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Testing cameras used in active safety systems with regard to the impact of temperature

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***Abstract*—The paper presents and discusses the requirements related to testing cameras used in active safety systems. It also includes the results of temperature tests of the MTF (Modulation Transfer Function) parameter of a camera developed by Aptiv, conducted across a wide range of ambient temperature variations in the company's laboratory.**

***Keywords*—active safety; automotive safety system camera; MTF; measurements**

I. Introduction

CURRENTLY, in automotive technology, cameras are a crucial and mandatory component of systems that ensure driving safety, known as ADAS (Advanced Driver Assistance Systems) [1, 2]. They enable the observation and recording of the vehicle's surroundings, allowing advanced image processing algorithms to support systems such as Traffic Sign Recognition (TSR), Lane Departure Warning (LDW), and Lane Keeping Assist (LKA). Cameras also play a role in monitoring driver behavior through the Driver Monitoring System (DMS) and in detecting and identifying various road obstacles (e.g., pedestrians) via systems like Automatic Emergency Braking (AEB), Forward Collision Warning (FCW), Adaptive Cruise Control (ACC), and Blind Spot Intervention (BSI). By leveraging cameras, these so-called active safety systems [2–4] significantly enhance the safety of drivers and other road users (including passengers and pedestrians), even under challenging driving conditions. Cameras are also used for additional functions, such as gesture control, weather condition assessment, and adaptive headlight control. Alongside lidars, radars, and other sensors (e.g., those related to steering wheel angle detection), cameras are a vital component in systems implemented in autonomous vehicles [5–7].

The key role of cameras in systems responsible for the safety of vehicles on public roads requires high operational reliability, including stable optical and electrical parameters, as well as diagnostic mechanisms that remain consistent regardless of road conditions. As noted in the literature, and as also confirmed by the authors' work, both ambient temperature and temperature resulting from self-heating significantly affect the parameters and characteristics of semiconductor components and electronic systems [8–11]. Camera testing also involves studying the impact of temperature on their performance, covering various scenarios, from checking parameters across a wide range of ambient temperature fluctuations to assessing reliability in simulated atmospheric conditions that may occur on the road. Additionally, such tests, conducted in climatic chambers and accounting for device aging, allow for simulating the camera's full lifespan of up to 15 years in just a few months (typically 3 to 5) [12]. These tests provide a thorough examination of the camera's technical capabilities before its use in real-world conditions.

The most important optical parameter of cameras used in active safety systems, which is subject to testing, is the MTF (Modulation Transfer Function). The MTF determines the ability of the camera's optical system to capture details of the observed object through the camera's sensor matrix, particularly in terms of contrast [13]. This parameter allows for assessing how accurately the camera reproduces contrast in various areas of the recorded image, which is crucial for the quality of detail reproduction and the proper functioning of systems that process the camera's surrounding image.

This paper presents the requirements for testing cameras used in active safety systems of road vehicles, as well as the results of MTF parameter tests of a selected car camera conducted over a wide range of ambient temperature variations.

II. Standards and Requirements for Active Safety Cameras

The need to test components of vehicle safety systems arises from the ISO 26262 standard, which addresses the functional safety and integrity of electrical and electronic systems in road vehicles. Implementing the recommendations of this standard aims to reduce road accidents caused by system malfunctions and to improve overall system reliability.

In general, determining the test parameters for an active safety camera depends on its function within the vehicle. Cameras must comply with specific ASIL (Automotive Safety Integrity Level) classifications defined by ISO 26262, which determine the criticality of their role in ensuring safety. Cameras used in systems where a camera failure does not pose a direct threat to the driver's life, because the driver can still react to the situation, are typically required to meet ASIL-B. An example of this are cameras used in TSR system. These types of cameras are not required to include diagnostic mechanisms for detecting image sensor faults. Cameras used in more safety-critical systems, such as automatic emergency braking or adaptive cruise control, must meet the ASIL-C

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level, as a failure could result in a collision or accident. Compliance with ASIL-C requires the integration of diagnostic mechanisms that monitor the camera's performance in real time, enabling the detection and response to potential faults. Cameras at this level are equipped with internal mechanisms for monitoring the correct operation of the image sensor. Validating a camera in accordance with the ASIL-C safety level involves monitoring a range of additional parameters responsible for detecting pixel, row, column, or frame errors. Faults in the physical transmission of data from the camera to the active safety system can be identified through cyclic monitoring of dedicated image sensor registers, enabling early detection of potential irregularities. Due to the dynamic nature of visual data transmission, the detected errors may be either permanent or transient. Therefore, test systems must be designed to reliably detect both types of faults [14].

Guidelines and requirements for conducting climatic (environmental) tests, such as those involving varying ambient temperatures, are defined in the ISO 16750-4 standard (and its earlier editions) and the IEC 60068-2 standard. Camera validation is performed in climatic chambers, where diverse environmental conditions are simulated. The temperature change rate follows a programmed gradient specific to the given test type. This may involve either gradual variations or sudden shifts in temperature, aimed at assessing the camera's resistance to thermal shock. Testing is carried out on a defined number of randomly selected cameras from a production batch, with comprehensive documentation maintained for each unit throughout every stage of the testing process. The test plan includes real-world usage scenarios reflecting the intended application of the camera. The most critical temperature-related tests include [14]:

- variable ambient temperature test (the temperature range from -40°C to 85°C) – this test is conducted by changing the temperature inside the climatic chamber in 5°C increments; its purpose is to assess the camera's resistance to failures that may occur due to wide variations in ambient temperature;
- high temperature test (85°C) – this test simulates prolonged exposure of the camera to high temperatures during vehicle operation; it is designed to evaluate the quality and reliability of the camera under thermal stress, and the typical test duration is approximately 60 days;
- low temperature test (-40°C) – this test simulates the operation of the camera in extremely low temperatures; it is used to verify the functionality of camera components after extended periods of vehicle inactivity or operation in cold environments; the test typically lasts about 50 hours;
- thermal shock test (temperature changes from -40°C to 85°C) – this test simulates the camera's exposure to rapid temperature transitions, representing thermal shock conditions that may occur during vehicle use;
- test at variable temperature and constant high humidity (relative humidity ~93%) – this test combines variable temperature with constant high humidity to evaluate the impact of moisture on the camera's performance and integrity; the duration of the test is approximately 150 hours.

Cameras are typically tested at various supply voltages, such as 8.5 V, 14 V, and 17 V. The camera's built-in analog-to-digital converters enable the measurement of internal supply voltages and currents within the camera system. These values are monitored via diagnostic interfaces integrated into the camera. For instance, monitoring the supply current enables the assessment of the product's energy efficiency. Additionally, a sudden increase in current may indicate potential component failures, enabling early detection of camera faults [14].

In turn, guidelines for testing the MTF parameter are based on the ISO 12233 standard, which describes the slanted-edge technique, as detailed in [13, 15–18]. Assessing a camera's ability to capture fine details of the observed scene using the modulation transfer function is a fundamental and critical indicator of camera quality. The MTF parameter is measured cyclically at various stages throughout the climatic testing process during the entire validation of cameras dedicated to active safety systems. This approach enables the detection of any degradation in the image quality produced by the device. MTF testing is performed using test charts containing slanted-edge patterns. These patterns are precisely positioned in selected areas of the test chart known as the Region of Interest (ROI). The design of the test chart is tailored for each specific camera, taking into account the optical system characteristics of the lens, such as distortions that alter pattern shapes, and the resolution of the image sensor matrix.

Figure 1 shows a slanted-edge pattern developed by Mobileye and used, among others, by Aptiv, highlighting the areas of the pattern utilized for MTF calculations through a dedicated company software. It should be emphasized that the edge inclination angle relative to the detector's pixel matrix grid should be 5°. However, the printed pattern's contrast must not exceed 60%. This specified edge angle is intended to intersect as many pixel columns or rows in the image sensor as possible. As illustrated in Fig. 1, the MTF analysis is performed within defined rectangular regions of each test pattern on the test chart. Each region encompasses a portion of the image containing a vertical or horizontal test edge. The integration window size for the analysis is 20×40 pixels. In the figure, dashed lines indicate the edge analysis areas used for MTF calculations, with corresponding MTF values labeled adjacent to these areas. The overall MTF value of 0.69162, unassigned to any specific edge, is recorded in the test report. The final MTF result for each test pattern is computed as the median of measurements from ten captured images [14].

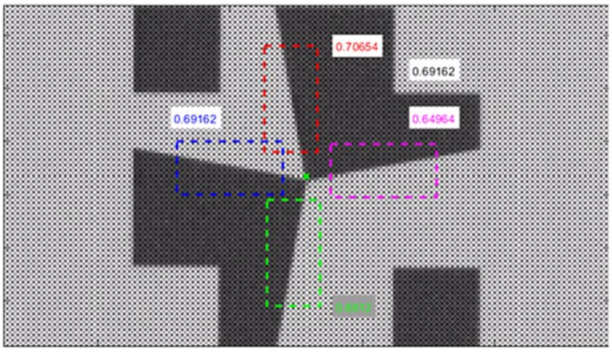

Fig. 1. Slanted-edge test pattern developed by Mobileye with areas used for MTF calculations

Figure 2 shows the test chart (board) developed by Aptiv for the selected camera, utilizing the pattern from Fig. 1 [14]. In Fig. 2, the test patterns are arranged relative to the surface of the image sensor.

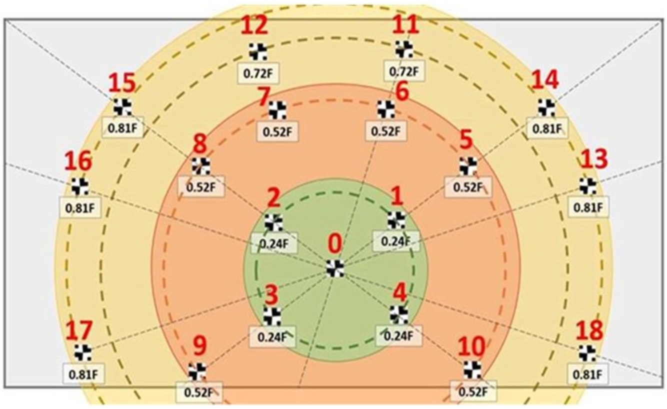

Fig. 2. Test board with slanted-edge patterns with marked detection areas of the camera image sensor

Note that individual test zones are marked with dashed lines. The image sensor's test surface is divided into zones, each with different MTF parameter requirements. For test patterns located within the central zone of 0.24F (24% of the camera's field of view), the MTF value must be at least 0.5. In the intermediate zone of 0.52F, all test patterns must have an MTF value of no less than 0.42. For the outermost zones (0.72F and 0.81F), the minimum required MTF value is 0.3. It should be noted that the MTF limits for patterns in each zone were specified by Mobileye.

An important aspect of MTF measurements and the development of a reference board is the design of an intermediate optical system. Such a system is necessary to replicate real-world operating conditions for cameras capturing images at distances ranging from 1 m up to 300 m within laboratory settings. To simulate camera operation for long-distance object observation, intermediate lenses are employed to create a virtual image corresponding to an object located at a far distance. Thanks to these intermediate lenses, it is possible, for example, to simulate a distance of 15 m while the actual physical distance between the tested camera and the test board is approximately 0.5 m. The intermediate lens is positioned between the camera under test and the board with printed test patterns.

Designing a test board with patterns involves transforming the coordinates of specific patterns from the image sensor surface to their corresponding positions on the test board, taking into account the characteristics of the intermediate optical system. In the case of so-called uniform intermediate lenses, where MTF maxima for individual patterns occur at the same distance from the lens, flat test boards are used. However, for non-uniform lenses, where MTF maxima for different patterns occur at varying distances from the lens, spatial test boards are created, as illustrated in Fig. 3 [14].

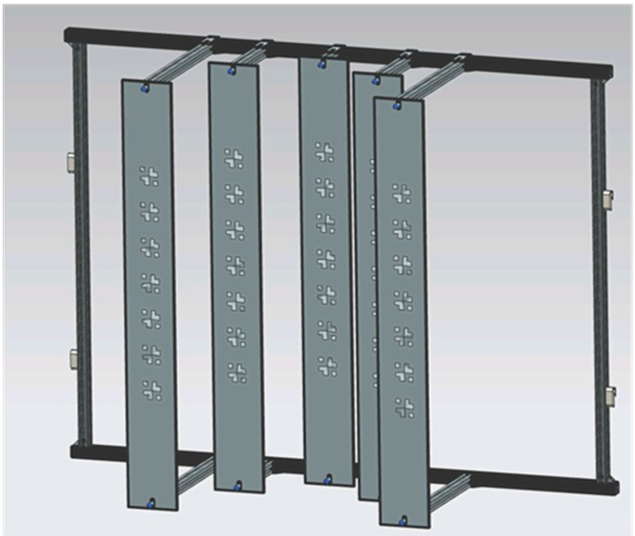

Fig. 3. Spatial test array with slanted-edge patterns

III. Laboratory Test System for Cameras

Tests of optical parameters for active safety cameras are conducted in specialized laboratories dedicated to measuring specific camera types. These laboratories are equipped with all necessary components to implement the prescribed research methodology, taking into account the aspects outlined in the previous chapter.

Figure 4 shows a photograph of the Aptiv high-resolution (4K) active safety camera optical testing laboratory located in Krakow [14]. The test setup includes, among other equipment, a climatic chamber (A) used for testing cameras at various temperatures, featuring a rotating mechanism inside to allow simultaneous testing of multiple devices; a robotic arm (B), employed to position intermediate lenses outside the chamber when needed; and a test board (C) containing slanted-edge patterns.

Fig. 4. Optical testing laboratory for high-resolution active safety cameras from Aptiv

Ensuring accurate measurement of a camera's optical parameters requires maintaining appropriate conditions, such as stable lighting and controlled temperature and humidity levels within the test laboratory. The walls of the MTF testing laboratory are painted matte black to minimize reflections of optical radiation. The test window of the climatic chamber is made of borosilicate glass due to its low thermal expansion coefficient and favorable optical properties, including stable transmittance across a wide wavelength range.

IV. Research Results

This chapter presents the results of MTF parameter measurements for the active safety camera developed by Aptiv. The tested camera is equipped with an AR0820AT CMOS sensor featuring a high resolution of 3840 × 2160 pixels and physical dimensions of 30×30 mm [14, 19]. Figure 5 shows the appearance of the tested camera.

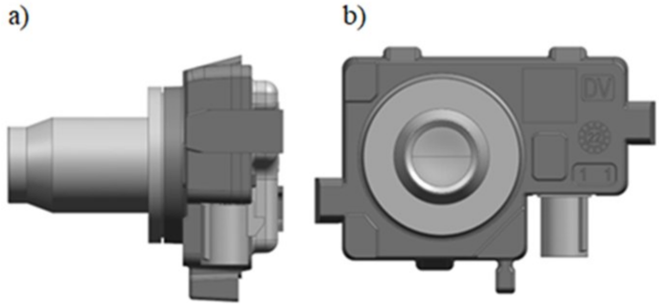

Fig. 5. Tested active safety camera: side view (a) and front view (b)

MTF measurements were performed prior to subjecting the camera to environmental testing. The camera underwent a 60-day incremental temperature test, conducted cyclically within a temperature range from -40°C to 85°C in 5°C increments, at a supply voltage of 14 V. It is worth noting that the incremental temperature test is the longest test conducted in the optical laboratory. Its purpose is to evaluate the resistance of camera components to a wide range of ambient temperature variations. Figure 6 shows the temperature profile of the incremental test [14]. As illustrated, the initial phase involves a gradual decrease in temperature from 25°C to -40°C. This is followed by a steady increase to a peak temperature of 85°C. The temperature then decreases again to 25°C. In the final phase, rapid and significant temperature changes are introduced, first a drop to -40°C, followed by a rise to 85°C. MTF parameter measurements are performed during the flat (stabilized) segments of the temperature profile, ensuring consistent conditions for accurate optical evaluation.

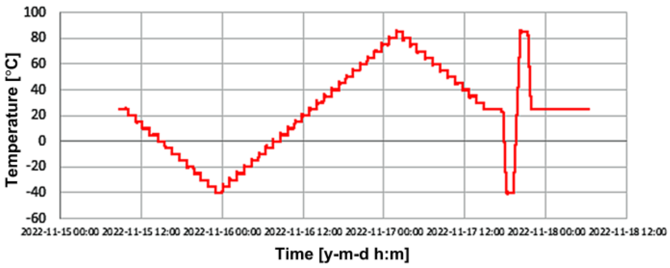

Fig. 6. Profile of the incremental temperature test

Figures 7 and 8 present a comparison of the measured MTF values for nineteen individual test patterns (ROIs) at three temperatures: 25°C, -40°C, and 85°C, recorded at the beginning (solid lines) and at the end (dashed lines) of the test period, respectively. In both figures, vertical dashed lines separate the ROIs corresponding to the three sensor detection zones defined in Fig. 2. The required minimum MTF values for each of these zones are also indicated.

As shown in Fig. 7, at the beginning of the test period, the MTF values obtained at 25°C and -40°C are largely similar. In contrast, at 85°C, a decrease of approximately 3% in MTF values is observed for ROIs located in the central and intermediate zones. Interestingly, in the outer zone, ROIs 13 and 18 exhibit an increase in MTF values of around 4% compared to the values measured at lower temperatures. Since the MTF value is determined by the optical response of pixels located within a given ROI, this suggests a non-uniform temperature-dependent pixel response across the sensor matrix, particularly at elevated operating temperatures. Moreover, noticeable differences in MTF values between ROIs within the same zone (especially in the central and outer zones) point to a degree of technological variation in pixel characteristics within the sensor matrix.

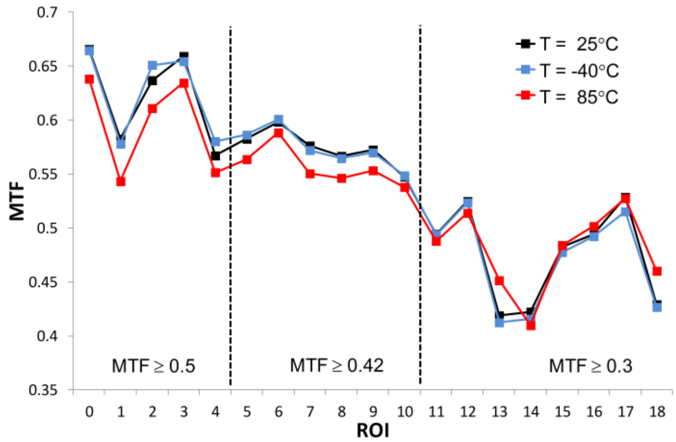

Fig. 7. Measured MTF values for individual ROIs for three ambient temperatures at the beginning of the test period

In turn, Fig. 8 illustrates the effect of long-term cyclic thermal loading on the MTF values. For most ROIs, MTF values measured at -40°C and 85°C at the end of the test period are higher than those recorded at 25°C. The smallest differences are observed in the central zone, while the largest, reaching up to 10%, occur in the outer zone.

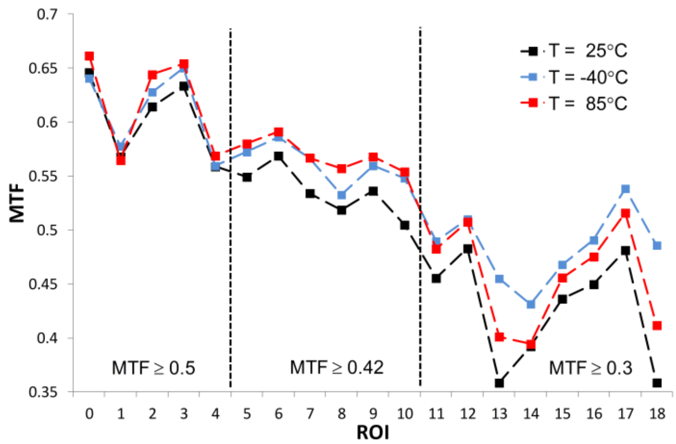

Fig. 8. Measured MTF values for individual ROIs for three ambient temperatures at the end of the test period

Notably, the highest MTF values in this zone were measured at the lowest temperature. Although the long-term effect of temperature cycling on MTF is evident, no measured MTF value fell below the threshold required for any of the defined sensor detection zones.

Figures 9, 10 and 11 compare independently for individual temperature values the measurement results of the MTF parameter: 25°C – Fig. 9, -40°C – Fig. 10, 85°C – Fig. 11. In the figures the solid lines represent measurements taken at the beginning of the test period, while the dashed lines correspond to results obtained at the end of the test period.

As shown in Fig. 9, aging effects associated with long-term operation under a wide range of ambient temperatures result in a noticeable decrease in MTF values across all detection zones of the camera sensor. The most significant reductions, reaching approximately 8%, are observed in the outer zone, particularly in ROIs 13 and 18.

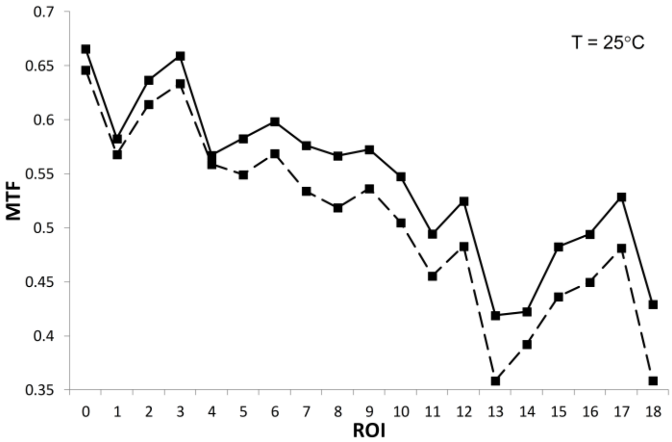

Fig. 9. MTF values measured at the beginning and end of the test period for individual ROIs at 25°C

In contrast, for measurements taken at -40°C (Fig. 10), the observed decreases are smaller. In fact, a slight increase in MTF values is visible for selected ROIs in the outer detection area (ROIs 11–18), indicating a possible positive influence of low temperatures on sensor performance in that region.

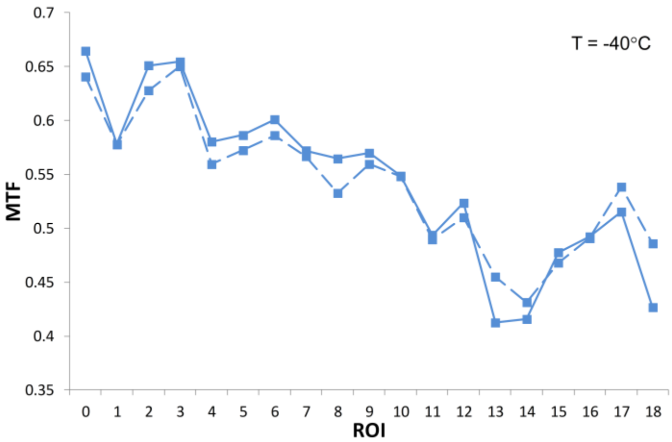

Fig. 10. MTF values measured at the beginning and end of the test period for individual ROIs at -40°C

In turn, for measurements conducted at 85°C (Fig. 11), most ROIs show an increase in MTF values of approximately 2% or more. These results suggest that the impact of prolonged exposure to temperature cycling on MTF performance is not uniform and depends on the specific ambient temperature at which the measurement is performed.

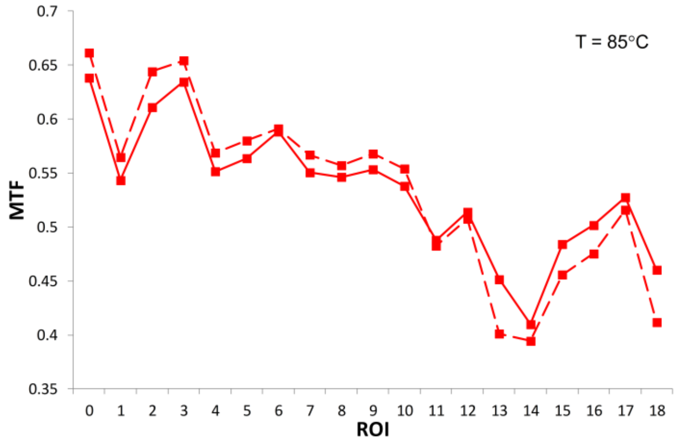

Fig. 11. MTF values measured at the beginning and end of the test period for individual ROIs at 85°C

V. Summary

This paper presents selected aspects of the requirements for testing cameras used in active safety systems, with a focus on optical measurements of the MTF parameter at various ambient temperatures. The obtained test results show that temperature has a noticeable, yet ambiguous effect on the MTF parameter, which also depends on the position of the test patterns within the sensor's field of detection. MTF measurements conducted at 25°C, both at the beginning and the end of the test period, indicate a slight decrease in MTF values due to prolonged camera operation across a wide range of ambient temperatures. Importantly, these values remain above the established lower limits. It should be emphasized that the measurements at 25°C serve as the primary basis for evaluating the camera's image detail reproduction quality, as this temperature is recognized as the reference condition according to automotive industry standards.

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