Investigation of the Radar Cross-Section and its Optimization Potential for ADAS Tests

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Received: 17 October 2024 | Revised: 5 November 2024 | Accepted: 9 January 2025

ABSTRACT

The objective of this study is to examine the Radar Cross Section (RCS) of instruments designed for Autonomous Driving Systems (ADAS) testing, with the intention of comparing the results to those of actual human subjects. The RCS values of both dummy and platform objects were documented at varying distances and positions, with the objective of ascertaining the extent to which dummies can serve as substitutes for human values in vehicle radar sensing tests. The findings, substantiated by graphical representations and statistical analyses (e.g., Pearson and Spearman correlation), reveal a moderately strong positive correlation between the RCS and human values, which is statistically significant. The outcomes of the tests demonstrate that the developed instruments can substitute for real human radar cross-section values within the range of 5-15 m. However, as the distance increases, larger deviations are observed. These discrepancies underscore the necessity for a refinement of the dummy design in future ADAS tests, ensuring that distance-sensitive tests accurately reflect real human measurements.

Keywords- dummy; RCS; autonomous driving systems; statistical analysis

I. INTRODUCTION

The notion of Industry 4.0 [1], which signifies the repercussions of the fourth industrial revolution, assumes a significant role in the preservation of a high-quality automotive industry. This overarching concept encompasses the implementation of cutting-edge technologies. This includes automation, data networks, modern production processes, modernized production processes, collaboration between humans and machines, and three-dimensional printing [2]. The proliferation of data analysis and artificial intelligence has profoundly transformed production processes, enhancing operational efficiency and resource utilization within companies [3]. The development of self-driving vehicles is inextricably linked to the ongoing fourth industrial revolution. To achieve breakthroughs in autonomous technologies, developers must use advanced software and tools that are globally available. The Society of Automotive Engineers (SAE) standard has established six levels of automation, ranging from Level 0, indicating no automation, to Level 5, signifying full automation. Level 0 signifies the absence of automation, while level 5 denotes full automation, where the vehicle is capable of handling all situations independently [4]. Authors in [5] demonstrated the efficacy of ADAS enhanced by radar and sensor fusion technologies, thereby enhancing efficiency. Authors in [6] identified the necessity of integrating multidisciplinary competencies, such as perception, localization, decision-making, and intervention, for effective self-management. The objective of ADAS systems is to provide support to drivers while they are operating the vehicle, aiding them in detecting and evading potential hazards in their environment [7, 8]. These systems can be categorized into two main types: passive, such as lane departure warnings, and active, such as lane-keeping assistance, which actively intervenes in driving [9]. Additionally, radars hold considerable potential for target detection and classification [10]. Furthermore, radar-based sensing and vehicle safety systems augment the sensing capabilities of vehicles, thereby enhancing safety [11]. Driving demands the coordination of numerous functions, which deteriorate with aging, hence increasing the risk of accidents in older drivers [12]. The decline in visual acuity, hearing impairment, and cognitive decline in older drivers further exacerbates the risk [15]. Notwithstanding, driving plays a crucial role in preserving mobility and independence among older individuals [16]. The efficacy of ADAS systems in reducing accidents across various age demographics has been demonstrated [17], with the potential to serve as early indicators of autonomous vehicle integration in the future [18].

In addition, effective testing of ADAS systems necessitates the establishment and evaluation of appropriate values for the RCS, which refers to the size and reflectivity of the object visible to the radar [19]. Conducting ADAS tests on actual humans would present significant challenges and pose considerable safety risks. To circumvent these challenges, the usage of dummies with well-calibrated RCS values is imperative. These dummies serve as proxies, ensuring that radar-based sensors perceive them as authentic human subjects. The absence of correctly set RCS values in ADAS systems can impede their capacity to accurately identify human figures, potentially resulting in inaccurate detection outcomes. This is particularly salient in the context of evaluating automatic emergency braking systems and collision avoidance systems, where rapid and precise detection is paramount to mitigate the risk of accidents. A substantial body of research has been conducted on analogous issues. A number of researchers have examined the calibration technology of emergency braking systems and dummies using radar and infrared reflected signals. The objective of this research was to enhance calibration methods and improve pedestrian detection accuracy by employing various sensors under laboratory conditions [20]. Authors in [21] sought to establish reference standards from RCS measurements in the 24 GHz and 77 GHz frequency ranges. Laboratory experiments were conducted to analyze the impact of the antenna height, dummy height, and clothing on RCS values, thereby supporting the development and standardization of pedestrian recognition systems [21]. The performance of ADAS experimental tests was evaluated by comparing millimeter-wave radar data collected from human and dummy models. Using the millimeter-wave radar, the electromagnetic wave echo characteristics were gathered at fixed distances and different angle positions, based on the Doppler effect, for both humans and dummies. The findings demonstrated a high correlation [22]. In contrast to these studies, the objective and novelty of this research lies in applying a new approach by conducting measurements in real environmental conditions rather than in laboratory settings. This approach will allow for the assessment and comparison of the RCS values of the dummy and its platform against those of real humans. The results of the measurements at different distances will provide insights into whether the created devices are capable of replacing real humans in ADAS tests.

II. MATERIALS AND METHOD

The objective of this study is to examine the radar cross-section of self-designed instruments for ADAS tests, with the intention of comparing the results with those of real people. In all cases, the dummy and the platform were tested together, as they function as a unit. The evaluation of the tests provides significant input for a further refinement of the instruments designed for future ADAS tests. To ensure the proper functioning of ADAS, it is imperative to test individual driver assistance units with meticulously adapted test devices, such as dummies or moving platforms. These dummies simulate human figures, thus enabling the evaluation of the effectiveness and reliability of various ADAS systems, including pedestrian detection systems, automatic emergency braking systems, and collision avoidance systems. Moving platforms, on the other hand, are designed to simulate realistic pedestrian movements, such as crossing the road, walking on the sidewalk, or stepping onto the roadway. This dummy represents an enhanced iteration, having evolved from a prototype developed in early 2023 and reaching its current, definitive form in 2024. The dummy's design and production underwent a staged approach, encompassing a comprehensive range of competencies. A meticulous examination of the extant literature and standard research guided the identification of critical components necessitating particular attention. The implementation sequence was developed using information from the standards defined by the European Automobile Manufacturers' Association (ACEA), which guided the construction of the final test device [20]. In terms of its characteristics, the size and weight of the dummy are important, as they should generally reflect the size and weight of an average person. Different-sized mannequins are used to represent various demographic groups (e.g., adult male, female, child). In this case, an adult male mannequin was designed, with a height defined by the standard as 1800 mm +/- 20 mm and a body weight of up to 7 kg. The mannequin's material is chosen for its durability and flexibility to withstand the forces and movements that occur during testing. The body is composed of foam and is externally covered with a partially waterproof polyester material that meets the color requirements specified in the standard. Additionally, the 3D printing technology was employed for specific components, such as the drive and shoulder connections. The plastic parts are encased in foam, ensuring that the harder components do not damage the vehicle during tests.

In addition to the dummy, a so-called dummy platform was also previously planned. The usage of moving platforms constitutes a significant element in the testing of dummies. These platforms ensure the execution of realistic simulations, facilitate the acquisition of precise measurement data, and enable the testing and development of advanced safety systems. Moreover, they offer a wide range of testing options and contribute to the reduction of research and development costs, as the undertaking of authentic crash tests can be financially burdensome and time-consuming. The utilization of moving platforms enables the execution of numerous test scenarios with greater efficiency and at a reduced financial cost. The collective impact of these factors is substantial in terms of enhancing vehicle safety and safeguarding human life. Figure 1 shows the platform with the dummy mounted on it.

Fig. 1. Dummy on the platform.

During the measurement, a Continental ARS 408-21 long-range radar mounted on a Nissan Leaf, along with the test devices, was used, as depicted in Figure 2. The data were recorded using a Jetson Xavier NX microcomputer, which communicates with the vehicle's CAN network via the Robot Operating System (ROS). To interpret the messages from the CAN network, a CAN module was connected to the microcomputer, and the radar messages were read and interpreted using open-source software designed for the radar. The raw data were recorded in the ROS format. Subsequently, a data processing program developed by the researchers was employed to filter the dataset after which the filtered data were exported into a CSV file. The measurements were carried out under moderate weather conditions, with no wind, and at a temperature of 25°C on the ZalaZONE Test Track. Regrettably, photographic documentation of the measurements was not possible, therefore, the measurement method is presented in Figure 3.

Fig. 2. The installed Continental ARS 408-21 long-range radar.

The measurement comprised two components. Initially, reference measurements were obtained through a radar cross-section examination of five individuals exhibiting distinct parameters. Following the establishment of a fixed position for the subject, the radar systematically recorded data at incremental distances from 30 meters to 5 meters, with each increment of 1 m. Ensuring the exact distance and perpendicular alignment to the target was facilitated by the radar, thus ensuring optimal conditions for the measurement. Each distance measurement was recorded for a duration of 30 seconds, resulting in the collection of an average of nearly 410 data points. The comprehensive database that emerged is a valuable resource. The progression of the final number of data points is portrayed in Table I.

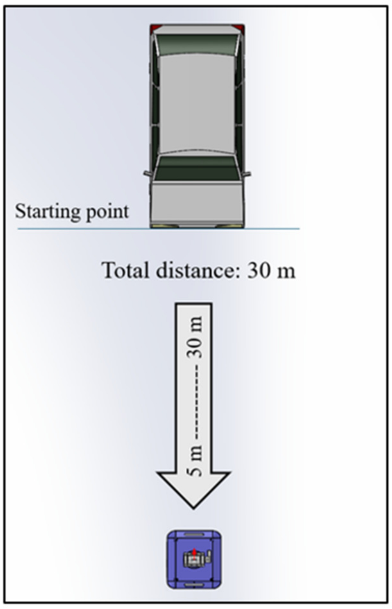

Fig. 3. Schematic presentation of the measurement.

TABLE I. NUMBER OF COLLECTED DATA

Number of data	
Dummy	10,624
Human 1	10,653
Human 2	10,991
Human 3	11,060
Human 4	11,044
Human 5	10,884
Total	65,256

Following the completion of the human reference measurements, the test devices, namely the dummy and the platform designed for it, were examined using a similar method. The collected data were converted into a CSV file format and subsequently evaluated utilizing Microsoft Excel. The data were then averaged to provide a general understanding of the differences in the RCS values. A correlation test was then performed to explore the relationship between the data and to estimate the degree of similarity between the dummy and human radar cross-section values. To facilitate interpretation, the RCS values were subsequently multiplied by 100. The data analysis was conducted using the Jamovi program.

III. RESULTS AND DISCUSSION

Figure 4 compares the RCS values of the dummy and five different human subjects as a function of distance. The measurement commenced at a distance of 5 meters and was conducted up to a distance of 30 meters. The mean of the five individuals' values was calculated, thereby establishing a reference point for the subsequent comparison of the dummy's values. The RCS values of both the dummy and humans were recorded at various distances, with the objective of determining the extent to which the dummy can substitute for a human in radar detection tests. The blue line signifies the variation in the dummy's RCS values as the distance increases, while the orange line denotes the mean human RCS data. The gray bars present the differences between the two values. The data reveal that the dummy's RCS values are frequently higher than those of humans, particularly after 15 meters. In the range between 5 and 15 meters, the dummy's and humans' RCS values are relatively close to each other; however, as the distance increases, larger differences can be observed.

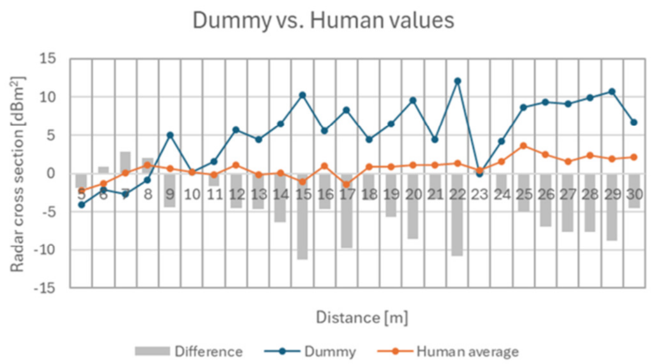

Fig. 4. Average RCS values and differences between dummy and humans.

An analysis of these differences enables the assessment of the reliability with which the dummy substitutes for the human in radar-based detection tests. Smaller deviations indicate that the dummy exhibits a radar detection behavior analogous to that of a human, while larger deviations suggest divergent radar reflection characteristics between the dummy and a human. The disparities become particularly evident beyond 20 meters, indicating the necessity for a further calibration or optimization within this distance range. A comprehensive analysis of the distribution of the RCS values is also imperative, as it provides additional insight into how the values are distributed across the measurement ranges. Through this distribution analysis, it can be determined how frequently certain values occur at different distances and whether there are any systematic variations that could affect the substitutability between the dummy and the human. These analyses facilitate the identification of factors causing deviations and the determination of the extent to which these factors affect the accuracy of the radar-based detection. The distribution of the average radar cross-section values of the dummy was examined using the histogram and density function of the data, as seen in Figure 5. The histogram illustrates the frequency of the RCS values across various ranges. The data distribution reveals several peaks, indicating that the values are not evenly distributed, with certain ranges being denser, while others are sporadic.

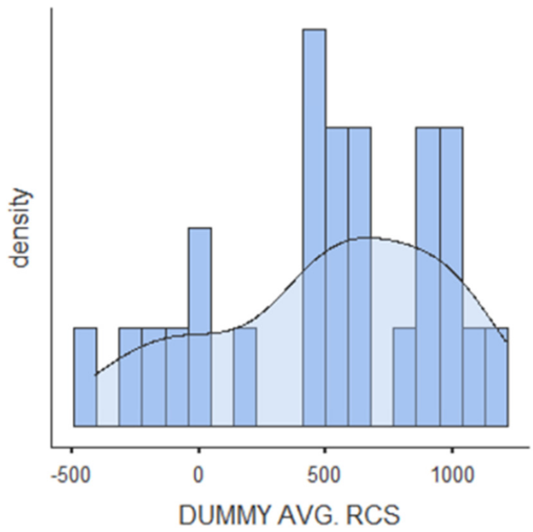

Fig. 5. Distribution of dummy average RCS values.

The distribution reveals that the majority of values fall within the range of 0 to 1000, with the presence of outliers that include negative and high positive values. The distribution does not exhibit a perfectly normal shape, suggesting that the RCS values of the dummy are contingent on multiple factors, including the measurement conditions, distance, and the material and surface characteristics of the dummy. The Q-Q plot, shown in Figure 6, was used to assess the normality of the RCS data of the dummy. The results indicate that the majority of data points are positioned along the diagonal line, suggesting that the data align with the normal distribution to a reasonable extent. However, deviations from normality were observed, particularly at the upper and lower extremes of the distribution, suggesting potential outliers. This observation indicates that while the dummy's RCS data appear to be largely aligned with a normal distribution, there may be non-normal fluctuations present at the extremes. The distribution of average human RCS values is represented as a histogram in Figure 7. A thorough examination of the distribution reveals that human RCS values adhere more closely to a normal distribution than those of the dummy. The majority of the values fall within the range of 0 to 200, with a few outliers located below -200 or above 400. The distribution exhibits a discernible peak around 0, indicating a tendency for human RCS values to congregate around a singular central value. As illustrated in Figure 8, the majority of data points align along the diagonal line of the Q-Q plot, suggesting that the human RCS values predominantly adhere to a normal distribution. The normal distribution of the human RCS data manifests greater stability in comparison to that of the dummy, where a higher degree of variation was observed.

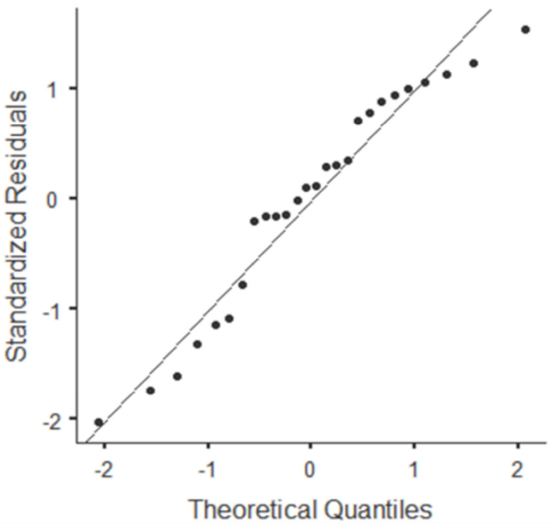

Fig. 6. Q-Q plot of dummy average RCS values.

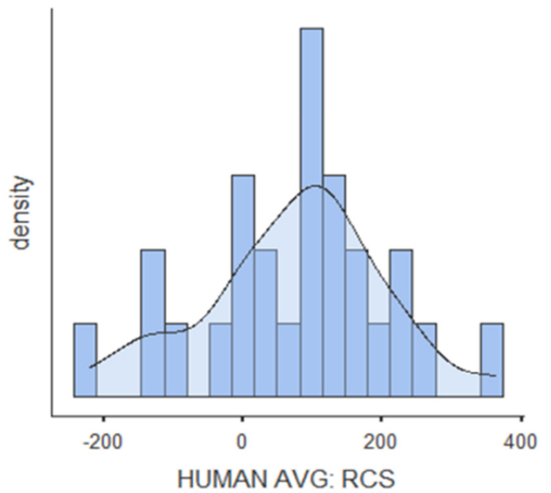

Fig. 7. Distribution of average human RCS values.

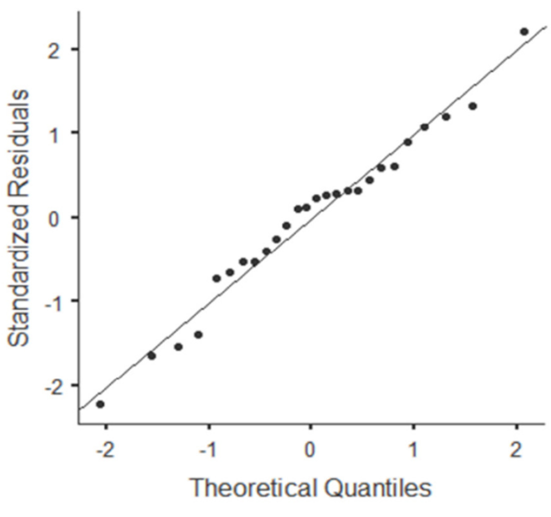

Fig. 8. Q-Q plot of average human RCS values.

The relationship between the RCS data was examined using the Pearson and Spearman correlation analyses to assess how well the dummy values model the human RCS values, as presented in Table II. The Pearson correlation coefficient, measuring the strength of the linear relationship between the dummy and human RCS values, was found to be 0.522 (p = 0.006). This indicates a moderately strong positive linear relationship between the dummy and human RCS values. This finding suggests that while the dummy and human data exhibit a similar trend, the relationship is not exact. The strength of the correlation suggests that the dummy's data reflect human values to some extent, but the relationship between the two samples is not entirely linear. The statistical significance of the correlation ($p < 0.01$) indicates that the observed relationship is unlikely to be merely coincidental. The confirmation of this relationship is further substantiated by the Spearman rank correlation result, which yielded a value of *rho* = 0.521, p = 0.007. This finding aligns with the outcomes of the Pearson correlation analysis, hence substantiating the hypothesis that the data exhibit a monotonically related pattern. This observation is particularly salient in light of the fact that even if the dataset does not conform to a perfect linear distribution, a consistent trend can be still discerned.

TABLE II. CORRELATION MATRIX OF AVERAGE RCS VALUES OF HUMAN AND DUMMY

Correlation Matrix		**DUMMY AVG. RCS**	**HUMAN AVG. RCS**
DUMMY AVG. RCS	Pearson's *r*	-	
	df	-	
	p-value	-	
	Spearman's *rho*	-	
	df	-	
	p-value	-	
	N	-	
HUMAN AVG. RCS	Pearson's *r*	0.522**	-
	df	24	-
	p-value	0.006	-
	Spearman's *rho*	0.521**	-
	df	24	-
	p-value	0.007	-
	N	26	-

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

IV. CONCLUSIONS

The impetus for this study stems from the necessity to develop tools (i.e., dummy, platform) for the future testing of Autonomous Driving Systems (ADAS). This necessity arises from the need to create a set of tools that can be used in an industrial environment and can adequately substitute for a human operator. To this end, radar cross-sectional studies have been conducted, the results of which have elucidated current gaps and areas for improvement. The findings of these tests demonstrate the potential of the Radar Cross-Section (RCS) values of the dummy to substitute, at least in part, for human values during vehicle radar detection tests. This is particularly evident in the 5 to 15 meter distance range, where the RCS values of the dummy approximate those of humans. A comparative analysis was conducted by examining the RCS values of both the dummy and human subjects at distances ranging from 5 to 30 meters. In this analysis, the human values were averaged to serve as a reference point for the dummy, thereby facilitating a more accurate and nuanced assessment of the dummy's RCS values. Graphs and statistical analyses (Pearson and Spearman correlation) demonstrated that there is a moderately strong positive correlation between the dummy and human RCS values, which is statistically significant. This finding indicates that dummy data exhibit a tendency to mirror shifts in human values, though the relationship is not entirely linear. Inferred from the observed correlation degree, it is plausible to imply that the usage of dummy values can offer valuable guidance during the testing phase. However, it is important to note that achieving precise substitution will necessitate a further refinement in subsequent research. The findings reveal that the dummy's values are predominantly elevated, especially at distances exceeding 15 meters. However, within the range of 5 to 15 meters, the RCS values of the dummy align relatively well with those of humans, and beyond this range, the differences become more pronounced. It is imperative to emphasize that a proper configuration of the RCS is essential for the efficacy of the ADAS system testing, thus ensuring the accurate operation of radar-based sensors. The findings suggest that while the utilization of the dummy is generally suitable for vehicle radar detection tests, disparities in the radar reflectivity characteristics between the dummy and human subjects at specific distances and positions may influence the data detected by radars.

In summary, the findings indicate that while the dummy can serve as a suitable surrogate for human test subjects in specific scenarios, particularly at closer distances, significant discrepancies emerge as the distance increases. These variations suggest the potential necessity for a further refinement and optimization of the dummy to more accurately model the human radar cross-section characteristics, particularly in remote sensing scenarios. Further research and refinement are necessary to ensure that the results provided by the dummy more closely approximate human radar reflectivity data, thereby increasing the accuracy and reliability of vehicle radar detection tests.

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