Digital Limits in Automotive Paint Colors

Digital representations of pigmented automotive paints quickly reach the limits of standard RGB color spaces. This article explains why real-world colors and effects often cannot be reproduced exactly – and examines the extent to which the discrepancies between measured values and on-screen displays are strong.

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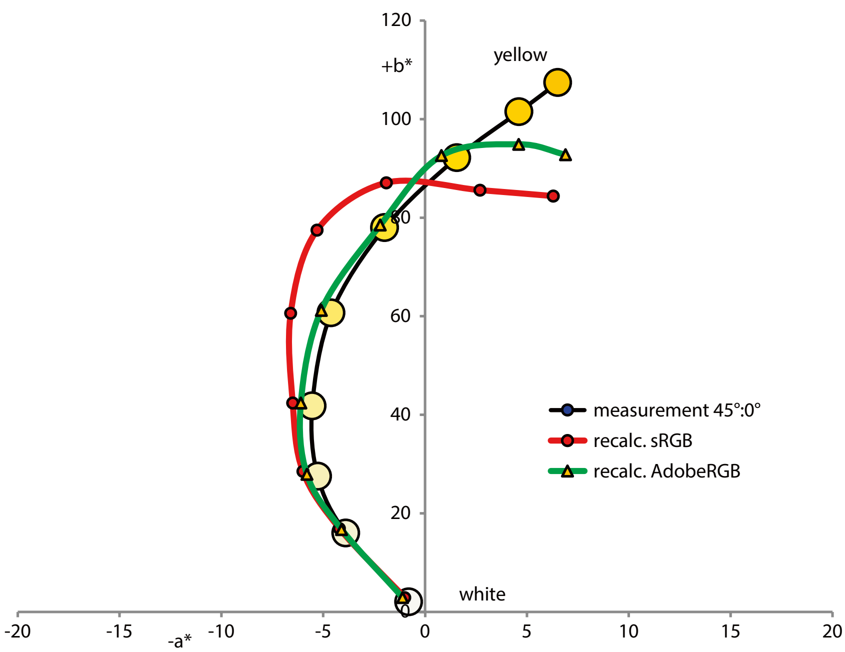
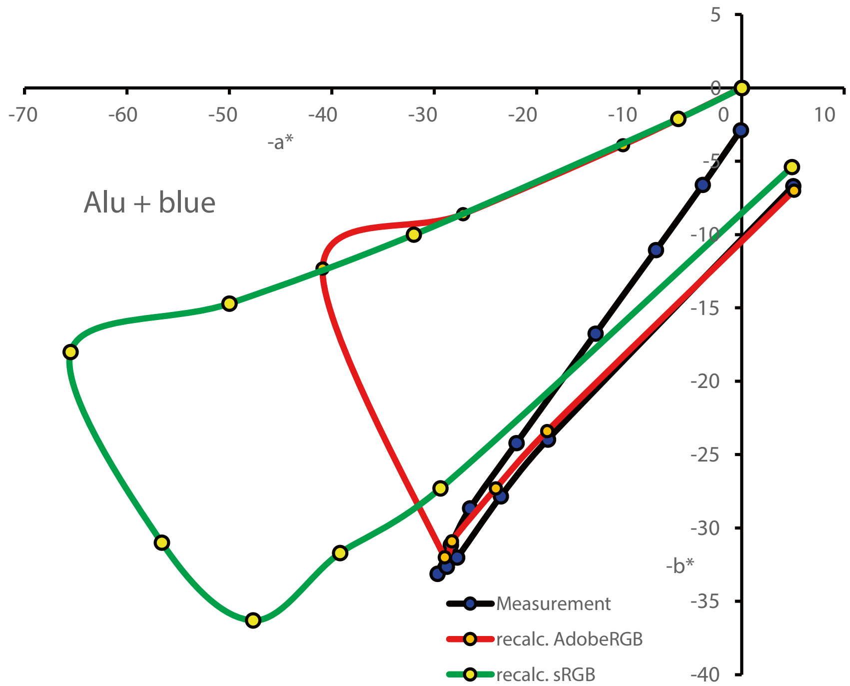
The colors of pigmented automotive paints are often displayed on smartphones or computer screens. For example, color formulations from a mixing system are presented digitally. Software is also used in the development of new automotive colors to adjust and modify shades. While we view a painted sheet of metal or vehicle directly with our eyes, our perception on a screen occurs indirectly through digitization into red-green-blue (RGB) values.
The RGB model is based on the three vectors red, green, and blue, which are perpendicular to one another and are defined by values ranging from 0 to 255. Yellow, cyan (blue-green), and violet (magenta) are produced by additive mixing of the three "primary colors" of the RGB color space. In this model, over 16 million colors can theoretically be displayed.



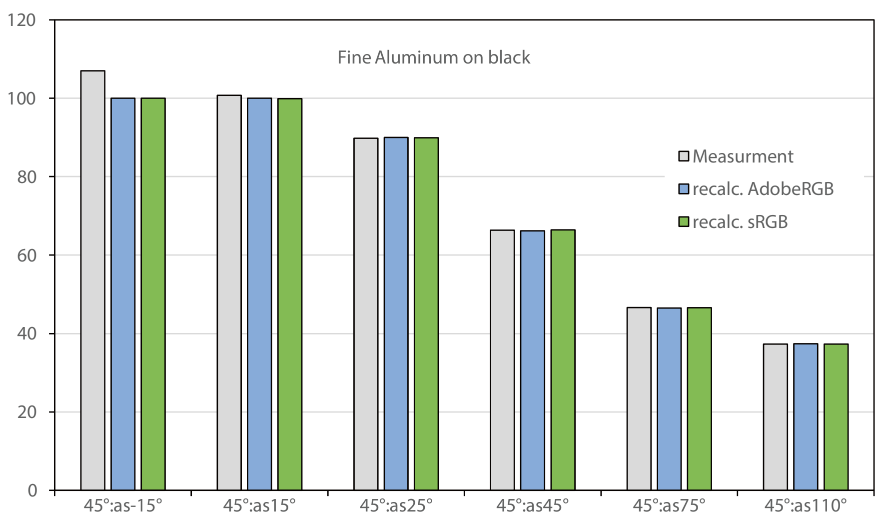
When a yellow pigment is mixed with a white one, the results are better when using the calculated Adobe RGB values than when using the sRGB values. Mathematical conversions appear to be problematic in both cases.

The limits of digital color spaces

In standard color measurement of a coating pigmented with solid, aluminum, and interference pigments, the reflections are measured relative to a white standard. These are expressed as percentages and converted into the color values X, Y, and Z. Based on these color values, the CIE values L* (luminance), a* (red-green values), and b* (yellow-blue values) are calculated. The X, Y, and Z values also serve as the basis for calculating the RGB values.
Two RGB models are most commonly used: sRGB was developed by Microsoft and Hewlett-Packard for monitors. The Adobe RGB color space was introduced by Adobe to match color printers to computer screens. Both color spaces are significantly smaller than the color space defined by the color components based on the X, Y, and Z values. The Adobe RGB color space is slightly larger than the sRGB color space.
To test the limits of both color spaces for pigmented coatings, colored, aluminum, and interference pigments were selected. These were measured colorimetrically, and the measured values were converted to sRGB and Adobe RGB. If RGB values exceeded 255 (the limit of RGB represen-



Typically, the mixing curve for an aluminum pigment with a blue color continues until it reaches a turning point. At this point, the curves for the calculated Adobe RGB and sRGB values show significant deviations.



Since the RGB values near the highlight are only slightly above the threshold of 255, the digital representation is quite good.

tation), they were reduced to 255. This procedure is also used in software programs and programming languages. Some programs do not allow values higher than 255 to be entered.

The modified values were then converted back to L*a*b* values and compared with the original ones. This allowed us to determine the deviations between the measured values and the RGB representations. The standard conversion formulas available on various websites were used for the conversions. To support the theoretical considerations with practical examples, various pigments were first examined individually and in series of mixtures.

Yellow absorbing pigment

A yellow paint from a mixing system was mixed with white in seven stages. While the brightness increases slightly from yellow to white, the chroma (C*) decreases dramatically. When calculating the sRGB values, the R values for yellow and the first five mixtures are above 255. In the corresponding calculations of the Adobe RGB values, all remained below 255.

In the next step, the RGB values were converted to L*a*b* values, with all values above 255 set to 255. The calculated a*b* values were plotted in comparison to the measured a*b* values of the mixing series from yellow to white.

With the exception of three a*b* value pairs for yellow and two white mixtures, the conversions of Adobe RGB values back to L*a*b* values yield values that are nearly identical to the measured ones. The strong deviations are not due to RGB values above 255, but rather to inconsistencies in the mathematical conversion formulas. This clearly shows that the formulas were not originally developed for representing automotive colors.

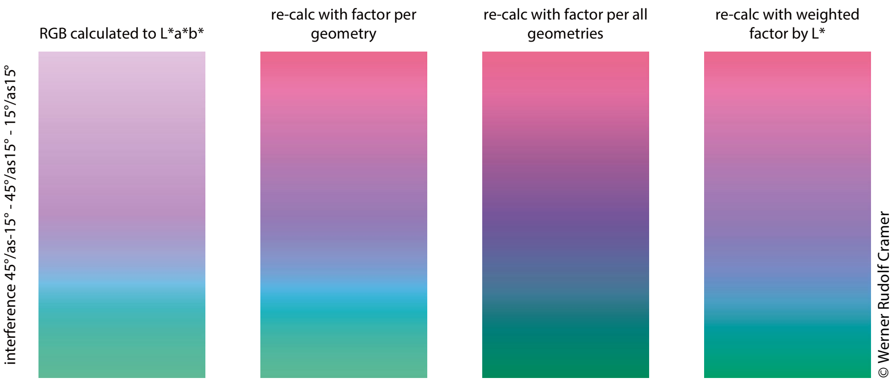
When converting the sRGB values, the deviations are more pronounced because several R values exceed 255 and were set to 255 for the calculation. All measurements were taken using the 45°:0° geometry. Based on the results of the yellow-white mixing series, the analysis was expanded to include combinations of effect and colored pigments in order to evaluate the behavior of more complex coating systems.

A blend of aluminum and blue

A medium-sized aluminum pigment was mixed with a blue absorptive pigment in several stages. The measurements were taken using the 45°:as15° geometry, i.e., at an angle of 15° from the specular angle.

The a*b* values of the mixtures clearly demonstrate the well-known behavior of blue color pigments when mixed with white or aluminum: When aluminum is mixed with blue, the chroma and lightness increase until a turning point is reached. At that point, the chroma decreases. However, the lightness continues to increase as the proportion of white rises further.

Both the Adobe RGB values and the sRGB values are, in some cases, well above 255. In both cases, the G values – and especially the B values – are greater than 255. The conversions to L*a*b* values show significant deviations from the measured values, with the deviations being strongly greater for sRGB.



The same pigment with different RGB representations: On the left are the reduced values, followed by the values adjusted in various ways.

The color representation of the aluminum mixtures with the blue pigments on a digital display differs significantly from the actual paint samples. In the next step, the focus shifted to pure effect pigments to determine how strongly the deviations would be without color-giving components.

Aluminum

In these tests, a fine-grained and a coarse-grained aluminum pigment were sprayed as base coats over black and white substrates and sealed with clear coat. Measurements were taken from 45°:as-15° to 45°:as110° (illumination: angle difference from gloss). Neither pigment exhibited a color reaction, which is why the L* brightness values were evaluated here.
For fine aluminum over black, all Adobe RGB and sRGB values above 255 are close to gloss. When converted to L*a*b* values, a* and b* are set to 0 and L* to 100. The measurements yielded L* values just above 100 for the near-glossy geometries 45°:as-15° and 45°:15°, which is why the deviations between the measured and calculated L* values were not strongly different.
The difference between the measured and calculated values is greater for the coarse aluminum. Both the calculated Adobe RGB and sRGB values are close to the gloss values at 45°:as-15° (over 500), at 45°:as-15° (over 400), and at 45°:as-25° (still over 255). Conversion to L*a*b* values yields a value of 100 for L* (luminance) in each case. The measured L* values for the three geometries are 181, 150, and 101. This coating, which contains an aluminum pigment, also cannot be displayed on a screen exactly as it is perceived visually.

The results of all measurement series paint a consistent figure: The stronger the effect and the further the values extend beyond the RGB limits, the more the digital reproduction deviates from the actual color perception.

Challenges and possible solutions

The problem with digitally representing automotive paint colors stems from the various color spaces. The sRGB and Adobe RGB color spaces are smaller than the XYZ color space, even though the RGB values are calculated from the XYZ values. For some pigmented paints, the calculated RGB values may fall outside the RGB color space. If the RGB values are reduced to 255, the resulting colors may differ from the measured and visually observed colors. When digitally displaying the color of a mixed paint, these deviations are unlikely to be very significant. However, if the digital representation is used to create new colors, these deviations play a major role because certain colors and effects cannot be reproduced exactly.
A solution is provided by a sprayed pattern that is evaluated visually. In particular, effects such as those that occur in coatings containing aluminum or interference pigments pose a major challenge for digital reproduction. This applies above all to representation across multiple measurement geometries. To ensure a plausible representation, various approaches were therefore tested, even if they do not accurately reproduce the effects. If a value in the RGB triplet exceeds 255, all three values can be adjusted using the calculated factor. However, there is a possibility that this triplet would then come too close to that of the next geometry. This would limit the color gradient of the effect.
Another option for effect pigments is to adjust all RGB values by the factor of the highest value. This shifts all colors, but they remain plausible overall. However, accurate representation through visual inspection can only be achieved using real, i.e., sprayed paint samples. Ultimately, it is always the human eye that makes the final decision and performs the verification. The digital representation of a color or an effect is based solely on numbers, which, on their own, have little meaning. Finally, the question arises as to whether alternative digital capture methods – such as cameras – could circumvent the limitations described.

Digital recording with a camera

Various considerations have been raised regarding the use of a camera to capture images digitally rather than performing color measurements. If the painted panels were digitally photographed with the colors shown, their RGB values would be reduced to 255. In this regard, it would definitely be necessary to investigate whether the colors displayed correspond to their visual perception. Effect pigments, in particular, are angle-dependent both during measurement and when viewed. This poses a special challenge for digital representation. //

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