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Use of Recycled-Based Light Guides and Their Impact on the CO_2 Footprint of Ambient Lighting Systems

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1. Abstract

Sustainability increasingly shapes societal and political discussions. At its core, sustainability means that within a given system, only as many resources are consumed as can be provided in the long term. [1]

In the context of climate change, sustainability implies that greenhouse gas (GHG) emissions must be reduced across all economic sectors to the extent that no GHG are emitted in the long term, thereby achieving climate-neutral processes. Simultaneously, the use of finite natural resources must be minimized. This is a declared goal of EU legislators, who are advancing these objectives through various regulations.

The automotive industry, which significantly contributes to GHG emissions and the use of natural resources in the transportation and industrial sectors, is particularly affected by these regulations. Specifically, reduction targets for GHG emissions and target values for the recycled content in new vehicles have been established.

This paper examines the feasibility of using recycled-based light guides according to optical criteria and whether the recycled content in the component can be significantly increased through these materials. Additionally, the impact of recycled-based light guide materials in ambient lighting systems on GHG emissions is investigated using a Life Cycle Assessment (LCA). This analysis includes emissions generated during production, operation, and recycling.

2. Introduction

With the Paris Climate Agreement [2], the majority of countries have committed to reducing GHG emissions to a natural level by 2050. Derived from this, the European Green Deal [3] sets targets for GHG emissions. As an interim goal, a 55 % reduction in GHG emissions by 2030 compared to 2005 has been established. [4]

Additionally, there are specific requirements for vehicles, that are binding for all vehicle manufacturers: The EU's End-of-Life Vehicles (ELV) Directive [5] aims to improve the circular economy of vehicles and limit the use of natural, finite resources. Accordingly, 25 % of all plastics in new vehicles should come from recycled materials in the future.

Since the assembly of ambient lighting systems is mostly made of plastic, they fall under the ELV Directive and affect the recycling rate. Typical ambient lighting systems consist of a power supply from the onboard network, digital control and LEDs. The emitted light is directed to the desired exit surface using light guides and diffusers made from plastics. Due to their electrical energy consumption, the light components also indirectly influence GHG emissions.

Since these indicators were not the focus in current designs, it is necessary to investigate the sustainability of ambient lighting systems concerning the indicators GHG emissions and recycled material usage through a Life Cycle Assessment (LCA). It is hypothesized that the use of recycled plastics improves the CO_2 footprint of the light components and thus helps to meet legal requirements. Particularly for optically effective components, the question arises whether light guides made from partially recycled plastics can be used to achieve the mentioned sustainability goals.

The optical properties such as luminous transmission and color shift must not be neglected, as they are crucial for the appearance of the light components. From these optical and sustainability requirements, a tension field illustrated in Fig. 1 emerges, into which the materials must be classified accordingly.

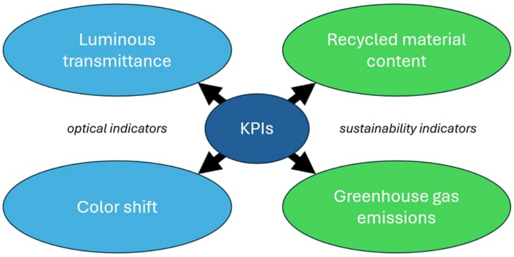

Figure 1: Key Performance Indicators (KPIs) for Light Guide Materials

3. Methode and Results

3.1 Investigated Materials

This work examines three Polymethylmethacrylat (PMMA) light guide material variants, which are examined regarding their mentioned optical properties and their impact on the mentioned sustainability indicators. PMMA materials are frequently used as light guides in the automotive sector due to their high luminous transmission and low color shift. In this study, three different PMMA variants from Röhm are examined:

- **PLEXIGLAS® 8N**: Currently used material as a reference
- **PLEXIGLAS® *pro*Terra 8N**: Mass-balanced variant of PLEXIGLAS® 8N from biological or chemically recycled sources with identical optical properties (according to the manufacturer)
- **PLEXIGLAS® *pro*Terra M5**: PMMA with 30% mechanically recycled content and slightly differing properties compared to PLEXIGLAS® 8N

3.2 Optical Indicators

The criteria of **luminous transmission** and **color shift** have been established for characterizing the optical properties of light guides. Both criteria are based on the light absorption of the material: Uniform absorption over the visible spectrum reduces the transmission rate and perceived brightness, while uneven absorption leads to color changes. The goal is to minimize the impact of the light guide material on these aspects to achieve a high optical efficiency of the lighting system.

3.3 Luminous Transmission

Generally, the luminous transmission results from the ratio of emitted light τ_2 to incident light τ_1 in the light guide material:

$$\tau_{luminous} = \frac{\tau_2}{\tau_1} \times 100 \qquad (1)$$

A higher luminous transmission improves the overall efficiency of a lighting component, as less electrical energy is required for the same brightness. The luminous transmission is determined according to DIN EN ISO 13468-1, which describes a method for determining the luminous transmission of transparent plastic samples up to 10 mm. For a sample thickness of 5 mm, the following values are obtained:

Table 1: Total luminous transmission for different material variants

Material Variant	**PLEXIGLAS® 8N**	**PLEXIGLAS® *pro*Terra M5**
total luminous transmittance τ_t	91,3%	90,4%

Slight optical disadvantages of the PLEXIGLAS® *pro*Terra M5 variant compared to the reference material PLEXIGLAS® 8N are noted, which, however, do not have a relevant impact on the optical appearance in most practical applications.

3.4 Color Shift

In typical applications, light is coupled into a lighting component from the side and continuously emitted along the light guide path, leading to a color shift along the light guide path. (Fig. 2) A visible color shift at the exit surface must be avoided.

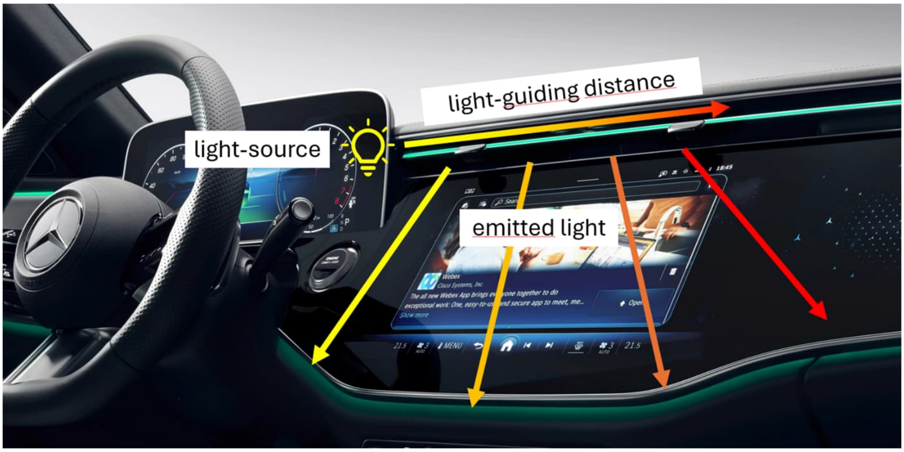

Figure 2: Illustration of light guide path

To best represent the mentioned application case with practical sample sizes, the color shift is examined using sample plates of 15 cm x 20 cm x 0.5 cm according to [7]. To determine this color shift using the sample, the color u’v‘(l,b) of the light emitted by the light guide is spatially resolved using a luminance camera (ILMD) and the CIELUV color space (Fig. 3).

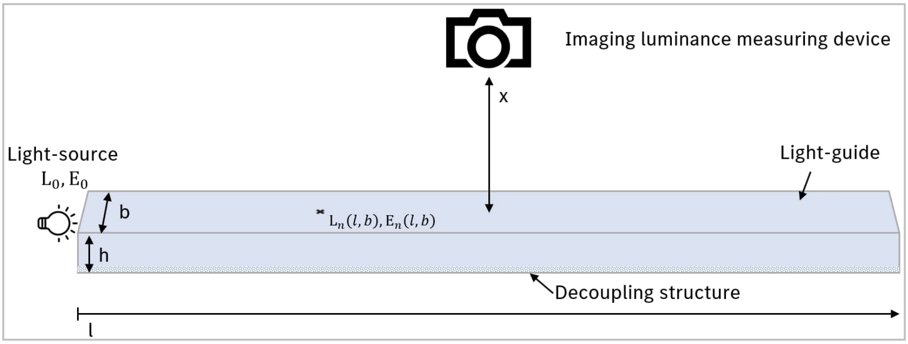

Figure 3: Measurement setup with ILMD

From this image, the color location along the light guide path *l* can be determined using the following formula:

$$u'v'(l) = \frac{1}{b}\int u'v'(l,b)\,db \tag{2}$$

By subtracting the color location at the light coupling point $u'v'(0)$ from the local color $u'v'(l)$, the local color shift $\Delta u'v'(l)$ can be determined:

$$\Delta u'v'(l) = u'v'(l) - u'v'(0) \tag{3}$$

The average expected color shift $\overline{\Delta\mathrm{u'v'}}$ is determined from the slope of the trend line of the obtained data and serves as the evaluation basis for the light guide material. The following graph shows the color shift $\overline{\Delta\mathrm{u'v'}}$ determined for the mentioned samples as a function of the light guide path l*l*. It is noted that the color shift of the partially recycled PMMA variant provides comparable results to the reference material PLEXIGLAS® 8N.

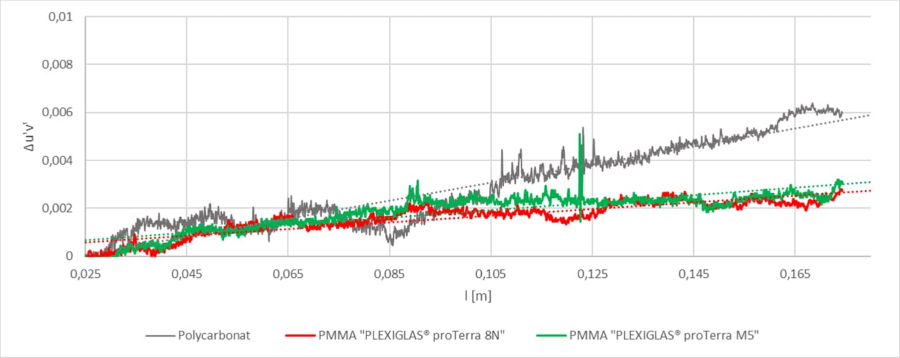

Figure 4: Color shift over light guide length for different materials

For the average color shift $\overline{\Delta u'v'}$ the following values are obtained:

Table 2: Average color shift for different material variants

Material Variant	**PLEXIGLAS® 8N**	**PLEXIGLAS® *pro*Terra M5**
Average color shift $\overline{\Delta u'v'}$ [1/m]	0,017	0,018

In experiments, no optical difference between PLEXIGLAS® 8N and PLEXIGLAS® *pro*Terra 8N was found, confirming the manufacturer's specifications and the assumption that in case of PMMA chemical recycling should yield the same quality as primary PMMA.

3.5 Recycled Content

As mentioned initially, the second sustainability indicator is the proportion of recycled materials. Based on the total component mass, the use of recycled-based light guides results in the following overall recycled material content depending on the material variants:

Table 3: Total recycled material content for different material variants

Material Variant	**PLEXIGLAS® 8N**	**PLEXIGLAS® *pro*Terra 8N**	**PLEXIGLAS® *pro*Terra M5**
Total recycled material content [%]	0%	4,1%	5,0%

3.6 Determination of the Environmental Impact Using a Life Cycle Assessment

The impact of partially recycled plastics on optical criteria should be weighed against the impact on the aforementioned sustainability indicators. For this purpose, a Life Cycle Assessment (LCA) is conducted according to DIN EN ISO 14040/14044. This systematic analysis encompasses all significant incoming and outgoing material and energy flows necessary for the production, operation, and recycling of a product.

To determine the impact of these flows on the environmental balance of a product, a Global Warming Potential (GWP) is calculated for each flow, normalized to a CO_2 equivalent. This allows the CO_2 footprint of material and energy flows to be compared in terms of their impact on climate change.

3.7 Test Object and Framework Conditions for LCA

For the LCA, a decorative light part was selected that uses common design principles and is thus representative of a wide range of ambient light components. It essentially consists of a Polycarbonate/Acrylonitrile butadiene styrene (PC/ABS) plastic carrier, a PC diffuser, a PMMA light guide, and two light modules (PC/ABS housing, PCB, LED and integrated circuits) (see figure 5).

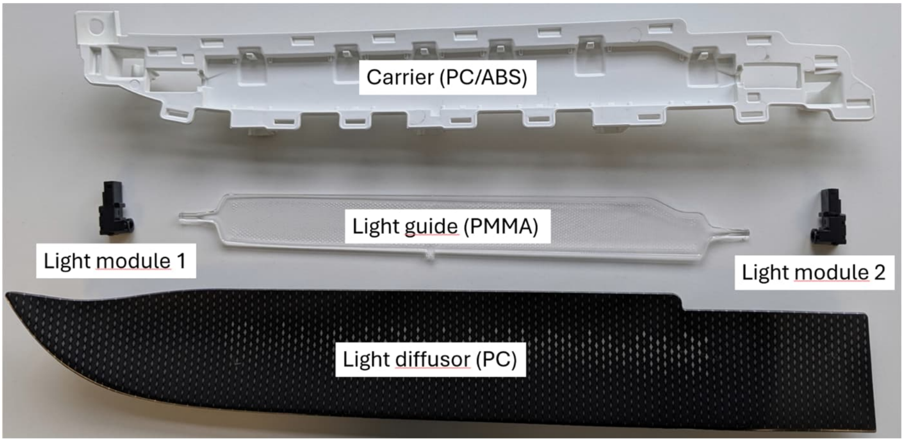

Figure 5: Disassembled light component

The LCA is conducted based on a cradle-to-grave approach, meaning the entire life cycle of the component from material extraction through the usage phase to recycling is considered. Thus, the operational phase of the component has a significant impact on the environmental balance. A vehicle lifespan of 240,000 km is assumed, with the energy demand required during this period included in the consideration. It is assumed that the component is used in an electric car and the electrical energy, along with corresponding charging losses, is provided from the projected European energy mix for 2030. These assumptions were made to estimate potentials for the next generation of vehicles based on the current state of technology. For the GWP of the materials and processes used, data from [8] in the Sphera database were used, or, if available, the latest manufacturer information and recent scientific publications were referenced.

3.9 Environmental Impact of the Materials Used

The table below, based on manufacturer information, shows that the alternative variants of the PMMA material examined have an approximately 25% better environmental impact. This suggests that they have the potential to significantly reduce the CO_2 footprint of the light guide.

Table 4: Relative Greenhouse Gas Emissions for different material variants

Material Variant	**PLEXIGLAS® 8N**	**PLEXIGLAS® *pro*Terra 8N**	**PLEXIGLAS® *pro*Terra M5**
GHG Emissions [kg CO_2 eq./kg]	3,45 kg CO_2 eq./kg	2,59 kg CO_2 eq./kg	2,56 kg CO_2 eq./kg
Relative GHG Emissions	100%	75%	74%

For a meaningful evaluation, however, the light guide must be considered in the overall context of a decorative light part. To do this, a Life Cycle Assessment (LCA) is first created for the reference material PLEXIGLAS® 8N under the above-mentioned conditions (see figure 6). Comparing the GWP of all sources it becomes clear that while the light guide plays a role in manufacturing compared to the other plastic components, it is relatively insignificant compared to other influencing factors. Especially the PCB manufacturing and the energy demand during operation dominate the environmental impact of an ambient light component.

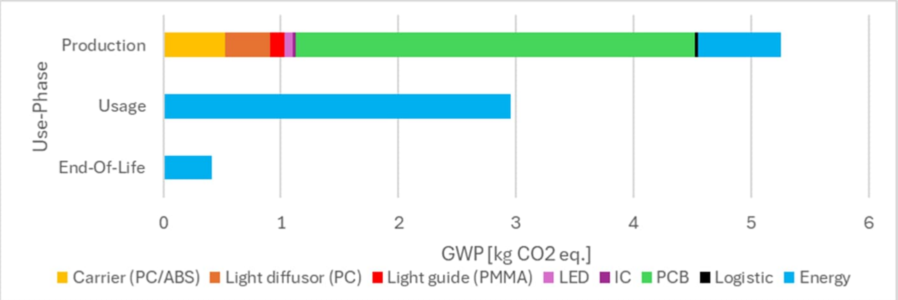

Figure 6: Reference LCA with PLEXIGLAS® 8N

Despite this observation, it should be investigated whether a positive impact on the environmental balance is measurable as a reduced transmission could have negative impact on the energy-consumption during the use-phase. For this purpose, the LCA for the other light guide materials is repeated. Since all other components remain unchanged in this comparison, only the impact of the light guide material in manufacturing and the energy demand during operation are considered, as this can be influenced by a changed luminous transmission of the light guide. Here too, it is shown that the relative difference between the three materials examined is negligible (see figure 7).

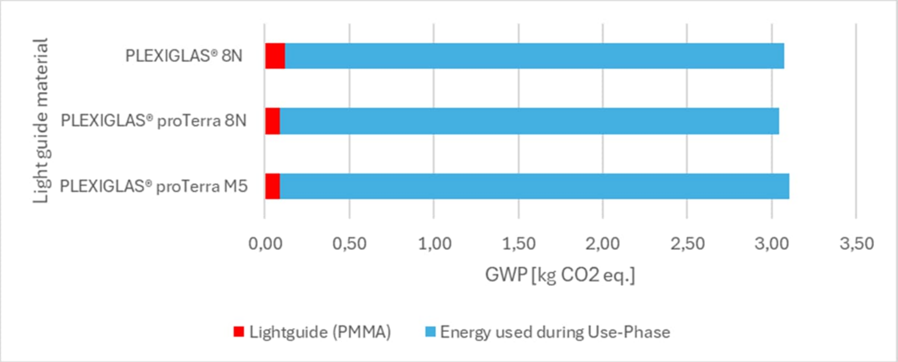

Figure 7: material influence on the environmental impact of the component

4. Conclusion

It can be generally demonstrated that the use of recycled-based light guide materials is possible and that they are optically on a similar level to virgin materials. However, depending on the variant (chemically recycled or mechanically recycled), only a very slight positive or negative effect on the overall environmental balance of ambient light components can be detected.

For optical components with different properties such as shorter light guide paths or less operating time, the effect of recycled-based materials is likely to be more significant. A possible application area is, for example, reading lights, whose manufacturing has a significantly greater impact on the overall environmental balance than their operation, as they are used very rarely.

However, the recycled content of the overall component can be influenced in such a way that a considerable part of the future 25% recycled quota can be achieved with the help of the light guide material.

5. Acknowledgments

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6. References

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