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# Synthesis of bibliographic analysis of WG2 project RMCAD (Road Marking for Connected Automated Driving), task group 100

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## Objective:

**Road markings are essential to ensure good driving conditions. They increase the road safety by giving information on the trajectory to follow, which is essential, especially in bad visual conditions (by night, face to glaring headlamps, etc.). Nowadays, the characterization of the road marking has been standardized by considering the perception of the human drivers. However, Advanced Driver-Assistance Systems (ADAS) and recently developed Automated Vehicles (AV) rely on a machine perception of road markings. This raises the question whether the current standards and models need to be adapted to enable a sufficient visibility of road markings for the human driver and AV & ADAS. The main objective of this synthesis is to summarize the current state of knowledge on this topic.**

## 1 Introduction

Advanced Driver Assistance Systems as for instance a Lane Departure Warning system (LDW) support the driver to prevent accidents. They have been installed in vehicles for many years and are becoming quite common in new vehicles and will be mandatory by Regulation (EU) 2019/2144 (General Safety Regulation) for all new vehicle registrations as of 2024. Nowadays, with the fast development in vehicle technology, also automated driving functions are introduced, which take over the driving task completely for a certain time. Most ADAS systems and automated driving functions need a Machine Vision (MV) system based on vehicle sensors as a camera, which plays the role of an "electronic eye" associated with algorithms and software. To be functional to the full extent, these systems must detect the road marking lines in all environmental conditions. Thus, one can ask, are the standardized indicators for the human driver (e. g. R<sub>i</sub>, Q<sub>d</sub>) still relevant for these MV systems?

To address this question, task 100 of the Working Group WG2 conducted a literature review to better understand the MV systems behavior and to see if there are correlations between the detection of road marking by automated devices and the current indicators of EN 1436 [1]. As the WG2 "RMCAD"-project aims at further developing the existing COST 331 visibility model for the human driver to include machine vision, the focus is on a comparison of human and machine vision of road markings. An Excel file that brings together the context and the results of 35 papers (articles, reports, ...) on the subject was completed. Its aim was to answer several questions in order to propose a new methodology to simplify future work. A total of 36 documents including 21 research studies [2–22], 8 recommendations [23–30] and one paper focused on algorithms [31]. All the relevant references were analyzed with the same list of questions and the complete excel file is attached to as an appendix to this work. This document constitutes a synthesis of the analysis. It addresses several questions and proposes future research orientations. With regard to the constantly progressing state of knowledge, the synthesis is understood as a living document. It is intended to be constantly developed further.

## 2 Comparison of human and machine vision

### 2.1 General

Intuitively, human vision and camera work the same, to a very large extent. For example, the camera as well as the eye automatically adjust to ambient luminosity. Also, both are sensitive to light and use contrast to differentiate two different objects. Moreover, for the camera and the eye, there is not a single specific observation geometry. However, the above assumption has not been proven in the analysed papers because they focus either on human or autonomous vehicles. To approach this question nevertheless, the literature findings about human and machine vision are compared in this chapter.

### 2.2 Relevant parameters of road markings for detection by human driver and AV

#### 2.2.1 Human vision

In many countries there are some recommendations for the performance of road markings after application. They are mostly based on human needs and can differ between the countries. At the moment, the performance of the road marking is quantified with criteria based on the human visual system and given e. g. in the EN 1436 and ASTM E1710 [1, 32]. Especially, the visibility by day and by night are central properties of the road marking. By day, the visibility of the road marking is mostly characterized by the luminance coefficient under diffuse illumination  $Q_d$  (expressed in  $\text{mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ ). It corresponds to the ratio of the luminance of the diffused natural light reflected by the road marking at 30 m from the driver's eye (with a height of 1.2 m), over the horizontal illuminance due the overcast sky at the road marking surface. Another factor can also be measured to assess the daytime visibility of the road marking: the CIE luminance  $\beta$  defined for a vertical viewing geometry and an illumination at  $45^\circ$  ( $\beta=Y/100$ ). At night, the road marking visibility is characterized by the light reflection of the car's headlamp on the road marking surface. It is quantified by the coefficient of retroreflected luminance  $R_L$  (in  $\text{mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ ) defined as the headlight reflection on a marking located 30 m in front of the driver. More specifically, it is the quotient of the luminance  $L$  of the field of the road marking in the direction of observation by the illuminance  $E_\perp$  at the field perpendicular to the direction of the incident light.

#### 2.2.2 Machine vision

Several indicators for AV are proposed in the scientific studies and recommendations, usually the coefficient of retroreflected luminance  $R_L$  by night and luminance coefficient under diffuse illumination  $Q_d$  by day. Other indicators are mentioned in the literature like CIE Y (see for instance Pike et al., 2018 [16]). Moreover, the contrast ratio  $CR$  of these indicators is also often calculated<sup>1</sup>: it is usually defined as the indicator characterizing the road marking over the same indicator characterizing the surrounding pavement. This contrast allows to take the reflected light of the road surface into account, which is not considered in standards yet. For example Storsæter [10] states the importance of contrast between the road marking and the road surface instead of the performance of the road marking alone for MV. Moreover, road markings could possess different visibility characteristics depending on the type of road surface they are applied on [33]. Also in Carlson [6], it was found that a lack of contrast between the pavement and marking (faded markings) could reduce the DQ. The results indicate a general trend between pavement marking contrast (luminance during the daytime and retroreflectivity during the nighttime) and MV performance. The Machine Vision detection ratings increase with the contrast, but not for each of the analysed road markings.

Other studies found no or no clear proof of the influence of road marking quality on the machine detection quality. For example in [34] and the study by El Krine et al. [9, 34], correlations could not always be demonstrated. Already in a 2007 study [10], the performance of LDWS (Lane Departure Warning systems)

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<sup>1</sup> The Weber contrast  $CW$  is sometimes preferred but actually this is almost the same indicator:  $CW=CR-1$

under dry and light rain conditions showed that the detection rate is up to 100%. In the researches [10, 20], the importance of contrast instead of performance of markings for MV was emphasized. By day, MV performance in most cases is very good [9, 34] even with low contrast ratio of retroreflection and luminance. Moreover, in these studies, no correlation between MV performance and EN 1436 [1] characterization were found.

The seemingly contradictory findings could be explained by the different definitions of detection quality applied in the studies. Machine vision is based on the analysis of a visual image created by a sensor like a camera or lidar-system, but can rely on powerful algorithms and further processes using AI and machine learning, if the whole Machine vision system is considered (MV-system). Some studies focus on the quality of the sensor created image to analyse the interaction between RM and DQ. Other studies analyse this interaction based on the outcome of a MV-system, accepting that the above mentioned algorithms and methods can improve detection quality / confidence in case of a low quality of the sensor image. It was found that the interpretation and comparison of the available study results is made difficult by the fact that the sensors and associated software change regularly and the output is not always the same between studies (for example scores with two or three numerical values, sometimes a confidence level of detection or a color code, ...). Further there are no or not sufficient information on the underlying data processing because the MV systems and algorithms are often protected by the manufacturers. According to the author's findings and interpretation of Stacy [18], to be able to analyse the relationship between Machine DQ and RM quality, it is not sufficient to rely only on the reduced output e. g. of a Mobileye score (0-3).

A graphical synthesis of all the indicators considered relevant for machine detection of the road markings according to the analysed publications is available in appendix of this document (file **MarkingParameterAndRequirement.pdf**).

## 2.3 Minimum requirements on road markings

### 2.3.1 Human vision

The aim of **COST 331 action** [35] was to investigate the requirements on road markings to ensure secure human driving. A PC program called "Visibility" was delivered as an output of the project. According to the program, the visibility level is proportional to the luminance difference between the marking and the road and also to the target size. This model was validated by several experimentations conducted on a driving simulator at the VTI and also field experiments in three European countries. More details on the program is in appendix where there is also a link to its new version that considers different spectrum of headlamps. In the final project report it was emphasized that the requirements of human drivers are complex because they depend on driver age, vehicle speed, headlamp intensity, road geometry, glare from opposing traffic and climate. It was not possible to answer all the questions of road marking design and its influence on road safety. But as a very general recommendation for maintenance of road markings, COST 331 recommends a threshold level for minimum performance of  $R_L = 100 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ . Increased visibility of road markings increased preview times as drivers did not increase their speed so much that all benefits were absorbed in higher speeds.

Based on the analysis of some member states practices, the **ERF** [24] recommends minimum values of  $R_L = 150 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$  and a minimum width of 15 cm. In the wet condition, the recommended minimal value is  $R_{L,wet} = 35 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ . According to the draft report prepared for the European Commission's **Expert Group on Road Infrastructure Safety** several studies have focused on determining the minimum retroreflective levels required for safe driving in different situations. The report concludes that the minimum level of retroreflection required by human drivers ranges between 100 and 150  $\text{mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$  in daytime and dry conditions.

A literature analysis conducted within the scope of the **research project** FE 82.0609/2013 on the effect of road markings on traffic safety [36] also found that there are inconsistent statements in the literature on

the relationship between the visibility of markings and the occurrence of accidents. Performing a statistically valid study where only the road marking visibility will vary, is very difficult and complex. Some studies found a relationship, other studies have found no evidence of this relationship. Studies, which mainly dealt with the connection between retroreflection of the marking and driver behaviour, report in the result minimum requirement of  $R_L = 80$  and  $150 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ .

Overall, it can be stated that there is a rather wide range of suggested minimum values from  $R_L = \text{ca. } 80$  to  $\text{ca. } 150 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$  for the human driver. The findings are subject to uncertainty, e. g. in view of the general difficulty that road markings are only one factor in a complex driving environment, and can be based on different methods and assumptions. Also, it should be noted that the human driver has different demands in different situations. For example, on the one hand there could be the need for a general minimum requirement, which is implemented in the whole network and on the other hand, for high risk areas as dangerous curves, entrance and exists of motorways, busy intersections, construction sites, higher requirements are necessary. Also, within human vision we deal with a large demographic range of drivers. Older drivers need much more light than younger drivers, which leads to higher requirements on road marking visibility.

To conclude this part, despite that some studies recommended a threshold value of a road marking indicator allowing to be well visible for the human driver in most of situations, it is clear that these thresholds will not be enough to fully estimate the real visibility of the road marking. Indeed, the environmental conditions (weather, glare, etc.) and the road infrastructure (tunnel, turn, geometry of road marking, etc.) play at least as important a role as the composition of the road marking. It is the combination of all these parameters that should be considered to have a complete representation of the road marking visibility.

### 2.3.2 Requirements on road markings for automated vehicles

First, it has to be stated that there are very different values in the literature: For the nighttime visibility in dry condition from  $34$  to  $200 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$  for  $R_L$  and for the nighttime visibility in wet condition from  $4$  to  $50 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$  for  $R_{L,W}$ <sup>2</sup>. For  $Q_d$  the value is between  $\text{ca. } 50$  and  $150 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ . The contrast ratio is also sometimes considered. For example, the  $R_L$  contrast ratio should be between  $2.5$  and  $10$ , and the  $R_{L,W}$  contrast ratio should be generally at least equal to  $2.1$ .  $Q_d$  contrast ratio is between  $2.5$  and  $3.0$  depending of the studies (see file **MarkingParameterAndRequirement.pdf**).

For the interpretation of the above-mentioned minimum requirements, it should be understood that these values rely on different conditions and assumptions. Some recommendations are based on studies conducted on test tracks or in laboratories under controlled conditions, while others on testing on open roads. Other recommendations do not rely on test results or scientific studies at all. If so, testing has been carried out e. g. with different sensors and devices (devices applied for CAD change quickly with further development).

In consequence, the results cannot be generalized and the comparability is limited. In general, all studies are dedicated to certain aspects, but cannot provide a comprehensive answer. It was also shown that the infrastructure of the road (regarding its complexity) and environmental conditions have an impact on the performance of AV sensors.

In other recent scientific studies like [9, 34], it was shown that standard characterisation of road markings using retroreflection does not correlate with AV performance, especially in dry conditions.

To conclude, **up to now it was not possible to find generally valid minimum values of performance parameters for machine detectability of road markings**. Neither driving tests on open roads nor on test tracks so far led to clear results because the relationships are often complex and the values both depends

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<sup>2</sup>  $R_{L,W}$  is the coefficient of retroreflected luminance under wet condition as defined in EN 1436

on the AV system and the experimental conditions. When machine learning is used, the MV performance is highly dependent on the training dataset that was used.

### 2.3.3 Conclusions

In view of minimum requirements, neither for the human driver nor AV a common minimal visibility level can be derived from the available literature. The proposed values for the human driver range e. g. from  $R_L = 80$  to  $150 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$  and for machine detection from  $R_L = 34$  to  $200 \text{ mcd}\cdot\text{m}^{-2}\cdot\text{lx}^{-1}$ . So far no clear conclusion can be derived whether there are equal, higher or lower requirements for the human driver or MV.

In this context it should also be noted that despite the existence of harmonised conditions for the evaluation of the daytime and nighttime visibility of road markings in Europe, these conditions represent a strong simplification of human perception of road markings. The specific conditions described by EN 1436 [1] for  $Q_d$  are well suited e. g. for the comparison of the performance of different road marking (products), but represent only a small percentage of the actual perception of road markings by human drivers or AV at daytime. For example,  $Q_d$  is defined for a certain light condition (D65 with overcast sky), a certain distance from the driver's eye or sensor to the road marking (30 m) and dry condition as well as a clean road marking surface. In reality, daytime visibility of road markings is subject to the type and color of pavement and also to the influence of different light and weather conditions, e. g. wetness and different sun angles. Also, road markings are used for visual guidance of the human driver in a distances from  $< 30$  m up to ca. 70-100 m. These and further conditions are not covered by EN 1436. In consequence, a comprehensive comparison of human and machine vision would require the development of additional parameters to evaluate daytime visibility of road markings. Also, the differences between real world driving and the limited measurement conditions of  $Q_d$  according to EN 1436 point at the need of further measurement methods e. g. to evaluate the performance of road markings in wet condition at daytime (see chapter 2.5). Finally, only the indicator of the road marking is considered in EN 1436. However, the human eye is sensitive to the contrast of a target observed on a background and especially to the difference between the marking and the surrounding road [35]. Thus, it seems illusory to describe the visibility of the road marking without considering the context in which they are obtained. Moreover, if the marking lines are not well detected, the reaction of the human driver may be different from the MV's one. For instance, the experience of the driver can help him to succeed his driving task despite an absence of road markings, whereas the MV system could suffer a loss of functionality.

## 2.4 Minimum preview time and detection distances

A further conclusion of the COST 331 action is that the preview time must be at least 1.8 seconds to allow that the driver stays within the driving lane and more than 3 seconds for comfortable driving. From the analysed publications, no information on a preview time for AV or a minimum visibility distance of road markings was found. In [Davies 2017] a "sweet spot" for the detection of road markings was found.

With regard to Mobil-eye performance, Babic [3] has shown that there is an increase of view range of 16 % at day time compared to night time. It shows that both DQ and view range are important.

## 2.5 Influence of adverse weather and light conditions on human driver and MV-Systems, further influencing factors

Many studies indicate that adverse weather conditions and glare caused by the sun or headlights of the other vehicles will negatively influence the detection of the markings. This is similar to the detection by human drivers. The LDW-system (measures DQ) registered road marking in daylight in the same way as humans [12]. The challenges come in darkness and wet road surfaces. Performance of LDWS of lane

markings was affected significantly by heavy rain conditions at night for typical lane-marking installations [10].

LDW had problems with the detection of glare. Strong direct light sources (especially when surfaces are wet) is an unsolvable issue for monocular MV with current technology and algorithms [13]. During daytime wet conditions [16], the glare from the sun severely impacted the MV detection confidence ratings.

On open roads, there are problems with bright overhead sun, nighttime, low sun angle (influence of shadows and glare analysed), overcast [18].

Specific design (with too wide marking) and shapes (at ramp exits or road entries) may confuse MV. Poor MV performance is obtained if road marking is missing or due to the complexity of the infrastructure, like lane change [9, 34].

In the study of Bares [2], the results show that there is a strong influence of the environmental conditions (dry/rain, day/night, etc.) on the detection quality (DQ) expressed by contrast in the camera picture: e. g. higher contrast at nighttime than at daytime, lower contrast at nighttime and wetness compared to nighttime and dryness.

Burghardt [5] carried out a test of MV sensors in a tunnel with fog & rain condition (3 cameras and 2 lidars). The analysis focused on the sensor response and did not take post processing into account. Correlation tests were done between contrast based on sensor intensity and classic EN 1436 [1] indicators. There was a big decrease of contrast under rainy & foggy condition but no significant difference according to the condition (type of road marking, day or night, with and without glare) and neither influence of rain intensity. The results were better by night with headlight compared to day.

Many studies [2, 5, 12, 13, 15, 17] indicate that adverse weather conditions and glare caused by the sun or headlights of the other vehicles will negatively influence the detection of the markings. This is similar to the detection by human drivers.

It is commonly agreed that machine vision requires more harmonized design of markings, amongst others to avoid false negatives or positives. There are still some cases where Machine Vision systems have problems, for example for road repair with bituminous joint and complex environments (e. g. a road narrowing or at a roundabout)<sup>3</sup>. A human will most likely not be confused in these cases, but the MV might register a false positive.

## 3 On-going research projects

### 3.1 SAM project

The French project SAM (Safety and Acceptability of Autonomous Mobility) consists in developing knowledge to build a technical and regulatory framework to facilitate the circulation of Autonomous Vehicles on the French road network [37]. The project targets six categories of autonomous vehicle use cases: autonomous driving, valet parking, VTC, new collective or shared mobility services, public transport, and last mile delivery. These experiments are done over the whole country, and cover situations in urban, suburban and rural areas. One of the tasks of this project is to evaluate the detection of road markings by camera-based driving assistance systems, by varying different parameters, both on the state of wear of the markings but also on the state of the road. The objective is to propose a characterization of the couple marking/pavement that is more relevant to what is perceived by MV systems (the entity in charge of driving), and thus to propose a characterization that could be more relevant to the AV. To compare ADAS

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<sup>3</sup> Practical examples available here <http://dx.doi.org/10.13140/RG.2.2.22951.06560>

system performance and more quantitative measurements, one shall define indicators but also consider a suitable scale of analysis.

### 3.2 Autonomous vehicles and road markings (AVRM)

The project is a collaboration between four road authorities in the Nordic countries Sweden, Norway, Finland and Denmark [34]. The aim is to detect minimum acceptable level of functionality of Lane departure warning (LDW) systems for remaining active and provide satisfactory guidance on different types of roads represented in the Nordic countries. The method used is to obtain data on the LDW systems' ability to register different kind of road markings under different weather conditions.

### 3.3 Analysis of influencing factors and parameters for the machine detection of road markings

The project "Analysis of influencing factors and parameters for the machine detection of road markings" (03.0581) [38], which is currently carried out on behalf of BASt, aims at describing the relationship between the machine vision detection quality on the one hand and road marking visibility expressed by the parameters defined by EN 1436 for the human driver on the other hand. For this, driving tests are conducted at day- and nighttime, using road markings of different visibility. Machine vision detection quality is evaluated by the resulting contrast between the road marking and the road surface in the camera picture.

## 4 Knowledge gaps and research needs

A review on the impact of road marking on driver behaviour and road safety was recently done by Babic [39] and also confirms the importance of higher retroreflection and marking maintenance for road safety for human needs.

The literature analysis on MV systems has shown that on dry conditions, they are able to detect road marking even when the contrast between marking and surrounding area is low. The sole presence of a RM sometimes seems to be sufficient, independent of the  $R_L/Q_D$  values [9, 34]. It is assumed that if there is a RM with sufficient remaining area, the MV system will be able to detect it in non-challenging conditions (i.e. a dry road surface). Some findings indicate that the influence of the geometry and design of road cross-sections in more complex areas like e. g. merging of lanes or similar is more decisive. For this reason, knowledge gaps are in view of machine detection of RM in challenging situations like driving in rain, etc.

Answer needed to a "simple" question: Which conditions are most challenging for AD? Example: Rain at daytime or nighttime? Glare due to headlamp or rising sun? Geometry of the infrastructure? A ranking of critical situations could help prioritize research activities.

MV of RM could be problematic in challenging conditions as e. g. rain, fog, sun ahead. Further research is needed on the question how to create a RM associated to its surrounding road surface which ensures good detection in all conditions [4]. Some RM-types seem to allow a good MD in one environmental condition but might not work in another.

Do we need completely new types of RM for situations in which MV cannot be improved by improving the quality of conventional RM? It could also be asked if the RM are to be blamed if sensors fail (e. g. sun blinds the camera) – maybe we need new sensors for these conditions (Lidar, radar?) and not new RM.

MV is based on the analysis of an image. Good and sharp contrast make it easy to identify the road markings. During the day, the illumination of the road and the marking will vary based on weather conditions and position of the sun. This will result in a variable contrast for the same road marking on the same road surface. The only reference to EN 1436 [1] is the  $Q_d$ , which is measured in a standardised way. For night



time conditions, contrast is mainly generated by the reflection of light generated by the car head lights. The  $R_L$ ,  $R_W$  and  $R_R$  represent the connection to EN1436 [1].

A clear threshold for each of these parameters to guarantee confident detection by MV is still lacking and it is not sure that such a threshold could be defined due to the different detection methods as well as machine learning training models and datasets. Feedback from the automotive industry indicates that under normal driving and dry weather conditions, human and machine detection are similar. Making the road marking better visible to the human eye will benefit MV detection. One could expect that improving RW and or RR performance would have a similar benefit during wet or rainy weather conditions.

Higher levels of automated driving, with less to no involvement of the driver, will require a safe system approach, where good MV visible infrastructure can play an important role to build a more robust ODD.

Infrastructure (better markings) can play an important contribution to improve automated driving in complex situations as mixed urban traffic or temp work zone environments. Research projects should focus on such situations to find out the design and minimum performance criteria of markings. As well as finding out the limitations.

Up to now, in view of necessary contrasts between road and road marking there are no specifications with regard to typical  $Q_d$  or  $R_L$ -values of the road surface. Further, so far specifications for the photometry of the road and the road marking are not the same. For example, there are different observation angles in the relevant CIE 144-2001 document [40]. The characterisation of the road marking is done at an observation angle of  $2.29^\circ$  while the characterisation of road photometry is conducted for an observation angle of  $1^\circ$ . These are conventional geometries. In reality for both humans and autonomous vehicles, the perception of a road marking is broader, and could be from 10 to more than 100 m.

## 5 Design of future research

### Which methodology should be used for future research - and why?

#### 5.1 Analysing minimum requirements for $R_L$ , $Q_d$ , etc.

For analysing influencing factors and minimum values for single road marking parameters (e. g.  $R_L$ ) for MV it is recommended to use a “white box” approach, as the interpretation and comparability of existing study results are limited due to the use of “black box” approaches relying e. g. solely on the Mobileye rating system. A white box approach which seems most suitable so far is to evaluate the detection quality based on the contrast between the road marking and adjacent road surface within the camera picture (Example in [2]). Further minimum contrasts or differences (as recommended in [35]) between the road marking and the road surface in the camera picture could be defined for different situations, where possible in exchange with camera experts to ensure representative values. It is assumed that this minimum contrast between road marking and road is a good base for the further interpretation of the picture by algorithms, machine learning, etc. If the road marking properties have been measured, the correlation between  $R_L$  and  $Q_d$ -values and the resulting contrast can be analysed. If a representative minimum contrast of road markings in the camera picture or lidar point cloud is known, minimum requirements e. g. for  $R_L$  and  $Q_d$  could be derived. This is a rather conservative approach in view of the application of very efficient algorithms and machine learning in the further process of interpreting a camera picture, which enables the automated vehicle to detect even road markings with a very low quality. Nevertheless, this approach is essential to understand the behavior of the MV systems and to assess the main limits of these devices.

For future research, in addition to the  $R_L/Q_d$ -values for contrast measurements, also the highest and lowest grey values measured in the camera frame of onboard vehicle camera sensors could be included in the analysis. It would be helpful for the evaluation of the contrast between the road marking and the road

surface to know if the overall range of grey values was rather small or large, e. g. due to special light and weather conditions.

Open questions, limitations, etc.:

- How to deal with the automatic adjustment of the exposure time and gain of the camera?  
There are two options: The testing can be done with automatic adjustment, having in mind that it is an automatic adjustment like our eye. If we want to take it into account, a high dynamic range ILMD could give reference information
- What about the spectrum of the camera, resolution, focal length? For future research, these parameters are required. Some cameras unfortunately also have a black box behavior.
- Is it possible to define a general minimum contrast or difference for road markings in the camera picture or lidar point cloud? But what type of contrast or difference?
- Shall we still base the daytime contrast on the  $Q_d$  values, even if it is difficult to measure it dynamically?
- Would it be useful to develop a portable measurement device with a camera sensor commonly used in MV systems of vehicles? This static device would be a kind of box that excludes external light and applies controllable light conditions. It would be able to view both marking and surrounding road to measure contrast.

When conceptualizing testing, please mind that in driving tests on open roads, too many factors apart from the road marking visibility can have an influence on the detection quality (geometry of the road marking, curves, road surface brightness, sun, etc.). Therefore, it is not likely that the results will allow a conclusion on the relationship between a single road marking parameter and the detection quality (overlapping influences could mask existing correlations). Also, in some cases, it is not possible to measure the road marking quality on the road, which is considered essential for further interpretation. It might be favorable to carry out testing on a large test track with controlled conditions (e. g. samples with defined  $R_L$ -values,  $Q_d$ -values, etc. with very low values) and perform driving tests in which only one parameter each is varied (e. g. only use one RM sample for one set of runs). However, creating RM sample with defined (e. g. very low) qualities, which in most cases have to be removable, takes time and effort. Verification of test track results by real world driving on open roads is recommended to ensure the transferability of the results to practice. For this, careful planning is necessary on how to conduct such testing in detail.

In view of the great variety of different MV-systems it should be considered to invite the WG2 RMCAD members to participate in testing with available MV equipment if a research study is carried out.

## 5.2 Analysing limitations of machine detection of road markings in critical situations

The provision of recent examples (video, data, etc.) of cases, in which machine detection failed in real life driving, by OEMs and suppliers would significantly facilitate and accelerate research on this topic. If this data is available, measurements of road marking performance should be conducted as soon as possible on the locations of MV-failures with static devices to be able to capture all RM parameters (like  $Q_d$ ). Further, the geometry of the road cross section and road marking design needs to be captured to allow for further interpretation beyond the visibility of the road marking. The strength of this approach lies in concentrating directly on the critical conditions, rather than spending time and resources on analysing many kilometres of road markings which provide a good DQ. The literature analysis showed that the interpretation of data from driving tests sometimes produced only little results as the DQ was predominantly very good [7, 9, 11–16, 34].

Open questions, limitations, etc.:

- Depends on the willingness of OEMs / suppliers. Alternatively, a car equipped with a MV-camera could be used, applying a white box approach using for example publicly available MV algorithms instead of OEM-specific MV systems.
- Requires static measurements, which is sometimes hard to achieve in view of necessary measures of traffic protection and interruptions of traffic. Dynamic measurements can be carried out alternatively, if only  $R_L$  is relevant, but not  $Q_d$ .
- Different parameters are used to evaluate machine detection quality, which reduces comparability of results and ...
- “Black box approaches” are applied, which limit deeper interpretation of results

For these reasons it is concluded that the development of a uniform European “white box approach” could contribute to the further progress. Such an approach could be understood as a tool to evaluate road marking quality analog to the parameters defined by EN 1436 such as  $R_L$  and  $Q_d$ . A future approach could e. g. be based on the contrast in the vehicle camera picture or an open source algorithm which can be applied to detect markings and at the same time gives out a rating of the detection quality.

### 5.3 Development of a visibility model for machine vision

One could also follow further the approach to verify that camera and human vision are very similar. A systematic analysis has not been conducted according to the available literature. On the human side, this would imply either modelisation of visibility or psychophysics tests. On the MV vision side, this calls for a better cooperation with LKA system providers to have access to the raw data or at least the camera properties and the images. It would be helpful to have the camera limitations and minimum requirements to compare with human.

### 5.4 Is it possible to define a common methodology to measure contrast?

The above discussed literature findings illustrate that in future research studies, a precise assessment of the road marking quality could contribute significantly to the analysis and understanding of the interaction between road markings and machine vision. For this reason, here the possibilities to measure road marking conditions in open road tests are discussed.

In general, static retroreflectometers are easier to use, because it just requires to put the device over the road marking or the road surface. The sensor gives a value of the indicator ( $R_L$  or  $Q_d$ ). Moreover, the static retroreflectometers are often used because they allow to measure the  $Q_d$  coefficient (not possible yet with the dynamic retroreflectometers). Disadvantages of static retroreflectometers are a. o. the need for elaborate traffic safety measures for the measuring team and the point-by-point measurement on small measuring areas, as the measurement is often conducted on a small rectangular area.

Dynamic retroreflectometers require a vehicle with a trained driver<sup>4</sup> to be operational. It is often located close to the rear wheel of the vehicle and conducts a measurement on a marking line in front of the car with an observation angle consistent with the standards (i. e. 2.29°).

In view of measurements of the daytime visibility, up to now dynamic systems cannot provide controlled lighting conditions. In consequence, the measurement results highly depend on the nature of the sky (sun and clouds). Only if the lighting conditions when carrying out measurements on roads comply with the light conditions defined in EN 1436 [1] over the whole measurements, dynamic measurement results could be assumed to correspond to  $Q_d$  according to EN 1436. This would also require that the lighting conditions are measured during the dynamic measurement. Due to these difficulties, the use of dynamic systems for the assessment of daytime visibility is often limited to the measurement of the luminance value to give a kind

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<sup>4</sup> The driver must take care that the whole width of the marking line is always contained within the measuring range of the sensor.

of approximation of the daytime visibility. Also, some systems measure the daytime contrast, but again, the same limitations apply due to the lack of controlled lighting conditions.

The area measurement is not always defined, but the sensors is usually divided into several measurement channels. For instance, Ecodyn3's sensor [9] is divided into 32 measurement channels allowing to have information over an area 1 m wide x 50 cm long, for others the resolution of a measurement channel is smaller because the sensor is a camera.

The marking area considered for dynamic devices is not always the same. For some devices, it is a maximum on the marking width, for others the whole width is considered. The localization and size of the surrounding road is also generally not known. Moreover, each consecutive measurement is able to give information on the whole marking line or classically each 100 m. That allows to conduct analysis at different scales (for instance at the scale of the marking skip, each 100 m or XX m, ...) and to facilitate the comparison with other devices.

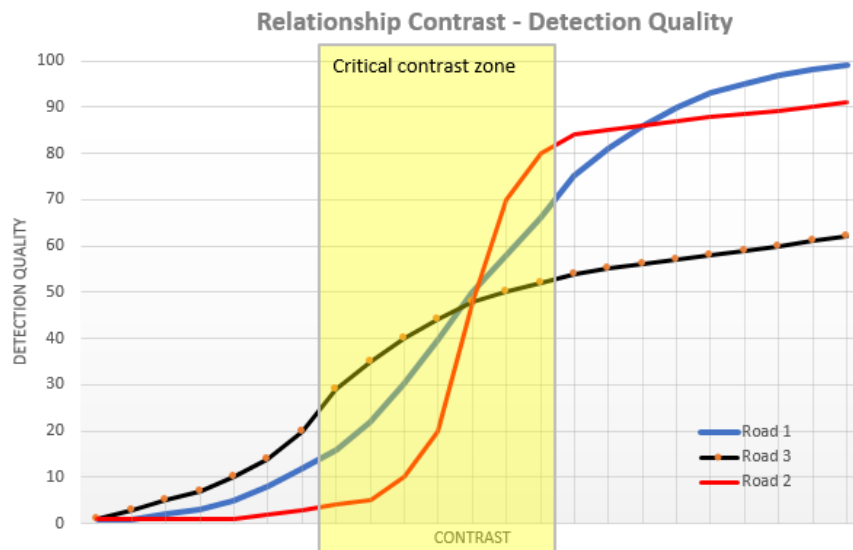
Since the measurement area is not the same depending on the type of device, it seems difficult to have exactly the same results of measurement from a device to another. Static devices provide punctual measurements. Thus, it is essential to do a lot of measurements in order to have a good characterization of the road marking and of the surrounding pavement. It is particularly important if the road marking (or the pavement surface) presents some degradations at some specific points.

Consequently, the choice of the area measurement is important but not only. The statistical indicator (mean, median, max, ...) used to characterize the measurement is also determining. In appendix, the contrast measurement methods of the literature is given. Very few authors really precise what they consider for their analyses. Despite this, they give some threshold values (of  $R_L$ ,  $Q_d$ , ...) to allow a good detection/visibility of the road marking, but the values are not comparable between them. That is why, it seems important to find a consensus on the measurement device and on methodology to use to be able to have a good interpretation of the results. This is also very important for the contrast calculation.

## 5.5 Developing new road marking maintenance strategies for AV

The foreseeable introduction of AV raised the question of minimum requirements for certain road marking parameters as  $R_L$  and  $Q_d$ , as discussed in the previous sections. But also, in view of the constant wear of road markings and the limitations with regard to the monitoring of in situ road marking quality, the question of availability of road markings and necessary adaptations of today's road marking maintenance is another area of possible research.

For example, a good road marking quality does not guarantee that there will always be a sufficient visibility with the surrounding road. There are ways to make road markings better visible when it rains at night, but still the brightness of a road marking has to compete with an extremely bright environment, especially with illumination of a rising sun on the road or with a wet road.



These theoretical graphs illustrate the complexity of nowadays challenges:

- For each road or specific section, there will be a minimum contrast needed to ensure MV detection.
- For each road, at a certain point, further increasing road marking contrast (visibility), will have a diminishing return on detection.
- For certain roads, an overall satisfying detection will be easier to reach (road 2)
- For certain roads, it might be impossible to achieve a satisfying detection covering all weather and traffic situations (road 3)

The critical contrast zone is the area where loss or gain of contrast has the highest impact on detection.

## 6 Final conclusions

- There is a wide range of minimum values so far depending on the studies and their experimental conditions. In the state of actual knowledge, it is not possible to provide a recommendation for a threshold minimum based on the current EN 1436 geometry.
- In EN 1436, properties and measurement geometries are defined for the road marking itself, but so far there is no definition of the contrast between the road marking and the road surface. If EN 1436 is also to support machine vision, the possible addition of a new characteristic and test conditions for contrast should be discussed. A further development of EN 1436 in view of dynamic measurements could also take into account contrast and its methodology of measurement. This would require a definition of the measurement details, e. g. whether it should be a maximum, a mean value, the considered length of road marking. Moreover, if adding contrast or differences, the corresponding area for the road should be defined.
- To further improve the understanding of the interaction between road markings and vehicle sensors, in the first step it is suggested to focus on the relationship between the contrast of the road marking in the sensor image and the road marking properties, without considering further algorithms in the process chain of machine vision. For this, the application of a white box approach with certain advantages and limitations explained in part 5.1 is recommended. For further research, also the potential of the use of algorithms, machine learning, etc. should be taken into account. So far, the sole output of machine vision systems showed to be not sufficient to understand its operating mode.
- It should be noted that a very good road marking quality by today's standards does not guarantee that there will always be a sufficient contrast with the surrounding road, e. g. in heavy rain, snow and glare, especially caused by an opposite low sun or opposing night traffic on a wet road. Both the human driver and automated vehicles would benefit from road markings with improved detectability in adverse conditions as e. g. rain.

### List of associated appendix

- An excel file called **WG2\_Task100\_Literature\_Analysis.xlsx** that contains references and summary of all documents and the analysis conducted on the same list of question.
- A pdf file called **MarkingParameterAndRequirement** that represents schematically all the thresholds found in the literature.
- A pdf file called **Interpretation\_of\_COST331\_Requirements\_for\_road\_markings** that describes the spirit of COST331 and give explanations and a link to the updated version of VISIBILITY software.
- A pdf file called **WG2\_ListOf\_ContrastRatio\_Calculation** that gives a synthesis of all the contrast methodologies founded in the analysed studies.

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