity value of 100 mcd/lx/m^2 as minimal or sufficient.

Zwahlen and Schnell conducted a field study aimed at testing and validating the hypothesis that drivers adjust their spatial scanning behaviour and driving speed as a function of road markings visibility [51]. The study was conducted on four rural two-lane roads. In the first part of the study, the roads contained existing (old) road markings, and in the second part, the markings were renewed. The results indicated that drivers have very short eyes-on-the-marking time and that they do not reduce driving speed in low visibility conditions (with existing markings) compared to the speed at higher visibility levels (with renewed markings). However, the longitudinal distance of eye fixations of the drivers has systematically and consistently reduced in conditions of low visibility of road markings. By using a computer-aided road markings visibility evaluator, the authors found that there was a significant difference in subjective ratings of minimum levels of retroreflectivity between young and older drivers [52].

Similar research has been conducted in 2000, 2003, and 2007 [53–55]. The results of the studies suggested the retroreflectivity values of 120, 150, and 130–140 mcd/lx/m^2 as the minimum required for safe driving for human drivers.

In addition to the above studies aiming to determine the minimum retroreflectivity values in dry conditions, a number of studies have been conducted to gain insight into drivers' needs in wet night-time conditions.

Gibbons and Hankey by conducting the experimental study found that tape as a road marking material has the best visibility and the longest detection distance in wet conditions [56]. Thermoplastic materials have similar results, while paint scored the lowest. The authors also determined the existence of a log-linear relationship between the detection distance and the retroreflectivity value. Higgins et al. evaluated the visibility of road markings with specially designed retroreflective materials (glass beads) for wet conditions in experimental field study [57]. The study included three types of retroreflective materials on paint road markings and tape road markings. All the systems were tested at night in dry, wet, and rainy conditions in a closed test site. In wet conditions, all three types of glass beads on both materials (both paint and tape) retained between 60% and 80% of their average daily detection distance, while in rainy conditions it dropped to values between 50% and 70% of their average daily recognition distance. In comparison, standard retroreflective materials on paint road markings maintained between 17% and 28% of their average daily recognition under the same conditions. Based on a subjective assessment of visibility of road markings made of four different materials in experimental field study with simulated rainy conditions, Gibbons, Williams, and Cottrell propose 150 mcd/lx/m^2 as the minimum retroreflectivity value for both white and yellow markings in dry and wet conditions [58]. This minimum is the same for white and yellow road markings.

Overall, road markings retroreflectivity (initial as well as long term) depends on a number of different factors, such as quality, embedment and density of glass beads, material type, age, road type, number of lanes per roads, snow maintenance activities, amount and speed of traffic, direction of stripping, and type and roughness of roadway. In this section, we will only focus on the main factors: glass bead quality and the effects of their embedment and density, direction of stripping, and type and roughness of roadway on the retroreflectivity of road markings.

An extensive laboratory study of glass beads quality was conducted in 2013 within the National Cooperative Highway Research Program [59]. The quality of glass beads was evaluated based on their characteristics: gradation, roundness, colour, air inclusion, and coating. Although there is a connection between glass beads properties and retroreflectivity, a definitive relationship has not been determined. The project developed a recommended laboratory test to predict the initial retroreflectivity of road markings on the field, based on the quality of glass beads.

The embedment of glass beads directly affects retroreflectivity and service life of road markings. If a glass bead is underembedded, its retroreflectivity and service life will be decreased. Underembedded beads will not have a strong enough attachment to the material and will easily fall off due to the effect of friction and forces of vehicle tyres or snowploughs, which will lead to a faster degradation of the road markings retroreflectivity and their service life. Due to the small surface inside the material, a light ray will not always be able to reflect from the material back to the driver, but it will pass through the bead, which will decrease retroreflectivity. On the other hand, if the glass bead is overembedded, its initial retroreflectivity will be reduced because the surface through which light can enter the bead and be reflected to the source will be smaller. However, road markings with overembedded beads will generally have a longer service life than road markings with underembedded beads. In the course of exploitation and wear of road markings, these beads will slowly emerge onto the surface of the material and maintain retroreflectivity over a longer period. The optimal embedment of glass beads is between 50% and 60%. Generally, new road markings will have 70% of all beads embedded over 60% or fully embedded, and 30% of the beads will be optimally embedded or underembedded [59–61]. Deviations from optimum embedment are to a certain extent desirable because the underembedded beads will provide initial retroreflectivity, while the overembedded ones will provide consistency of retroreflectivity over time.

Zhang et al. analysed the impact of bead density on retroreflectivity of paint road markings [62]. The authors defined bead density as "the surface percentage of glass beads exposed above the paint marking material." Using a computer-aided counting method, the authors analysed 108 images of road markings to obtain the bead density value for each image. The findings of the study showed that bead density values have a positive correlation with road markings retroreflectivity readings and that higher bead density leads to higher retroreflectivity. The authors also concluded that white paint markings have significantly higher retroreflectivity values than the yellow ones of the same bead density values.

The type and roughness of the roadway also affect the retroreflectivity of road markings. Based on the data collected on two-lane highways in North Carolina, Zhang et al. found that the mean values of retroreflectivity measurements for the plant-mixed roadways are significantly higher than those for the bituminous surface roadways [63]. In addition, the mean left-wheel international roughness index (IRI) values and right-wheel IRI values for plant-mixed roadways were lower than those for the bituminous roadways. Based on the results, the authors proposed the use of thicker and more compact road marking materials on bituminous surface roadways in order to provide drivers with a more consistent and uniform road markings retroreflectivity.

During practical work related to the placement of road markings, it has been found that glass beads have a horizontal velocity when sprayed from a pressurized dispenser, which may cause more paint resin to cover one side of their surface than the other, i.e., more headlight will enter and be retroreflected back from the glass beads in one direction than in the other. This may result in different retroreflectivity values of the same marking for the opposite driving directions. This effect was first analysed by Rasdorf et al. in 2009 [64]. Based on field measurements made using a handheld retroreflectometer in both directions, the authors concluded that retroreflectivity values of paint centre line measured in the direction of paint striping are significantly higher (up to 66 mcd/lx/m^2) than the values measured in the opposite direction. Sarasua et al. obtained similar results based on the same methodology [65]. On average, waterborne markings exhibited 29.8% higher directional readings, while thermoplastic markings exhibited 9.6% higher directional readings. Babić et al. used the dynamic measuring method to evaluate the effect of the directionality of road markings retroreflectivity for paint, thermoplastic, and structural cold plastic markings [66]. As stated by the authors, the dynamic measuring method has a longer and wider measuring field which covers the whole width of the marking compared to static devices which cover just a small part of it. Greater measuring field (≥1000 × 880 mm) and greater amount of collected measurements enabled a more objective evaluation of the quality of retroreflectivity along the entire length of the road section. Based on the results of dynamic measurements on 30 roads (20 had paint road markings, 5 thermoplastic markings, and 5 structural cold plastic road markings), the authors concluded that the impact of the directionality of paint and flat thermoplastic markings on their retroreflectivity is negligible, while the absolute mean difference is evident for structural cold plastic markings (from 49.60 mcd/lx/m^2 to 62.80 mcd/lx/m^2). In another study, same authors (2016) modelled the daytime visibility of road markings based on their night-time visibility [8].

3.2.2. Road Markings and Occurrence of Road Accidents. Studies related to the impact of road markings on road safety investigated how their presence and visibility or retroreflectivity affects the occurrence of road accidents. One of the first such studies was conducted in 1981 with the aim of analysing the impact of road marking enhancements on road safety. Road marking enhancement implied adding centre and/or edge lines on the roadway. After comparing the number of road accidents involving injuries and/or fatalities before and after the enhancement of road markings, it was concluded that their number decreased significantly (ranging from 3% to 16% depending on the method of road marking enhancement) [67]. In 1994, Al-Masaeid and Sinha evaluated the safety effectiveness of road markings on 100 randomly selected undivided rural roads in the state of Indiana [68]. The analysis was done based on determining a proportion of expected accident rates from an estimation based on accident reduction factors at the individual site level. In order to eliminate the effect of regression to the mean, authors used a Bayesian approach to estimate expected accident rates in the before and after periods. No statistically significant safety impact was observed when markings were considered at all sites without respect to their accident experience. On the other hand, at hazardous sites, road markings provided a significant level of accident reduction. Tsyganov et al. conducted a before-and-after impact assessment of adding edge lines on road safety on a two-lane road in Texas [69]. According to the results of the study, the authors concluded that roads without edge lines have an 11% higher risk of road accidents than roads with edge lines. The presence of edge lines also had positive effects on road safety in low visibility conditions.

Park et al. analysed the impact of road markings width on road safety on rural two-lane highways in the area of Michigan, Kansas, and Illinois [70]. The study was based on a before-and-after analysis of road crash data, and the results indicated that wider edge lines reduced vehicle crashes with the highest crash reduction percentage in the fatal plus injury category (Kansas: 36.5%, Michigan: 15.4%, and Illinois: 37.7%).

Several studies were focused on establishing a correlation between visibility and retroreflectivity of road markings with the occurrence of road accidents, especially in night-time conditions when the retroreflectivity comes to the fore. Namely, during daytime, the visibility of road markings is based on the colour contrast between the marking and the roadway and is generally not an issue since there is sufficient light. On the other hand, during night-time, the amount of light available to the drivers reduces, which narrows and shortens the human field of vision and impairs the perception of colour, shape, texture, contrast, and movement. For us to see the road markings, there has to be luminous contrast between them and the road surface, which is determined by the road markings retroreflectivity [62].

As part of the National Cooperative Highway Research Program, a study was conducted in 2002 to determine the impact of road markings retroreflectivity on road accidents [71]. In the first stage, the analysis included locations with solvent-based markings (48 locations in total) and epoxy paint markings (7 locations in total). In the second stage of the study, new road markings were made using longer-lasting materials on 55 locations. The length of the section, the time for conducting the study (in days), the annual average daily traffic, and the proportion of annual daily traffic in daytime, night-time, dry, and wet conditions was taken into account in all locations. The results showed that the number of road accidents in night-time conditions decreased by 6% after renewing the road markings, i.e., increasing their retroreflectivity.

A New Zealand study from 2006 analysed the impact of road markings retroreflectivity on the occurrence of road accidents and thus on traffic safety. The overall conclusion was that there is no statistically significant correlation between the number of road accidents and road markings retroreflectivity [72]. Similar study was conducted in 2006 under the National Cooperative Highway Research Program, where it was concluded that the difference in road safety in night-time conditions on roads with high markings retroreflectivity and those with low retroreflectivity is approximately zero [73]. However, that same year Horberry, Anderson, and Regan, using a driving simulator, showed that participants were better able to maintain lane position and speed with the "enhanced" markings than with the "standard" markings [74]. The participants also reported that the run with the "enhanced" markings was much easier and that they were feeling more confident in being able to drive safely. This was to some extent, in 2008, confirmed by Smadi et al. [75]. The authors concluded that low retroreflectivity markings are not associated with more road accidents. However, road markings with a retroreflectivity greater than 200 mcd/lx/m^2 have a negative correlation with the number of road accidents. According to the authors, this correlation is still too small to be of any significance on the practical side.

The above three studies [72, 73, 75] also have certain limitations that ultimately affect their results. In the New Zealand study, the authors also considered roads with raised reflective road markers [72]. In the second study [73], the retroreflectivity of road markings used in the analysis was not measured but modelled, which is why discrepancies and errors are possible. In the third study [75], the retroreflectivity of road markings was measured in an area about 60 m long and the average retroreflectivity in the area was taken as the reference for the whole section about 8 km long. As retroreflectivity may vary within a few metres, it is possible that the values used in the study are inconsistent with the real situation. Another shortcoming of the study, as the authors emphasized, is the lack of complete data on road accidents.

A follow-up to the last study [75] was carried out in 2010 on the basis of retroreflectivity data from the previous five years and data on 1343 road accidents. Based on the analysis, it was concluded that road markings retroreflectivity is a significant factor affecting the probability of occurrence of road accidents when considering only data from interstate roads and when the data are divided into three subsets by line type, namely, white edge lines, yellow edge lines, and yellow centre lines. Ultimately, the analysis of white edge lines and yellow centre lines led to a conclusion that the probability of occurrence of road accidents increases as the road markings retroreflectivity decreases [76].

Carlson et al. conducted a study that considered only road accidents that occurred at night on road sections with no intersections and in dry conditions [77]. In the analysis, the authors considered only accidents that occurred during the night, namely, those involving only one vehicle without injuries or fatalities, accidents involving fatalities and injuries, and accidents involving one vehicle with fatalities and injuries. The results of the study supported the assumption that road markings retroreflectivity have a positive impact on road safety. Avelar and Carkson in 2014 found that there is a statistically significant correlation between road markings retroreflectivity and road accidents in night-time conditions and that locations with higher retroreflectivity are associated with fewer road accidents compared to locations with lower road markings retroreflectivity [78]. Likewise, locations with lower retroreflectivity of centre lines, compared to the retroreflectivity of edge lines on the same road, are associated with a more frequent occurrence of road accidents. In a 2016 study, Aldemir-Bektas et al. investigated the impact of road section length, type of road marking, and the value of their retroreflectivity on the frequency of road accidents [79]. The results of the study showed that the analysis of shorter road sections and actual measured values of road markings retroreflectivity led to a statistically significant correlation between road markings retroreflectivity and the rate of road accidents and that the expected annual rate of road accidents is significantly reduced with the increase of retroreflectivity of white and yellow edge lines. The results also indicated that maintaining road markings has significant positive effects on road safety.

In a recent study based on empirical Bayes before-and-after analysis and full Bayes before-and-after analysis with comparison groups, Park et al. found that wet weather road markings may provide positive safety effects on wet-night road accidents [80].

The summary of the studies related to the impact of road markings on road safety is presented in Table 2.

4. Discussion, Future Recommendations, and Limitations

As part of the traffic control plan, road markings delineate the traffic surface and provide visual guidance for road users. Since their first application to present day, road markings have become a common element of transport infrastructure. The aim of this paper is to provide a systematic review of the most significant academic activities to date regarding the influence of longitudinal and transverse road markings as well as road markings for hazard locations (curves, intersections, and rural-urban transitions) on driver's behaviour and overall road safety.

This review included 52 peer-reviewed journal studies, 4 conference proceedings, and 15 professional reports, which were divided into two categories as follows: (1) studies on the impact of road markings on driver behaviour and (2) studies on the impact of road markings on road safety. Most of the studies, 45 of them, were field-based studies, followed by driving simulator studies, 22 of them, while others were laboratory-based.

In terms of impact on driver behaviour, the research has principally analysed the lateral position of the vehicle within the lane and driving speed. Their results indicate that road markings impact both the lateral lane position and driving speed of vehicles. On roads without edge lines, drivers drive closer to the centre line. One reason for this is that the centre line is located on the driver's side of the vehicle, providing a clear and convenient reference used by drivers for lateral lane positioning in the absence of road edge demarcation. While this may reduce the likelihood of running off road, it

Table 2: The summary of the studies related to the impact of road markings on road safety.

Authors and year	Type of the study	Conditions	Variables	Highlights
Visibility of road markings: detection and recognition distance of road markings				
Aktan and Schnell (2004) [48]	Experimental field study	Night-time, dry, wet, and simulated rain	Detection distance, retroreflectivity	Maximum detection distance for road markings increases with an increase in their retroreflectivity
Finley et al. (2002) [49]	Experimental field study	Night-time	Legibility and detection distance, vehicle type (passenger car vs. commercial vehicle), marking material	
Zwahlen, et al. (1999) [47]	Experimental field study	Daytime and night-time	Recognition distances	(1) Elongated full-scale arrows provide significantly longer recognition distances compared to standard full-scale arrows (2) Successive pairs of half-scale standard arrows provide longer recognition distances than a single application of the full-scale standard arrow
Visibility of road markings: defining the minimal retroreflectivity values required for drivers in different conditions				
Graham et al. (1996) [50]	Field study	Night-time	Subjective evaluations, quantitative measures of markings	More than 85% of participants over 60 years old rated the retroreflectivity value of 100 mcd/lx/m^2 as minimal or sufficient
Zwahlen and Schnell (1997) [51]	Field study	Night-time	Eye-scanning behaviour, driving speed, markings visibility	(1) Drivers have very short eyes-on-the-marking time and that they do not reduce driving speed depending on the visibility of markings (2) The longitudinal distance of eye fixations of the drivers has systematically and consistently reduced in conditions of low visibility of road markings
Zwahlen and Schnell (2000) [52]	Computer modelling	Night-time	Driving speed, preview time, presence of raised pavement markings	Derived minimum retroreflectivity values for fully marked roads without and with raised pavement markers
Visibility of road markings: defining the minimal retroreflectivity values required for drivers in different conditions				
Loetterle et al. (2000) [53]	Experimental field study	Night-time	Markings visibility (separately for the edge and centre lines)	Minimal retroreflectivity values required for safe driving between 120 and 150 mcd/lx/m^2
Parker and Meja (2003) [54]	Field study	Night-time	Subjective ratings, retroreflectivity measurements	
Debaillon (2007) [55]	Computer modelling	Night-time	Marking configuration, road surface type, vehicle speed, vehicle type, presence of raised pavement markers	
Gibbons and Hankey (2007) [56]	Experimental field study	Rain, night-time	Detection distance, material type, lighting condition, glare, pavement type, vehicle type	(1) Lighting improved visibility and mitigated the effects of glare (2) Wet retroreflective tape provided the longest visibility distance, followed by a profiled thermoplastic (3) Large glass beads with standard paint provided the shortest visibility distance

Table 2: Continued.

Authors and year	Type of the study	Conditions	Variables	Highlights
Higgins (2009) [57]	Experimental field study	Night-time, dry, wet, and rain	Type of retroreflective material, detection distance	(1) In wet recovery, all three prototype marking systems and the wet-reflective tape sustained 60% to 80% of their dry average detection distances (2) In rain, they sustained 50% to 70% of their dry average detection distances (3) The average wet-recovery and rain detection distances for the conventional glass beads-on-paint benchmark system dropped to 28% and 17% of the dry detection distance, respectively
Gibbons et al. (2012) [58]	Experimental field study	Wet, night-time	Type of material, detection distance	Minimum retroreflectivity of 150 mcd/lx/m^2 for white and yellow pavement markings in both dry and wet night-time conditions
NCHRP (2013) [59]	Laboratory testing	—	Type of retroreflective material	(1) Established connection between glass beads properties and retroreflectivity (2) Developed a recommended laboratory test to predict the initial retroreflectivity of road markings on the field, based on the quality of glass beads
Visibility of road markings: determine the influence of different factors on retroreflectivity of road markings				
Burns et al. (2008) [60] O'Brien (1989) [61]	Laboratory testing	—	Embedment of glass beads	(1) Optimal embedment of glass beads: between 50% and 60% (2) New road markings have 70% of all beads embedded over 60% or fully embedded and 30% of the beads optimally embedded or underembedded
Zhang (2010) [62]	Field and laboratory study	—	Bead density, markings retroreflectivity	Bead density values are positively correlated with road markings retroreflectivity
Zhang et al. (2013) [63]	Field study	—	Asphalt type and roughness	Mean values of retroreflectivity measurements for the plant-mixed roadways are significantly higher than those for the bituminous surface roadways
Rasdorf et al. (2009) [64]	Field study	—	Direction the markings application, markings retroreflectivity	Retroreflectivity values of paint centre line measured in the direction of paint striping are significantly higher (up to 66 mcd/lx/m^2) than the values measured in the opposite direction
Sarasua (2013) [65]	Field study	—	Direction the markings application, type of the material, markings retroreflectivity	Waterborne markings exhibited 29.8% higher directional readings, while thermoplastic markings exhibited 9.6% higher directional readings
Babić et al. (2016) [8]	Field study	—	Daytime and night-time visibility	Developed model for calculating daytime visibility of road markings based on their retroreflectivity
Babić et al. (2018) [66]	Field study	—	Direction the markings application, type of the material, markings retroreflectivity	(1) Impact of directionality of paint and flat thermoplastic markings on their retroreflectivity is negligible (2) A significant difference was noted with structural markings made of cold plastic
Road markings and occurrence of road accidents				
FHA (1981) [67]	Field	Before-after comparison	Number of road accidents involving injuries and/or fatalities	From 3% to 16% decrease in the number of accidents

Table 2: Continued.

Authors and year	Type of the study	Conditions	Variables	Highlights
Al-Masaeid and Sinha (1994) [68]	Field	Before-after comparison	Proportion of expected accident rates	No statistically significant safety impact except at hazardous sites
NCHRP (2002) [71]	Field	Before-after comparison	Length of the section, annual average daily traffic, proportion of annual daily traffic in daytime, night-time, dry, and wet conditions	6% decrease in the number of road accidents in night-time after the marking's renewal
Tsyganov et al. (2006) [69]	Field	Before-after comparison	Number of road accidents	Decrease in the safety risk with implementation of edge lines
Dravitzki et al. (2006) [72]	Field	Before-after comparison	Retroreflectivity of road markings, number of accidents	No statistically significant correlation between the number of road accidents and road markings retroreflectivity
NCHRP (2006) [73]	Field	Before-after comparison		
Horberry (2006) [74]	Driving simulator	Comparison of the treatments	Driving speed, lateral position	Improved lane position and speed with "enhanced markings"
Smadi et al. (2008) [75]	Field	Comparison of the treatments	Retroreflectivity of road markings, number of accidents	Low retroreflectivity markings are not associated with more road accidents. Markings with higher retroreflectivity (>200 mcd/lx/m^2) have a low negative correlation with the number of road accidents
Smadi (2010) [76]	Field	Comparison of the treatments	Retroreflectivity of road markings, number of accidents	Retroreflectivity significantly affects the probability of occurrence of road accidents
Park et al. (2012) [70]	Field	Before-after comparison	Daytime and night-time	Crash frequency and width of the markings
Carlson et al. (2013) [77]	Field	Comparison of the treatments	Retroreflectivity of road markings, number of night-time accidents	Positive impact of markings on safety
Avelar and Carlson (2014) [78]	Field	Comparison of the treatments		Statistically significant correlation between markings retroreflectivity and number of accidents
Aldemir-Bektas et al. (2016) [79]	Field	Comparison of the treatments		
Park et al. (2019) [80]	Field	Before-after comparison		Wet weather road markings provide positive safety effects on wet-night road accidents

may increase the risk of a head-on collision. With the presence of wider road markings (≥15 cm), drivers approach the edge of the road more closely, which reduces the risk of head-on collisions, although it may increase the risk of run-off-road collisions in certain situations. Nevertheless, delineation of both the roadway centre and edge will, in most cases, improve vehicle lane positioning and reduce lane departure crash risk.

Different road marking designs (transverse lines, herringbone and dragon teeth patterns, optical circles, etc.) proved to be a positive speed reduction and compliance measure, especially in hazard locations, i.e., places where road geometry and trajectory change (curves, rural-urban transitions, intersections, etc.). All measures showed a statistically significant impact on driver behaviour. In principle, flat and rumble transverse lines were found to be the most effective in reducing the speed prior to curves. A herringbone pattern reduced driving speed along the curves and influenced the lateral position of the vehicle, thus reducing the risk of head-on collisions in curves.

Road markings are particularly important in night-time conditions when the amount of light available to the drivers reduces, which narrows and shortens the human field of vision and impairs perception of colour, shape, texture, contrast, and movement. In these conditions, the most significant characteristic of road markings is their retroreflectivity, that is, the potential of the material to reflect light by creating a greater luminosity of the surface during night-time conditions. Although studies carried out to date regarding the impact of road markings retroreflectivity on the occurrence of road accidents provided inconclusive results, the prevailing opinion is that road marking retroreflectivity has a positive impact on road safety. In other words, road markings of higher retroreflectivity will provide better visual guidance during darkness and thus reduce the risk of road accidents. Academic studies have shown that the maximum detection distance for road markings increases with an increase in their retroreflectivity and that drivers require a minimum level of retroreflectivity ranging from 100 to 150 mcd/lx/m^2 in dry conditions and about 150 mcd/lx/m^2 in wet conditions.

The summary of the main findings of analysed studies is presented in Table 3.

Although there is a considerable amount of research on road markings, there are still some "gaps" in the available literature. This relates primarily to a more detailed study of the correlation between the retroreflectivity of road markings and the incidence of road accidents in dry and wet conditions. Due to the complexity of road accidents and the number of contributing factors, determining the exact impact of retroreflectivity on road safety is a complex task. Therefore, further, a highly controlled research evaluation is needed to better understand how and to what extent the level of retroreflectivity affects road safety. The main problem related to this is data collection. Namely, available studies connected the accidents which occurred on the specific road sections with the markings retroreflectivity which was, in most of the studies, measured on the segments of analysed road section using handheld retroreflectometer which has some shortcomings. Due to their small measuring range, the static retroreflectometers fail to measure retroreflectivity along the entire width and length of road markings. Furthermore, moving the static device by less than a centimetre in any direction on the road marking might lead to significantly different measurements. Finally, the accuracy of the measurement may be influenced by the controller: an experienced controller might find places showing high or low retroreflection and thus directly affect the measurement results [81]. An additional problem is related to the accuracy of the accident data. In order to get more relevant insight, the retroreflectivity of the markings should be measured immediately after accidents occur using a dynamic measuring method which provides more relevant results on the entire road section. By connecting the true retroreflectivity values with the data from in-depth analysis of specific accidents (mainly single vehicle night-time crashes), a clearer impact of markings on road safety during night-time conditions could be achieved.

In connection with the aforementioned, research activities should also be focused on the evaluation of the glass bead quality on the retroreflection of road markings. Namely, the quality of the glass beads is determined based on their granulation and refraction index, gradation, roundness, colour, air inclusion, and coating. The impact of these variables on the retroreflectivity of road markings is still underexplored.

Since the world population is aging, the need for "good" road markings (a "good" is marking that at all times remains visible to both the driver and the intelligent vehicle irrespective of light conditions (day vs. night), weather conditions (dry vs. wet vs. wet and rainy), and age (young vs. old) [101].) is becoming more important. Namely, drivers over 60 tend to display lower reactivity times compared to their younger counterparts as a result of a gradual loss of visual accuracy, difficulty in close vision, changes in colour perception, problems seeing in low light or night-time conditions, etc., and need more information related to the visual guidance. The surveys done in England, Scotland, Wales, and Sweden show that, overall, the condition of road markings is generally not good. For example, around 40% of markings on the motorway and dual carriageways in the aforementioned countries need immediate replacement [82].

For these reasons, further investigation of the marking's visibility and driver's detection distance is needed. Although several studies evaluated this in dry conditions [50, 53–55], the visibility and detection distance of markings during night-time in wet and rainy conditions are still not studied sufficiently. One study that analysed the visibility of the markings under rainy conditions proposed 150 mcd/lx/m^2 as the minimum retroreflectivity value for white and yellow markings [56]. The practical experience shows that this is extremely hard to achieve and standard requirements for many countries are substantially lower. On the other hand, European Road Federation proposed that the minimum performance level in wet and rainy conditions should be 35 mcd/lx/m^2. Based on the aforementioned, we advise researchers to conduct this type of study in order to get more valid results which could then be used for redefining standard requirements related to the wet and rainy visibility of the markings.

Also, future studies should be focused on evaluating the impact of different and innovative road markings perceptual measures, in accordance with the "self-explaining roads" concept, on drivers' behaviour at traffic locations of high risk such as rural intersections and transitions or gates between highways and rural or urban roads in order to reduce the effect of highway hypnosis.

Furthermore, the development of an increasing degree of vehicle autonomy requires a satisfactory level of quality of the road infrastructure, including road markings. On top of researching the impact of road markings visibility on driver behaviour, future research should also focus on investigating the impact of visibility on machine vision and systems in modern vehicles such as Lane Departure Warnings (LDW), Lane Keeping Assistance (LKA), and Forward Collision Monitoring (FCM).

Despite the value of this study, several limitations should be considered. First, the review included only studies published in an English language peer-reviewed journal, conference proceeding, or as a professional report. Namely, because of the language barrier, we did not include studies written in other languages, although they might provide valuable results and findings. Also, the time range was, based on the authors' experience, limited between 1980 and 2019 which could result in noninclusion of potentially valuable studies. Furthermore, this review was focused on the studies related to the impact of road markings on driver behaviour and overall road safety, thus excluding the studies which investigated different aspects of road markings such as their service life, environmental impact, acoustic properties, monitoring and maintenance, as well as influence of road markings on the machine vision and different levels of autonomous vehicles. Based on the literature survey and experience of the authors, some of the mentioned issues are still unexplored which is the reason for their noninclusion in this review.

Table 3: Summary of the findings.

Research area	Number of studies	Highlights
Impact of road markings on driver behaviour	36	(1) Presence of road markings impacts both the lateral lane position and driving speed (2) The impact of different lengths of broken line on the driving speed and lateral position is relatively insignificant (3) With wider markings, drivers tend to approach the edge of the road more closely (4) Wider marking (especially edge lines) reduced vehicle crashes (5) Different road marking designs (transverse lines, herringbone and dragon teeth patterns, optical circles, etc.) proved to be a positive speed reduction and compliance measure (6) Flat and rumble transverse lines are most effective in reducing the speed prior to curves, intersection, and rural-urban connectors and transitions, while markings in herringbone pattern reduce driving speed along the curves and influenced the lateral position of the vehicle
Impact of road markings on road safety	35	(1) Analysed studies have mixed and inconclusive results; however, the prevailing opinion is that road markings have a positive impact on road safety (2) Road markings with higher retroreflectivity (>200 mcd/lx/m^2) are associated with the lower number of road accidents (3) Maintaining road markings has positive effects on road safety (4) Retroreflection of markings in dry conditions is significantly higher than that in wet conditions (5) Minimum level of retroreflection required by drivers ranges between 100 and 150 mcd/lx/m^2 in dry conditions and about 150 mcd/lx/m^2 in wet conditions (6) In general, road markings retroreflectivity (initial as well as long term) depends on a number of different factors, such as quality, embedment and density of glass beads, material type, age, road type, number of lanes per roads, snow maintenance activities, amount and speed of traffic, direction of stripping, and type and roughness of roadway, etc.

Conflicts of Interest

The authors declare that they have no conflicts of interest to disclose.

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