

Development of Surrogate Grass for the Evaluation of Vehicle Road Departure Mitigation Systems

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Abstract— Vehicle road departure mitigation system (RDMS), as new active safety technology, has been introduced into the market in recent years. This system can detect roadside objects and road edges to reduce the risk of roadway departure crashes. To evaluate and improve the performance of RDMS, surrogates of roadside objects, which have the same camera, radar, and LiDAR characteristics of the real objects, need to be developed. Grass is the most common road edge in the U.S. as seen from the real road data. This paper describes the development of surrogate grass. The LiDAR (infrared) and radar characteristics of the selected artificial turf (grass) are obtained and compared with those of real grass. In order to make the surrogate grass match the real grass in the view of sensors (LiDAR, radar and camera), a special color coating with high reflectance material is applied to the artificial turf. Both LiDAR and radar measurements confirmed that the surrogate grass closely match the key characteristics of the real grass. Five grass colors and eighteen color patterns were identified based on 1,021 grass road-edge samples from all states of the U.S. 300-meter long surrogate grass was made and successfully used on the test track for the vehicle RDMS evaluation.

I. INTRODUCTION

Road departure is a major cause of fatal vehicle crashes in the U.S. [1-4]. Based on the data from the Federal Highway Administration (FHWA), an average of 19,223 fatalities occurred per year due to the road departure from 2015 to 2017, accounting for 52% of all the traffic fatalities in the U.S. [5]. Considering the severity of the road departure crash, advanced active safety technology, such as roadway departure mitigation system (RDMS), has been developed and introduced into the market in recent years for reducing the road departure crashes [6-18]. The RDMS is designed to have the capability of detecting the road edges/boundaries and recognizing the roadside objects, even when the lane marking is unclear or does not exist.

However, to the best knowledge of the authors, the standard testing procedures and equipment for evaluating the performance of RDMS have not been fully developed. Hence, it is imperative to research and develop methods,

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scenarios, and software and hardware tools for objective evaluation and testing of the RDMS. Among these tasks, developing roadside surrogates that have the representative characteristics of the real roadside objects from the view of automotive sensors is crucial. For various commonly seen roadside objects, such as metal guardrail, concrete divider, grass, etc., 56% of the road edges are categorized as grass in the U.S. [19]. It is not practical to test the RDMS using real grass road edge since the real grass can be easily damaged in several runs over, which makes it not suitable for further testing. Moreover, the color of real grass changes in different regions and in different seasons, which makes the testing results not comparable. Therefore, it is essential to develop surrogate grass with representative sensing characteristics of real grass for testing and evaluating RDMS.

To develop surrogate grass that can satisfy the color, LiDAR (infrared, IR), and radar characteristics of real grass, we have investigated the characteristics of real grass in the view of RDMS sensors (LiDAR, radar, and camera) [20-22]. Yi et al. [20] developed a grass dataset, including 2,443 locations with grass road edge from their road edge samples database that covers all different road levels in 50 U.S. states. Based on this grass dataset, four parameters were identified to describe the visual characteristics of grass, i.e., color, color evenness, height, and height evenness. Two representative grass types were successfully derived for the surrogate grass development [20]. They are (1) short, mixed yellow and green color, and large random uneven patches grass, and (2) short, green, and even grass.

Lin et al. [21] focused on the radar characteristics of real grass and took the grass RCS (radar cross section) measurements using both 24 GHz and 77 GHz radar. It was found that different kinds of grass samples have similar mean RCS, and the shapes of mean RCS plots are quite similar under 77 GHz radar frequencies, although their magnitudes are different. Based on the measurements, the radar characteristics of grass under various measurement conditions were recommended [21]. Shen et al. [22] studied the near-infrared (LiDAR) spectral features of eight selected kinds of grass and determined the reflectance range of grass in various measurement conditions. The representative IR reflectivity of grass at 0°-70° viewing angles were identified for guiding the surrogate grass development.

The studies mentioned above provided the most important requirements for making surrogate grass in terms of RDMS sensors. This paper describes the development of the surrogate grass for vehicle road departure testing based on the data and results obtained from those studies. The developed surrogate grass should meet not only all the

requirements of the camera, LIDAR, and radar characteristics, but also be usable and durable in the vehicle testing.

The remainder of this paper is structured as follows. Section 2 describes the color, IR, and radar characteristics of a selected artificial turf. The detailed methods for making the satisfied surrogate grass are discussed in Section 3. The comparison and analysis of the measurement results are given. Section 4 shows the applicability of vehicle testing using the 300-meter-long surrogate grass. The conclusions are presented in Section 5.

II. APPROACH FOR THE DEVELOPMENT OF SURROGATE GRASS

Unlike other roadside objects, such as concrete divider and metal guardrail, the appearance of grass on the roadside varies significantly in different seasons and environments. Therefore, developing surrogate grass that satisfies the color, I.R., and radar requirements is a complicated and challenging task. Since it is cost-prohibitive to custom design and make specific surrogate grass for vehicle testing, we develop the surrogate grass by modifying the commercially available artificial turf.

A. Selection of artificial turf as the base for surrogate grass development

The common materials of artificial turf are nylon and polyester. We selected polyester artificial turf as the candidate for the base material of surrogate grass due to its strength and lifetime. It is known that the representative grass is a mix of short (3-5 inches tall) and median (6-9 inches tall) grasses [20]. However, for the artificial turf, the tallest blade that can be found without the need of filler is only about 2 inches. For any artificial turf blade taller than 2 inches, it needs to be filled with filler (sand or plastic ball) to support the erection of grass blade, which makes the artificial turf not movable after been installed. In addition, our previous studies revealed that the IR and radar features are not affected by the height of grass, and the color evenness and height evenness are closely correlated [21, 22]. Therefore, it is believed that the shorter blade of artificial turf may be modified to satisfy all requirements of surrogate grass.

In this work, many types of commercially available artificial turf samples were collected and tested for their radar, IR reflectivity, and color properties. Since it is more difficult to meet the RCS requirement than the IR and color requirements of the surrogate grass, we first focused on finding an artificial turf that can satisfy the 77GHz RCS requirement, and then considered the satisfaction of IR reflectivity and color requirements.

B. Radar characteristics of artificial turf

1) Measurement equipment

An off-the-shelf commercial 24 GHz software-defined radar (SDR) and a 24 GHz-77 GHz up/down converter were used to measure the 77 GHz RCS of artificial turf. A trihedral corner reflector was used as the reference object for calibrating the RCS of artificial turf. The details of the

equipment have been described in [21]. The measurement method is the same as that used to measure the RCS of real grass [21]. The radar measurement setup is shown in Fig. 1.



Figure 1. 77GHz radar horizontal polarization measurement setup.

2) 77 GHz RCS measurement results

After measuring the 77GHz RCS of various artificial turf samples, one type of polyester artificial turf with 2-inch-tall blades was selected that can satisfy the 77GHz RCS requirement of the surrogate grass. The measurement results at different depression angles under 77 GHz radar horizontal polarization are shown in Fig. 2. The horizontal axis is the distance from the antenna, and the vertical axis is the RCS. The vertical blue line is the location of the trihedral corner reflector, where the center beam of the radar aimed. The first major peak of RCS close to the vertical axis is not the grass RCS. It is the mixed signals of antenna coupling and near the side ground reflection. The second peak, as indicated by the vertical blue line, is valuable for data analysis and comparison. This peak region is covered by a radar center beam and valid upward side beams that can best describe the grass/turf property.

The region between the red and green lines in Fig. 2 shows the representative RCS of the real grass, which was obtained from the previous study [21]. The mean RCS of the real grass is also added as the yellow line. The RCS of the finally selected artificial turf is marked as the black line. It can be seen that the RCS plots of selected artificial turf at different pitch angles are all within the minimum and maximum RCS plots of the real grass. The RCS of the chosen artificial turf matches well with the mean RCS of the real grass at pitch angles between 10-25 degrees, while it is much closer to the maximum value at high pitch angles at 30 and 35 degrees. Therefore, we consider that the selected artificial turf is acceptable as a grass surrogate for 77GHz radar sensors.

3) Effects of underneath material and blade lean direction on RCS

Since the surrogate grass will be placed on the test track for RDMS testing, it was unclear how much reflected radar energy is from the surrogate grass or from the material underneath the surrogate grass. A preliminary study was conducted to evaluate the effect of different underneath materials on the RCS of the surrogate grass. Clay, sand, and asphalt were selected as the underneath material. It is found that these three materials have no effect on the RCS properties of surrogate grass. In addition, the effect of the blade lean direction on the 77GHz RCS has been investigated by measuring the RCS of the artificial turf from three blade leaning directions at a 15-degree depression angle. The results indicate that the 77GHz RCS result is not influenced by the radar viewing direction, either.

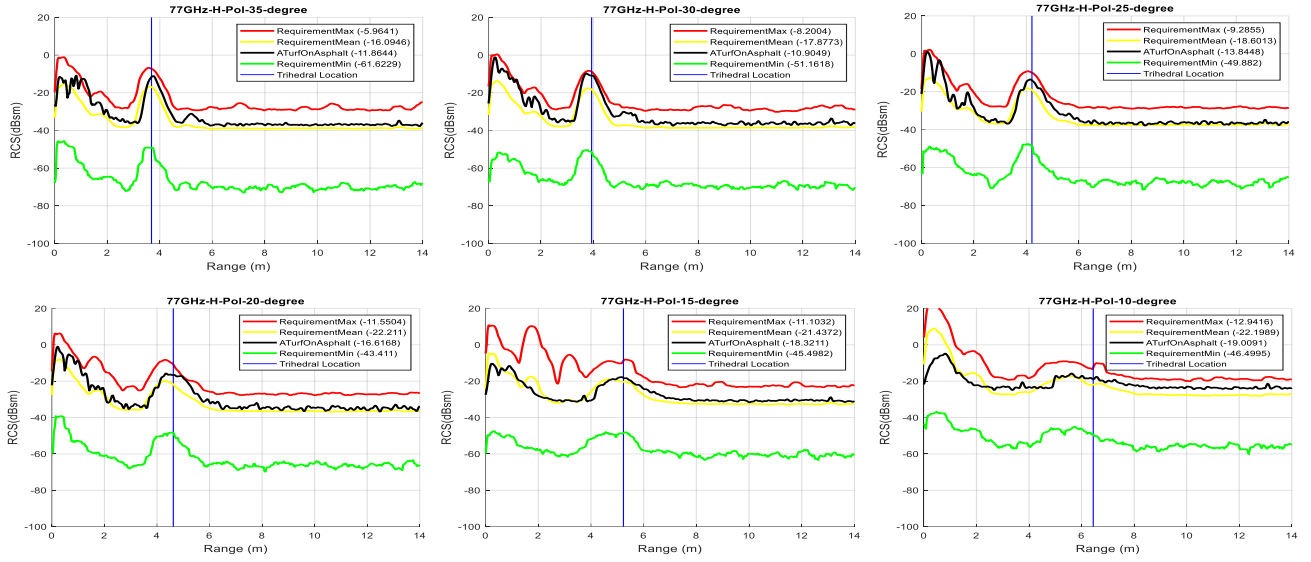


Figure 2. RCS measurement results of artificial turf (black line) at different pitch angles under 77 GHz horizontal polarization.

C. IR characteristics of artificial turf

After selecting an artificial turf that can satisfy the RCS requirement, we checked the IR reflectivity of that artificial turf. It is found that the blades of artificial turf always lean towards one direction since it is rolled during storage and transportation. Therefore, its IR reflectance was measured from three orientations to find out their effect on the measurement results, as shown in Fig. 3.

- Blades leaning towards the probe of the spectrometer
- Blades leaning away from the probe of the spectrometer
- Blades leaning sideways from the probe of the spectrometer

An ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Inc.) was used to measure the reflectance spectra of the artificial turf. The detailed description of the measurement methods, equipment, and setup can be found in [22]. The definition of the illumination angle and measurement angle is shown in Fig. 4. To mimic the lighting condition of LiDAR, the illumination angle and measurement angle are set the same in reflectivity measurements.



Figure 3. Leaning directions of artificial turf with respect to the measurement probe.

Fig. 5 shows the IR reflectance of the turf from three blade leaning directions at 0°, 20°, 40°, and 70° measurement angles, respectively. The representative IR reflectance range (upper and lower threshold) of surrogate grass [22] is also shown as red curves. The black, blue and green curves are the IR reflectance of the grass blades leaning away and sideways from the probe, and towards the

probe, respectively. It can be seen that the IR reflectance of the artificial turf is lower than the lower end of the representative range in most blade leaning directions. However, it is closer to the lower end of the representative IR reflectance required for surrogate grass when the blades are leaning away from the probe or sideways. To make the IR reflectivity of the surrogate grass within the required range, we considered applying a coating to the artificial turf to increase its IR reflectivity.

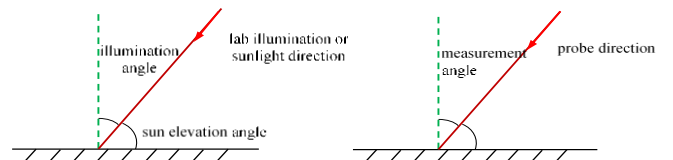
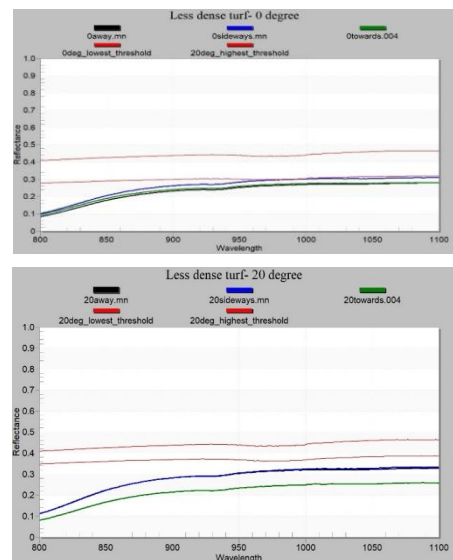


Figure 4. Description of illumination angle and measurement angle.



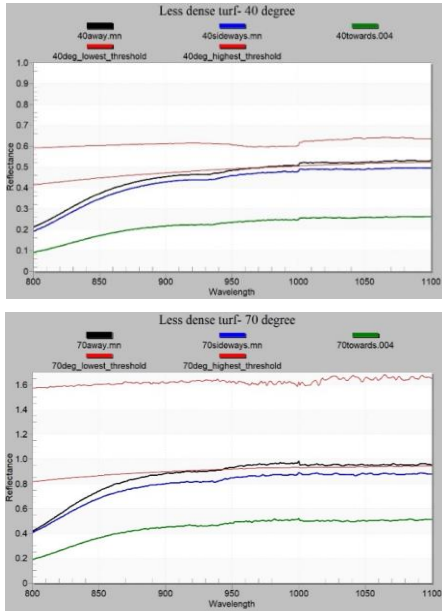


Figure 5. The reflectance of artificial turf measured from three viewing orientations and compared to the suggested IR reflectance of surrogate grass for 0°, 20°, 40° and 70° measurement angles (illumination angle equals to measurement angle, and 20° phase angle).

D. Color of artificial turf

Our previous study [23] showed that the real grass has various colors and can be represented by many color patterns. However, the artificial turf that we can find on the market has either a uniform color or one color pattern. Therefore, we need to modify the blade color of the artificial turf to create the required colors and color patterns. The color requirements for the surrogate grass obtained from 1,021 grass road edge samples were described in [20]. The details of the representative colors of grass are listed in Table 1. It is noted that the RGB values of dark green and medium green (colors 2 and 4) are similar, so in this paper, a medium green color is selected for both dark and medium green, and thus the total number of colors is reduced to 5.

TABLE 1. THE REPRESENTATIVE COLORS OF GRASS [20].

Color	Yellow/Brown			Green		
	Brown	Dark Yellow	Light Yellow	Dark Green	Medium Green	Light Green
Color ID	5	1	6	2	4	3
RGB	111 95 65	146 130 96	170 162 135	99 100 55	105 110 44	139 141 87

III. DEVELOPMENT OF SURROGATE GRASS USING ARTIFICIAL TURF

As described in section II, we have selected an artificial turf that can satisfy the 77GHz RCS requirement but does not satisfy the IR reflectance and color requirements. Thus, the remaining two key issues that need to be solved before the use of artificial turf as surrogate grass are the modification of its color and IR reflectance.

Finding a coating that matches the required colors only is not a difficult task. However, to find a second clear coating that does not alter the color coating but satisfies the IR

reflectance requirement is quite tricky. Since both the IR reflectance and color are the surface properties of the surrogate grass, our approach is to consider them together. For increasing the IR reflectivity of the selected artificial turf to the desired level, a coating material with high reflectance and selectable colors needs to be found or developed and applied to the turf.

In this study, a mix of color pigments of high IR reflectance spectra was used to make a special kind of paint to satisfy both IR reflectance and color requirements for surrogate grass. Five paint colors (i.e., green, medium green, yellow, light yellow, and brown) were prepared to match five representative grass colors. Fig. 6 shows the colors of these paints painted on the artificial turf. For each color sample of painted artificial turf, its IR reflectance was measured at five points between 0-70° angles with an increment of 10°, and its color was compared with the desirable color on the computer and with the real grass.



Figure 6. Five surrogate grass samples painted with the mixed paints.

The IR reflectivity of the artificial turf painted with each of four colors (light green, medium green, dark yellow, and light yellow) was measured and shown in Fig. 7. The measurement was in 800-1100 nm range from 10° to 70° viewing angles. The measurement results indicate that the IR reflectivity of these four colored paints satisfies the IR requirement of the surrogate grass. For the green colors at 0° LiDAR viewing angle, the reflectance is 0.01 below the lower bound in a small spectrum region so we considered it as acceptable. We still could not figure out the brown colored paint to satisfy the desirable IR reflectivity. However, since the brown grass emulates the soil/dirt and only accounts for 1.9% of all grass colors, it could be neglected in the current study.

Once the paints that satisfy each individual color and IR reflectance of surrogate grass were developed, a large piece of surrogate grass was made and used for the 77 GHz RCS measurement. Fig. 8 shows the 77 GHz radar measurement of surrogate grass at 10° and 15° depression angles, respectively. For each figure, the yellow curve shows the maximum RCS, and the green curve shows the minimum RCS. The mean and median RCS are plotted using the red and blue curves, respectively. The location of the trihedral is also added using the vertical purple line. Both measurements confirm that the shapes of RCS of the surrogate grass are similar to that of real grass. The purpose of developing the surrogate grass is to use it as the roadside object during vehicle testing. In the current study, 300 m long, 1.5 m wide surrogate grass was made with 18 color patterns. These 18 grass color patterns were generated based on our previous

study using 901 grass samples all over the U.S. [23]. Fig. 9 shows four examples of the 18 color patterns of surrogate grass we made.

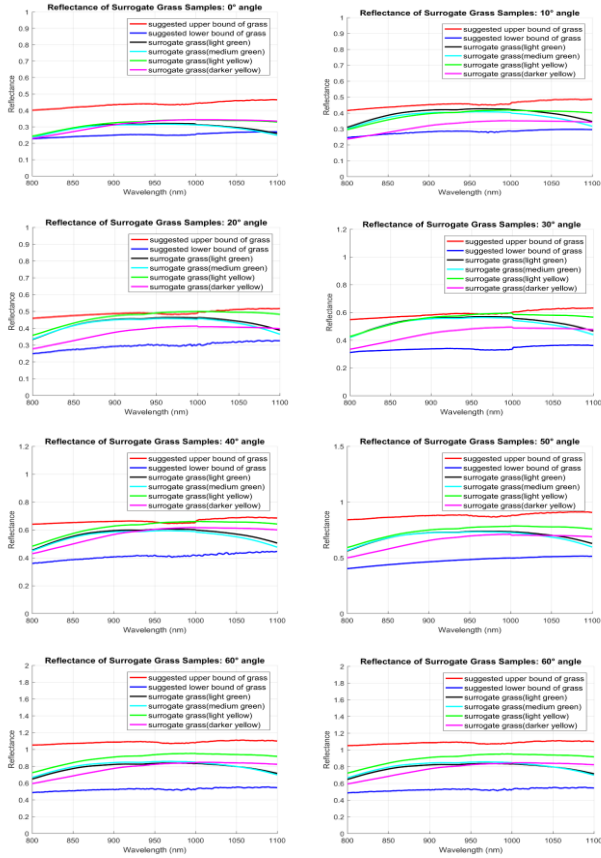
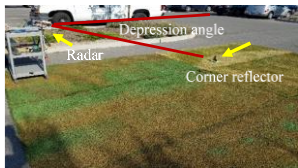
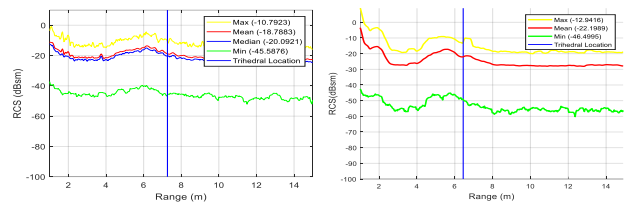


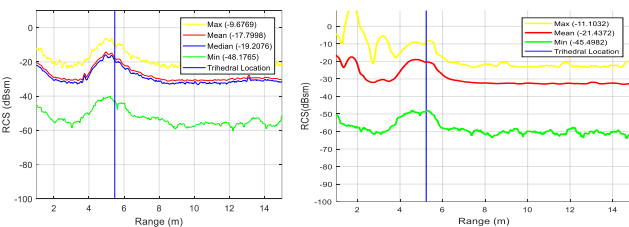
Figure 7. IR reflectance of surrogate grass with different colors at 0°-70° measurement angles.



(a) 77 GHz radar measurement setup



(b) 10° depression angle (left: surrogate grass; right: real grass)



(c) 15° depression angle (left: surrogate grass; right: real grass)

Figure 8. Comparison of 77 GHz RCS of surrogate grass (left) and real grass (right) measured at 10° and 15° depression angle.



Figure 9. Examples of four surrogate grass patterns.

IV. VEHICLE TESTING USING SURROGATE GRASS

The effectiveness and durability of the surrogate grass were evaluated by using a vehicle with the RDMS on a test track in Indiana, U.S. Fig. 10 shows that 450 m² (300 m long and 1.5 m wide) surrogate grass were set up on the test track. The top image shows the shipment of 450 m² surrogate grass using three pickup trucks. The bottom left image shows the straight surrogate grass road edge. The bottom right image shows a 200 m radius curved surrogate grass road edge.



Figure 10. 450 m² surrogate grass on the test track.

The details of test scenarios, data collection, and data post-processing systems used in the vehicle testing were described in [24]. 320 test runs were conducted based on the comprehensive scenarios considering (winter and spring), vehicle speed, road geometry, departure angle, departure side, light condition, etc. The main purpose of this test was to check the differences between the surrogate grass and the real grass in terms of RDMS detection. Among the 320 tests, half (160) of the tests used the surrogate grass, while the other half (160) tests used the real grass. The data analysis reveals that the overall rate of the surrogate grass successfully being detected by that particular RDMS is around 33%, while the overall rate of the real grass being detected by the RDM system is 26.25%. The difference is expected since the surrogate grass covers all seasons and grass types, but the real grass is one particular type and in one season. Therefore, it is believed that in the view of the RDMS sensors, the characteristics of surrogate grass is similar to those of real grass. Hence, we consider that the surrogate grass developed in this study can be used as a roadside object to replace the real grass in the vehicle RDMS evaluation. In addition, our tests on the real grass road edge revealed that the real grass road edge on the test track is not suitable for RDMS evaluation. Fig. 11 shows the images of

real grass road edge before and after being run over in daylight, dust and dark conditions. The real grass was severely damaged after several tests run, so it could not be further considered as a grass road edge for a reliable test environment. The tests of the same scenarios were conducted on the surrogate grass, but the surrogate grass did not have noticeable damage after 120 test runs.



Figure 11. The real grass before and after run-over tests.

V. CONCLUSIONS

This paper has described the process for the development of surrogate grass using a commercially available artificial turf. An artificial turf that matches the RCS characteristics as the real grass was selected first. A special color coating with high reflectance material was developed and applied to the turf to achieve the desired color and IR reflectivity. Both the LiDAR and radar measurements confirmed that the surrogate grass is able to represent the corresponding characteristics of real grass. In addition, five typical grass colors have been extracted, and eighteen color patterns were identified based on 1,021 real grass road edge samples. 300-meter long surrogate grass with various color patterns were made and used in vehicle testing on the test track. The test results showed that the surrogate grass could be successfully detected as the real grass by an RDMS, and it can be repeatedly used for RDMS testing. Therefore, the surrogate grass developed in this work is able to work as one of the surrogate roadside objects in vehicle testing.

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