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Potential Analysis of Car Headlight Repair through Lens Replacement and its Implications for the CO_2e Footprint

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1. Abstract

The automotive industry set itself ambitious goals for net zero vehicles in around 15 years. First measures like requirements for secondary and low carbon materials are already in place but will leave big gaps towards the aimed near total reduction of emissions. The impact of service and aftermarket parts is usually neglected or underestimated in LCA studies although service parts are produced in high volumes. Highly complex parts such as automotive lights underline the need for consequent repair solutions. The study showcases the impact of ZKWs repairable solution for modern lights in combination with a medium size car fleet to quantify the positive impacts on the lifetime emissions of climate gases in a model-based approach. Improving repairability without compromising mechanical robustness is one puzzle piece to reach net zero industry goals.

Keywords: Circular Economy, Automotive, Headlight Repair, CO_2e Savings, Right to Repair, Modular Design, Sustainability

2. Introduction

The Necessity of a Circular Economy in the Automotive Sector

The global automotive industry is in a state of transformation, driven by technological innovations like electromobility and autonomous driving, as well as a growing awareness of ecological sustainability. While research and development heavily focus on reducing emissions during the driving phase (use phase), the environmental impacts across a vehicle's entire lifecycle – from raw material extraction, production, and use to recycling and disposal – are increasingly coming into focus. Here, the Circular Economy is a key concept. It aims to minimize waste and maximize the value of products and materials through reuse, repair, and recycling [1]. This represents a paradigm shift: moving away from a linear "take-make-dispose" approach towards a circular one that extends product lifecycles and keeps resources within the system.

A significant portion of a vehicle's environmental impact already arises in the production phase (Embodied Carbon). This is particularly true for the manufacturing of complex components and the use of materials such as plastics and electronics [2]. Studies show that these "upstream emissions" can account for a considerable share of a vehicle's total CO_2e footprint, especially in the production of batteries for electric vehicles, but also for other complex components. At the same time, the prevalent practice of completely replacing defective parts leads to unnecessarily high consumption of new materials and energy. This paper examines the potential for repair through the replacement of individual components – specifically the outer lens cover – using vehicle headlights as an example and quantifies the significant CO_2e savings associated with this approach. The underlying calculations are based on internationally recognized standards to ensure a robust evaluation. The goal is to highlight the relevance of modular design and improved spare part availability for a more sustainable automotive industry, and to strengthen the arguments for a "Right to Repair" in the automotive sector.

3. Problem Statement

The Headlight as a Resource sink and the Potential of Lens Replacement

Modern vehicle headlights are highly complex systems that represent far more than just a light source. They integrate advanced lighting technologies (e.g., LED, ADB, laser light), adaptive control systems, sensors, and intricate optics. This complexity and the use of various materials like metals, electronics, and especially plastics (such as polycarbonate for the lenses) make their production energy- and resource-intensive [3], [4].

Polycarbonate, a commonly used plastic, is characterized by high impact resistance and transparency, but its production and disposal are ecologically relevant.

The common practice for headlight defects is the complete replacement of the entire unit. This happens even when only the outer lens cover is damaged – for instance, by a minor accident, a stone chip, or vandalism, but also due to age-related wear. The reasons for this practice are multifaceted and technical, economic, and political in nature:

Constructive Design: A large proportion of headlights today are permanently glued or even welded. This ensures sealing and stability but makes a simple lens replacement extremely difficult or impossible without destroying the rest of the headlight. This "Design for Obsolescence" or "Design for Replace" practice is problematic from a circular economy perspective.

Manufacturer's Spare Parts Policy (OEMs): For many vehicle models, individual components like the lens cover are often not available as separate spare parts. This forces workshops and end-consumers to purchase the entire, often very expensive unit. This is often justified by margin strategies and the desire for control over the aftermarket.

Economic Efficiency from a Workshop Perspective: Complete replacement is often simpler and faster to perform. Given high labor costs in workshops, this is sometimes seen as the "more efficient" solution, even if the material costs are higher for the customer. Repairs are often more labor-intensive and require specialized knowledge.

Regulations and Safety Standards: The complexity and safety-relevant function of headlights mean that repairs are often only permitted with certified parts and according to precise specifications. This aims to ensure road safety but can also limit the scope for repair-friendly solutions. Compliance with homologation regulations is central here (§ 11 KDV 1967) [5].

This practice leads to significant resource loss and avoidable environmental pollution. Functional, often expensive internal components such as LED modules, control units, or electronic components are disposed of as electronic waste along with the defective lens. The production of a new headlight causes considerable emissions that could be avoided through repair.

Our approach therefore focuses on the technical and ecological feasibility of replacing only the outer lens cover, provided the internal function of the headlight remains unaffected. The main causes for such a replacement are:

Accident Damage (primarily lens affected): Minor collisions, parking bumps, or stone chips often lead to cracks, fractures, or deep scratches on the outer polycarbonate lens. Here, the main part of the headlight remains intact.

Age-related Damage (yellowing/clouding): Polycarbonate, the material of many headlight lenses, is exposed to UV radiation, heat, and environmental influences over the years. This leads to oxidation, yellowing, clouding, and micro-cracks on the surface [6]. Material fatigue not only impairs the aesthetics of the vehicle but also significantly reduces light output and can even lead to the invalidation of the operating license. A new lens could restore the full optical and functional performance of the headlight.

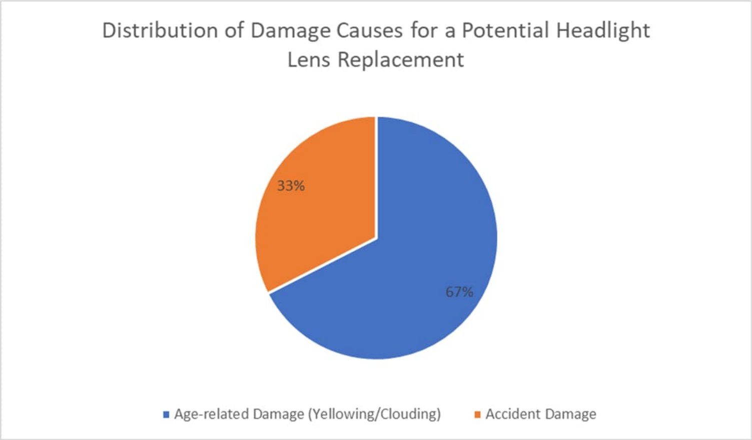

Diagram 1: Main Causes for the Potential Need of a Headlight Lens Replacement (Qualitative Distribution)

4. Methodology and Potential Calculation

For quantifying the repair potential, an absolute fleet of 300,000 vehicles is used as a reference. This fleet size is representative and allows for a tangible projection of the potential. For the calculation, an ideal scenario is assumed, prioritizing technical possibilities: It is presumed that all headlights in these vehicles are designed such that their outer lens cover is principally removable and replaceable. Furthermore, the hypothetical availability of spare lenses as separate parts and the economic advantage of lens replacement over a complete replacement are assumed for this model calculation. These idealized assumptions allow for the evaluation of the maximum technically achievable potential, irrespective of current real market constraints such as missing spare parts, complex bonding, or lack of acceptance.

Since specific, comprehensive lifecycle data for individual component damage like headlight lenses are not explicitly recorded in publicly accessible statistics (e.g., from Destatis [7], GDV [8], or BASt [9]), the following estimates are based on realistic assumptions regarding the probability of such damage over the entire service life of a vehicle (typically 10-15 years or longer). These assumptions consider both accident-related and age-related causes that would make a lens replacement worthwhile.

Assumption on the proportion of vehicles with potentially repairable headlight damage over their lifetime:

It is estimated that between 15% and 25% of the vehicles within this fleet could, over their entire service life, have at least one headlight where a lens replacement would be technically feasible and advantageous. This range accounts for variations in usage intensity, environmental influences, and individual accident risk over the vehicle's lifespan.

Calculation of the total potential for the fleet:

Lower Estimate (15% of the fleet affected): 300,000 vehicles * 0.15 = 45,000 headlights

Medium Estimate (20% of the fleet affected): 300,000 vehicles * 0.20 = 60,000 headlights

Upper Estimate (25% of the fleet affected): 300,000 vehicles * 0.25 = 75,000 headlights

This analysis demonstrates that over the lifespan of a fleet of 300,000 vehicles designed for lens replacement, potentially between 45,000 and 75,000 car headlights could be repaired by replacing only the lens cover, instead of being completely replaced. This represents a significant, currently largely untapped potential that would extend the lifespan of components and conserve resources.

5. CO2 Savings and Environmental Impact

Promoting the repairability of vehicle components is a direct and effective lever for reducing the environmental impacts that arise during the production phase. The manufacturing of a complex car headlight, like many car parts, is energy-intensive and requires the use of various raw materials (metals, plastics, rare earths in electronics), whose extraction, processing, and assembly cause CO_2e emissions. By repairing the lens instead of a complete replacement, the energy- and material-intensive new production of a complete headlight is avoided, which directly leads to significant emission savings.

The basis for calculating greenhouse gas savings in this study is the internationally recognized standards ISO 14040/44 (Environmental management – Life cycle assessment) [10], [11] and ISO 14067 (Greenhouse gases – Carbon footprint of products) [12]. For this, an internal calculation tool was implemented, whose methodology and results were verified and validated by a third party based on various concrete projects.

In this specific study, this validated approach was applied to an ongoing project, using the actual materials and weights of the headlight as input for the calculation. Emission factors are based, where possible, on primary data from suppliers (e.g., for specific plastic granules or electronic components), supplemented by data from the renowned Ecoinvent 3.11 database for generic materials and processes [13].

The quantified CO_2e savings for the determined repair potentials are as follows:

For the medium estimate scenario, where 20% of the headlights in the lifecycle of the considered fleet of 300,000 vehicles are repaired (corresponding to 60,000 headlights), a CO_2e saving of approximately 5,300 tons of CO_2e results.

For the upper estimate scenario, where 25% of the headlights in the lifecycle of the fleet are repaired (corresponding to 75,000 headlights), the CO_2e saving amounts to approximately 6,700 tons of CO_2e.

To put these values into perspective: The manufacturing of a single passenger car, especially a modern electric vehicle, can cause between 10 and 20 tons of CO2 depending on the model, battery size, and production process [14], [15]. The saving of 5,300 tons of CO_2e through headlight repair is thus comparable to avoiding the production of several hundred new vehicles, emphasizing the direct and significant positive influence of such a repair approach on the global climate balance and resource conservation. The saving primarily results from avoiding the primary production of materials, energy consumption for manufacturing processes, logistics (transport of new parts), and the subsequent disposal of intact internal components.

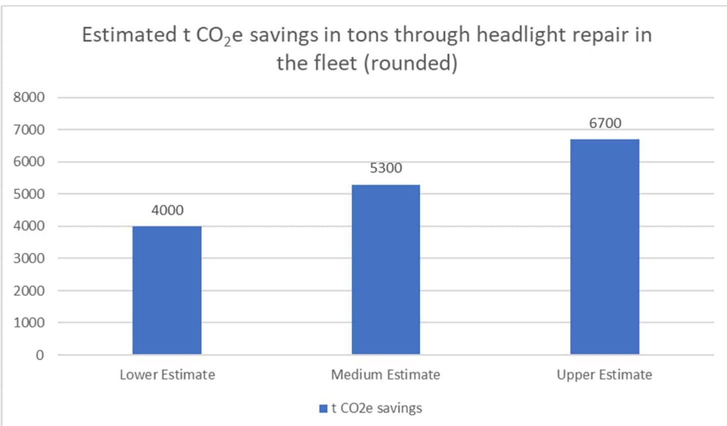

Diagram 2: t CO_2e Savings through Headlight Repair

6. Discussion and Implications: The Path to Greater Repairability and a True Circular Economy

The results of this potential analysis impressively underscore the enormous long-term benefits for resource conservation and cost savings that the systematic repair of headlights through lens replacement could offer. It is a concrete example of the practical application of circular economy principles in the automotive sector, which aims to keep products, components, and materials in use and at their highest value for as long as possible [1]. This contrasts with the currently dominant linear economy ("take-make-dispose") and addresses the "Fast-Moving Consumer Goods" (FMCG) mentality that has unfortunately become established for many components in the automotive industry.

The challenges in realizing this potential are multifaceted and require a concerted effort from all stakeholders in the value chain, from manufacturers to legislators, workshops, and consumers:

Constructive Design and Modularity ("Design for Repair"):

The lack of modular design is the biggest technical hurdle. Many modern headlights are permanently glued or even welded, which makes lens replacement extremely complex or impossible without destroying the entire component.

The automotive industry must increasingly integrate the concepts of "Design for Repair" and "Design for Disassembly" into its development processes. This means designing components to be easily accessible, detachable, and re-attachable without compromising safety or performance [16]. Such approaches could facilitate the repair not only of headlights but also of other complex assemblies like infotainment systems or battery modules.

Spare Parts Availability and Legislation ("Right to Repair"):

Even if headlights were principally repairable, individual lens covers are often not available as original spare parts. This restrictive OEM strategy is a significant obstacle.

The "Right to Repair" movement is gaining momentum in Europe and the USA. It demands that manufacturers ensure access to spare parts, repair manuals, diagnostic tools, and software updates to enable independent workshops and consumers to perform repairs [17]. Extending these principles to specific vehicle components like headlights through binding regulations could significantly improve the situation and promote fair competition in the spare parts market.

Economic Efficiency, Training, and Acceptance:

For independent workshops and authorized dealerships, lens replacement must be not only technically feasible but also economically attractive. This requires fair prices for replacement lenses and efficient work processes that minimize the time required. Investments in training and specialized tools for repair are necessary.

At the same time, awareness among end-consumers and motor vehicle insurers regarding the benefits of repair (cost savings, environmental protection) must be raised to foster acceptance. Insurers could prefer repairs over complete replacement through adapted tariffs or incentives. Transparent communication about environmental benefits and cost savings could be crucial here.

Implementing such a repair strategy would not only lead to the quantified CO_2 savings but also extend the lifespan of vehicles, significantly reduce repair costs for consumers, and potentially increase the value of a vehicle in the used car market, as it would be easier and more cost-effective to maintain. This also fosters the local economy by strengthening repair service providers. It is an essential step towards more sustainable, resource-efficient, and customer-friendly mobility that goes beyond more energy consumption and considers the entire product lifecycle.

7. Conclusion

The present potential analysis of a fleet of 300,000 vehicles, equipped with headlights that are repairable, reveals a considerable, currently largely untapped potential: between 45,000 and 75,000 headlights could be repaired over the lifespan of these vehicles by simply replacing the outer lens cover. This repair volume, in the case of the medium estimate, leads to an estimated CO_2 saving of approximately 5,300 tons of CO_2, while at 25% of the potential, approximately 6,700 tons of CO_2 could already be saved.

The robust calculation of greenhouse gas savings based on ISO 14040/44 [10], [11] and 14067 [12] standards, supported by an internally developed and third-party validated tool, underpins the credibility of these results. This is a strong argument for establishing the repairability of vehicle components as a central pillar of sustainability strategies in the automotive industry. It shows that through targeted changes in product development (modular design), spare parts policy (provision of individual components), and political regulation (Right to Repair), a significant contribution to environmental protection and the conservation of valuable resources can be made. A proactive shift towards greater repairability is not only ecologically imperative but also economically sensible and aligns with the growing demands of a circular and sustainable society. It is time for the automotive industry to recognize and implement the full potential of repair to minimize emissions throughout the entire vehicle lifecycle and to shape future-proof mobility.

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