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# The Impact of the Minimum Ductility Requirement in Automotive Castings on the Carbon Dioxide Footprint throughout the Useful Life of an Electric Car

**Murat Tiryakioğlu [1,*], Anders E. W. Jarfors [2] and Martin Leitner [3]**

1 School of Engineering and Technology, Jacksonville University, Jacksonville, FL 32211, USA
2 School of Engineering, Jönköping University, 55111 Jönköping, Sweden
3 Institute of Structural Durability and Railway Technology, Graz University of Technology, 8010 Graz, Austria
* Correspondence: mtiryak@ju.edu

**Abstract:** There is a trend in the automotive producers to require that foundries use more secondary aluminum alloy ingots to reduce the $CO_2$ footprint of car production. The merits of this trend have been investigated in this study. Results have shown that requiring the use of more secondary ingots while simultaneously reducing the elongation requirement of aluminum alloy die castings is counterproductive, i.e., increases the $CO_2$ footprint of the car over its useful life by not taking advantage of the weight reduction possible. It is recommended that (i) foundries improve their melt handling capabilities to reduce and minimize the entrainment damage made to the melt in the melting and casting process chain, and (ii) automobile producers reduce the weight of die castings by increasing requirements on elongation, to secure a reduced $CO_2$-footprint in the designs, materials usage and life-cycle of cars.

**Keywords:** liquid metal damage; sustainability; strain energy density; crashworthiness; fatigue



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## 1. Introduction

High pressure die casting (HPDC) is the most common process for producing large, thin-walled castings. Although HPDC process is capable of producing large, complex and thin-walled castings at high production rates, the process is known to entrain air as well as surface oxides, which greatly impair mechanical properties and fatigue performance. Nevertheless, there has been a growing trend to use more die castings in automotive applications, especially after Tesla introduced the "megacasting" for Model Y [1], weighing 130 kg, to replace hundreds of parts used in the assembly of the rear structure of the car [2]. Other car companies are now trying to replicate the success of Tesla in its structural die castings, which has accelerated innovation in casting equipment and casting processes.

Another driver in the automotive industry, especially in Europe, is the reduction of the environmental impact of the cars produced. Here, weight reduction is one critical element, especially during the transition for fossil-based electricity generation to a fully decarbonized system [3]. Specifically, automotive industry has zoomed in on its aluminum usage [4]. By requiring that secondary ingots be used along with primary ingots during the production of aluminum castings, automotive companies are trying to increase the sustainability of their products. This effort is aligned with the findings of Cecchel et al. [5] who showed that the largest energy consumption in the production of an aluminum high-pressure die casting for an automotive application was, by far, the use of primary aluminum. The wider use of secondary ingots in automotive castings, however, lowered the expectations for ductility from the final castings. It has been shown [6] secondary ingots have much higher number density of defects than primary ingots because of entrainment damage [7] in liquid state. Hence a specification of 1% elongation in as-cast condition has become the norm. Although the carbon footprint of die castings has been studied before, to the authors' knowledge, a study on the impact of low ductility expectations form die castings has not been conducted before. This study is motivated to fill this gap.

## 2. Background

Tensile failure in metals can be considered as the outcome of a competition between the processes of plastic deformation (shear flow) and fracture (tensile separation) [8]. If the stress required to initiate permanent deformation by shearing of atomic planes is less than the stress necessary to permanently separate atoms by tensile distortion of their atomic bonds, flow occurs in preference to fracture. However, stress due to various sources of stress concentrators, may reach the level necessary to initiate fracture. Plastic deformation is a more preferable "failure" event, because plastic flow preceding fracture markedly increases the work accompanying the fracture. The energy absorbed during a tensile test can be written as:

$$\Psi = \int_0^{\varepsilon_f} \sigma d\varepsilon \tag{1}$$

where $\Psi$ is the strain energy density (MJ/m$^3$), $\sigma$ is true stress (MPa), $\varepsilon$ is true strain and $\varepsilon_f$ is true fracture strain. One of the authors and his coworkers have analyzed stress-strain curves of high quality Al-7Si-Mg [9], hot isostatically pressed (HIPed) Al-Cu-Mg [10] and aerospace aluminum alloy castings [11], and determined that strain energy density can be written as a function of elongation, $e_F$ (%) as:

$$\Psi = \Psi_0 e_F \tag{2}$$

The constant, $\Psi_0$ was found to be 3.85 MJ/m$^3$ for high quality Al-7Si-Mg alloy and HIPed Al-Cu-Mg castings, and between 2.79 and 3.42 MJ/m$^3$ for aerospace aluminum alloy castings. Hence, elongation is an excellent estimate of the energy absorbed during tensile fracture of aluminum alloys. Moreover, elongation of aluminum castings is mainly determined by the strength of the alloy (intrinsic effect) and the density of defects in them (extrinsic effect) [12–14]. Subsequently, one of the authors and his coworkers collected hundreds of data points from the aerospace and premium castings literature for Al-7Si-Mg, A206 and A201 [14–16] and plotted elongation versus yield strength, which is minimally affected by structural defects. Analysis of these data from different components and production lines showed that the highest elongation points formed a linear trend, as presented in Figure 1, which can be written as:

$$e_{F(max)} = \beta_0 - \beta_1 \sigma_Y \tag{3}$$

where $\beta_0$ and $\beta_1$ are alloy-dependent coefficients. For Al-Si-Mg cast alloys, $\beta_0$ and $\beta_1$ are 36.0 and 0.064 MPa$^{-1}$, respectively. Equation (3) can be used to estimate the ductility potential of aluminum and magnesium alloy castings [12,13].

The ductility potential was proposed [13,16] as a metric to determine structural quality. Therefore, the quality index, $Q_T$, can then be found by:

$$Q_T = \frac{e_F}{e_{F(max)}} = \frac{e_F}{\beta_0 - \beta_1 \sigma_Y} \tag{4}$$

The quality index, $Q_T$, is a measure of how much damage the metal has received in the liquid state. The damage comes from the entrainment of surface oxide films as well as air when liquid surface is disturbed. The entrainment mechanism results in the creation of double oxide films, i.e., bifilms [7], with dry-side-to-dry-side contact. As a result, no bonding can occur between these ceramic interfaces; they act as cracks in the liquid. In contrast, the outer faces of the bifilm are in perfect atomic contact with the matrix and serve as heterogeneous nucleation sites for intermetallics and the Si phase. The simultaneous properties of zero and total bonding within the bifilm are unique features of this defect [17]. The oxide-to-oxide interfaces ensure that such cracks remain stubbornly resistant to bonding, despite significant amounts of pressure during the casting process and even hot isostatic pressing [18,19].

Today, a common practice to reduce the $CO_2$-footprint is to mix secondary aluminum with primary aluminum alloy ingots in the melt or to switch to secondary alloy solutions. The current study is aimed to demonstrate that producing better quality material with reduced levels of damage to the melt, that has taken place prior (preexisting damage in ingots [6]), during handling and/or casting, offers an additional route to reducing the $CO_2$ footprint. This matter is not primarily a question of primary or secondary materials, but rather a foundry melt handling and quality assurance capability as illustrated by the large spread in material performance found between the foundries, Figure 1.

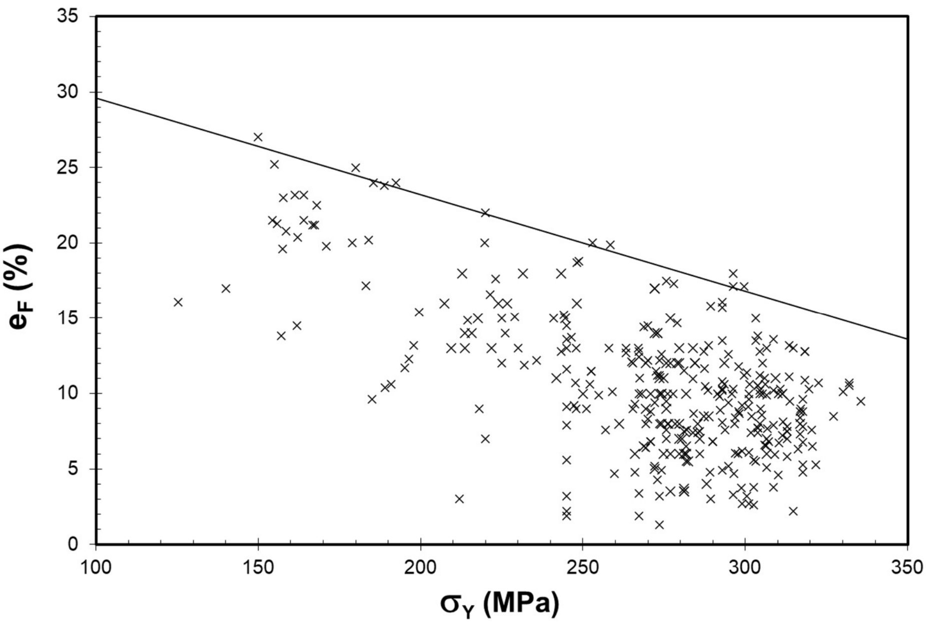


**Figure 1.** Elongation plotted versus yield strength for cast Al-7%Si-Mg alloy specimens excised from production castings (redrawn from data reported previously [13]).

## 3. Ductility and Crashworthiness

During a crash, the kinetic energy of the vehicle is absorbed by the vehicle's structure as well as its passengers. For safety reasons, it is important to maximize the energy absorbed by the vehicle (strain energy) while minimizing that absorbed by the passengers. For that reason, kinetic energy should be converted into strain energy within 40 ms as the crash is usually over within 100 ms [20].

There are several metrics that can be used as a measure of crashworthiness, one of which is specific energy absorption, $e_S$:

$$e_S = \frac{\int Fdl}{m} \tag{5}$$

where the denominator represents the strain energy absorbed by the part (J) and m is mass of the part (kg). Based on tensile test results for aluminum alloy castings, Equation (5) can be written as:

$$e_S = \frac{\Psi}{\rho} = \frac{\Psi_0 e_F}{\rho} \tag{6}$$

where ρ is density (kg/m$^3$). One can argue that the deformation conditions between a tensile test and crash would be different. Although this is true, a strong correlation between the two can be easily expected. Hence, a structure with a high density of entrainment defects (bifilms) can be expected to absorb a low level of energy in both tensile testing and in a crash.

Taking $\Psi_0$ and density to be 3.85 MJ/m$^3$ and 2700 kg/m$^3$, respectively, specific energy absorption can be plotted as a function of minimum elongation, i.e., the ductility requirement set by the automotive manufacturers, which is presented in Figure 2. The specific energy absorption for 6063-T6 extrusions has been found [21] to be approximately 15 kJ/kg. For aluminum alloy die castings to approach this level of $e_S$, a minimum elongation of 10% should be required by the automotive manufacturers. With the current elongation requirement of 1%, $e_S$ is only 1.4 kJ/kg for aluminum alloy die castings in automotive applications.

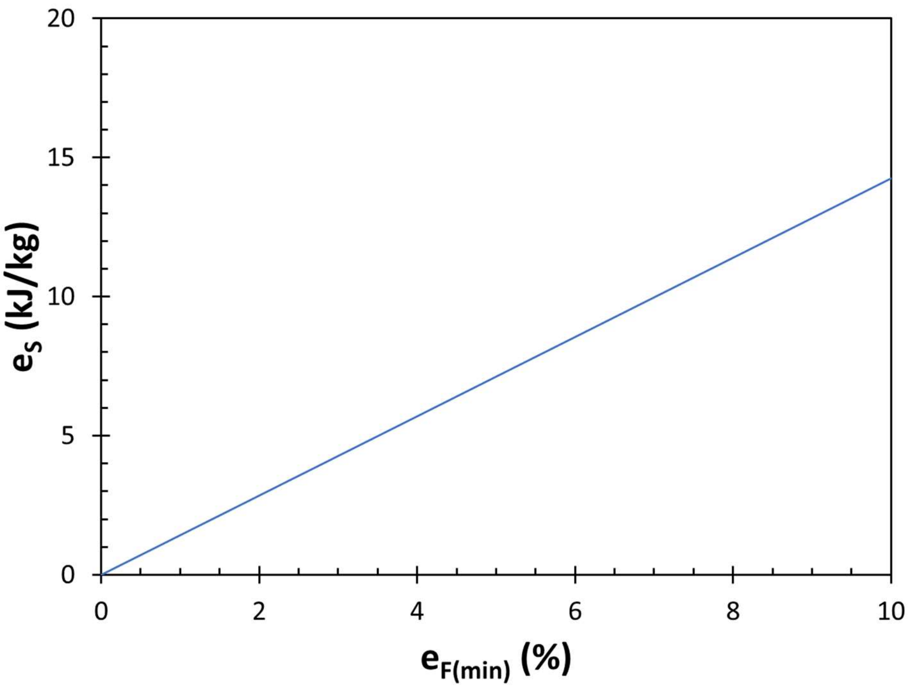


**Figure 2.** Specific energy absorption as a function of elongation requirement.

Based on Equations (5) and (6), it can be shown that weight of the part is directly correlated with the ductility of the casting for the part to absorb the same energy during the crash;

$$\int \mathrm{Fdl} = \mathrm{m}\,\frac{\Psi_0 e_F}{\rho} \quad (7)$$

Therefore, as the ductility of the casting increases, it would take less weight to reach the same level of energy absorption.

## 4. Ductility and Fatigue Performance

Similar to crash testing, it has been shown that fatigue life can be correlated to the total strain energy [22–25] such that cycles to failure can be estimated from the total strain energy absorption potential of the component. Hence, a component with fewer entrainment defects can be expected to have high ductility and a long fatigue life [26,27]. This correlation between elongation and fatigue life has been demonstrated [28] recently. Subsequently, Őzdeș and Tiryakioğlu [29,30] have developed a model to estimate fatigue life as a function of elongation. The model is followed in this study.

The change in fatigue life, $N_f$, with stress amplitude, $\sigma_a$, is known to follow the Basquin law [31]:

$$\sigma_a = \sigma_f' N_f^{\,b} \quad (8)$$

where $\sigma_f'$ is the strength coefficient (MPa) and b is the Basquin exponent. The exponent has been shown by Kun et al. [32] to be a measure of the degradation taking place at the micro-level. Based on this finding, Őzdeș and Tiryakioğlu [29,30] investigated the relationship between both parameters of the Basquin equation and $Q_T$, based on seventy two S-N curves of cast aluminum alloys reported in the literature. After combining with Equation (4), the model that they developed is as follows:

$$b = -0.136\ \exp(-1.236\frac{e_F}{\beta_0 - \beta_1\sigma_Y}) \quad (9)$$

$$\frac{\sigma\prime_f}{S_{T(max)}} = 0.405\frac{e_F}{\beta_0 - \beta_1\sigma_Y} + 0.280 \quad (10)$$

where

$$S_{T(max)} = 185.7 + 0.558\sigma_Y \quad (11)$$

based on the results reported previously [13]. This model can be used to estimate the fatigue life at a stress ratio of R = −1. For different mean stress conditions, the Walker equation can be used with the Walker exponent as a function of the quality index, Equation (4) [33].

This model has been applied to the scenario where yield strength requirement is 100 MPa and the minimum elongation is 1.0%. The estimated S-N curve for this elongation requirement is provided in Figure 3. Note that at a yield strength of 100 MPa, the ductility potential of Al-Si-Mg alloys approaches 30%. Hence a minimum elongation requirement of 1% is well below what the metal is capable of providing if there are no entrainment defects. The shift in S-N curves with increasing minimum elongation requirement is also shown in Figure 3. Note that fatigue strength at $10^6$ cycles significantly increases if the elongation is enhanced from $e_F$ = 1% to 10%, as demonstrated previously [30].

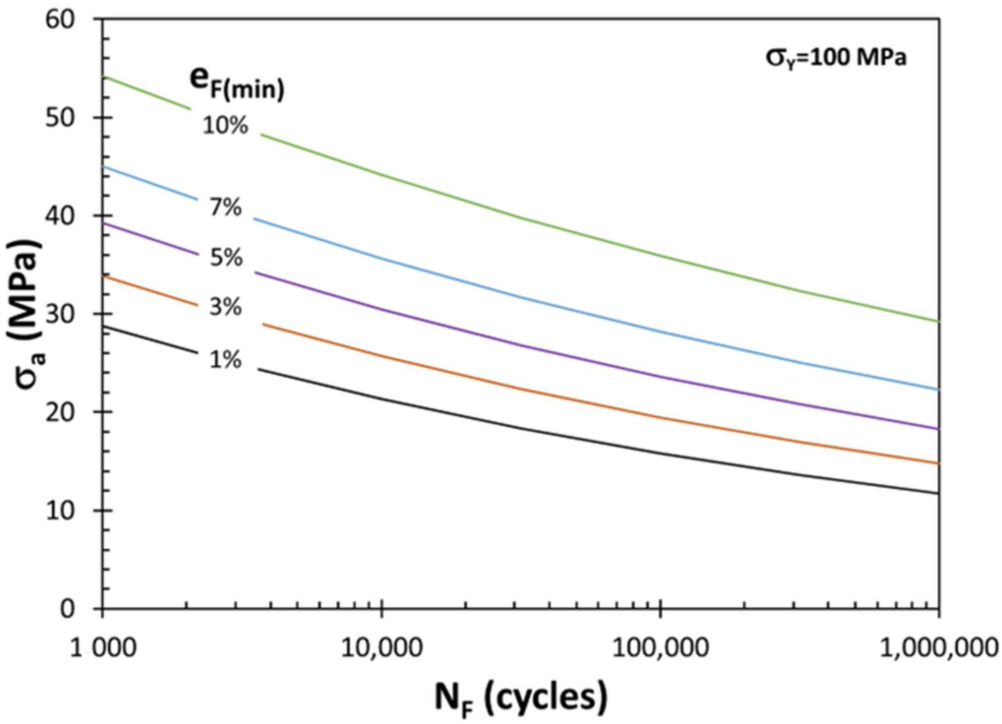


**Figure 3.** The S-N curves estimated by following the method developed previously [29] for a yield strength of 100 MPa and different levels of elongation. Fatigue strength is determined from these curves at $N_F$ = $10^6$ cycles.

It can be assumed that the design strength of aluminum castings, $\sigma_D$, is a fraction of the estimated fatigue strength $\sigma_f$ (at 1 million cycles), such that,

$$\sigma_D = a\ \sigma_f \quad (12)$$

where a is an arbitrary number lower than 1.0. To estimate the effect of the minimum elongation requirement on the weight of the casting, design strength can be normalized by the value for $e_{F(min)}$ = 1.0% and can be plotted as a function of the minimum elongation requirement, which is presented in Figure 4. Note that design strength can be doubled if the minimum elongation requirement is raised from 1.0% to 7.5%. This provides the potential to reduce the weight of the casting up to 50%.

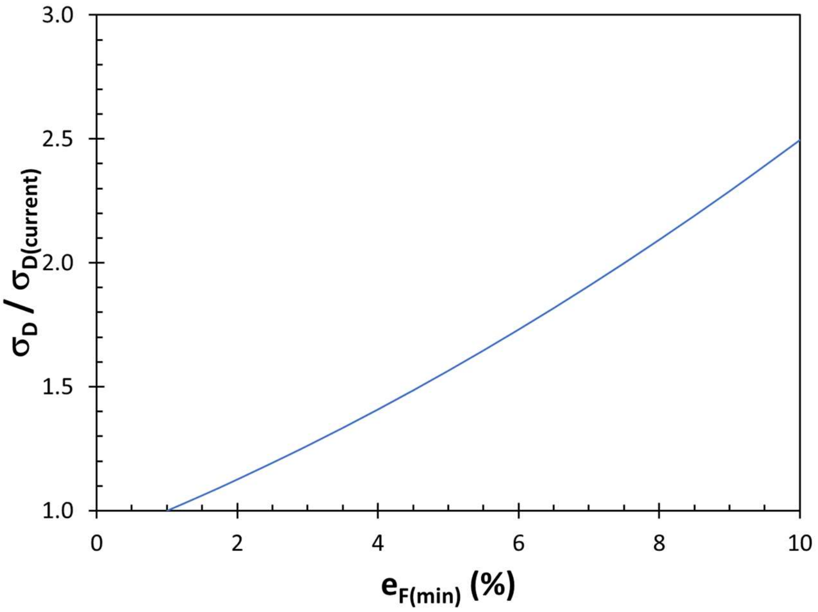


**Figure 4.** The change in normalized design strength with increasing minimum elongation requirement.

We can now analyze the relationship between the minimum elongation requirement and the casting weight to meet the same crashworthiness and fatigue performance requirements of the part. The reduction in weight (ΔW), normalized with its weight at $e_{F(min)}$ = 1.0%, is presented in Figure 5. Note that fatigue performance is the limiting factor between the two criteria.

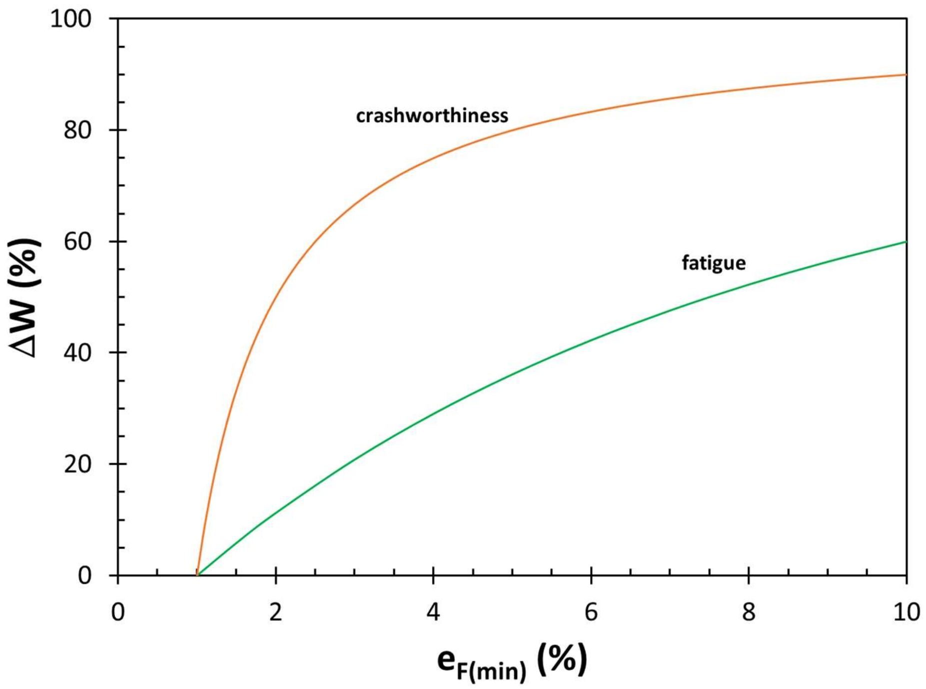


**Figure 5.** Weight reduction potential (%) as a function of increase in minimum elongation requirement for crashworthiness and fatigue performance. Fatigue is the limiting factor in this case.

## 5. The Environmental Impact of Elongation Requirements

We can now look into the environmental impact of the minimum elongation requirement, specifically the amount of $CO_2$ emission that can be reduced by increasing this requirement and therefore expecting foundries to produce castings with higher structural integrity.

For this purpose, we will make several assumptions:

The weight of the electric automobile is 2000 kg. This weight is well within the range of electric cars.

The weight of the die casting is 200 kg. Although this number is slightly higher than what we can expect now (~150 kg), the trend in aluminum casting use in automobiles [34] shows that this assumption will be justified in a few years.

The minimum yield strength and elongation requirements are assumed to be 100 MPa and 1%, respectively. These assumptions are based on the interviews made by the authors with the users and producers of automotive die-castings. The 1% elongation requirement is a typical number for many non-critical components, and therefore, may be considered low for structural components. However, the methodology presented in this study can be adjusted easily to a higher elongation requirement for structural components. It should be noted that the maximum elongation recorded in Figure 1 is 27% for a yield strength of 150 MPa. Therefore, there still remains much more potential for improvement beyond what is demonstrated in this study.

The electric consumption of this car is 0.2 kWh/km, which is average consumption rate of electric cars [35].

The $CO_2$ emission to produce electricity is 375 g $CO_2$/kWh. This number is near the midpoint among countries in Europe, and lies between that of Germany (349 g $CO_2$/kWh [36]) and of United States (388 g $CO_2$/kWh [37]). It is also assumed that the number remains constant over time.

The useful life of the electric car is 500,000 km. In cars with internal combustion engines, powertrains limit the useful life. In electric cars, it is the battery that limits the car's useful life. Recent research [38] has shown that 1.6 million kilometers is possible, with the latest findings updated to 6.4 million kilometers [39]. Although the useful life of an electric car is generally assumed to be 250,000 km, we consider this number to be too low in light of (i) the recent findings on battery life outlined above, (ii) the fact that some companies already offer factory warranties exceeding 150,000 km, and (iii) the finding [40] that none of the batteries produced by one automotive manufacturer in the last 12 years have been reported to have reached the end of their lives, delaying the plans for their recycling. Therefore, we think that 500,000 is a good, yet conservative estimate.

Weight is directly related to the design strength of the casting, such that the product of weight and design strength is constant.

The overall $CO_2$ emission for operating the car is directly related to its weight.

We will not analyze the $CO_2$ footprint of aluminum casting production for simplicity and assume that it will remain constant regardless of the minimum elongation requirement.

All foundries prepare their melts from 50% primary and 50% secondary aluminum alloy ingots commonly in the form of in-house returns.

Based on these assumptions, we can calculate the following for the current state of 1.0% minimum elongation requirement:

A useful life of 500,000 km means that this electric car is expected to spend 100 GWh over its life span.

This results in additional $CO_2$ emissions of 37.5 metric tons into the atmosphere due to the operation of the car.

The Aluminum Association lists the carbon footprint of primary and secondary aluminum as 8450 g $CO_2$/kg and 530 g $CO_2$/kg [41]. Foundries are usually required to have a 50-50 mixture of primary and secondary ingots in their production. Therefore, a 200 kg casting adds 898 kg of $CO_2$ into the atmosphere. The $CO_2$ savings accomplished by using secondary ingot is 792 kg of $CO_2$.

We can now analyze how increasing the minimum elongation requirement can affect the overall $CO_2$ emission due to both material and operation of the car. The results are presented in Figure 6. As can be expected, reduction in emissions will be mostly due to the operation of the car. Note that the reduction in $CO_2$ emission due to use of secondary ingot is lower than the one that would be accomplished by increasing the minimum elongation requirement to 3% (967 kg $CO_2$/car). Hence, requiring a lower elongation from castings so that secondary ingot can be used instead of primary ingot at best is ineffective in reducing $CO_2$ emissions per car, and at worst results in more $CO_2$ emitted into the atmosphere per car. Moreover, a minimum elongation requirement of 10% will reduce the $CO_2$ contribution of the car by more than 2.5 metric tons.

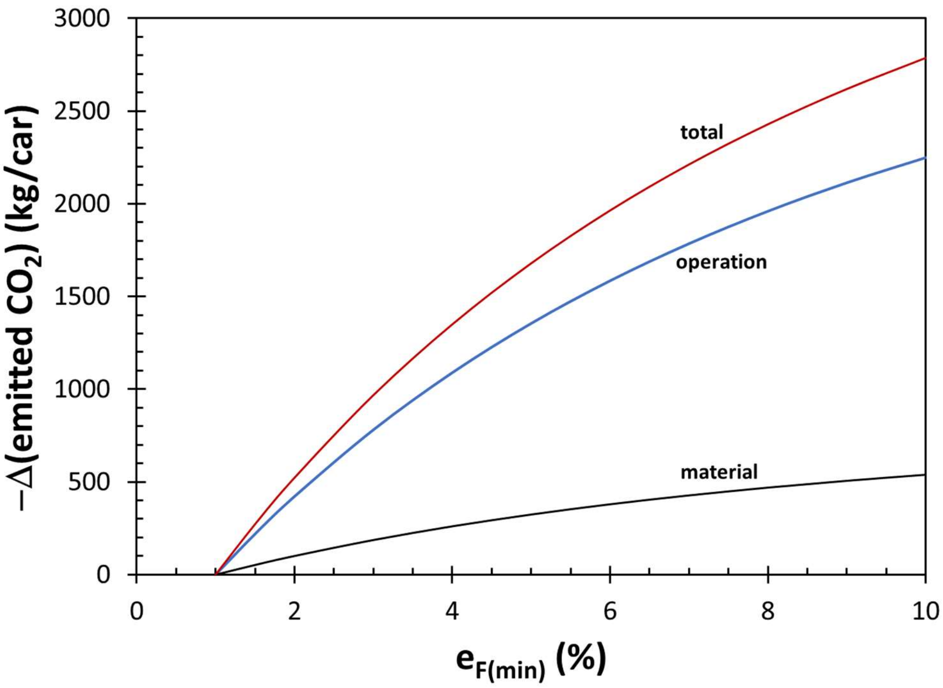


**Figure 6.** The change in the contribution of the car to $CO_2$ in the atmosphere as a function of the elongation requirement.

These results clearly demonstrate the importance of minimizing entrainment defects not only during the production but throughout the supply chain for aluminum castings. The technology to remove the oxide skins and not allow them into the metals exists currently. Moreover, high quality ingots are becoming more available. Careful production techniques that eliminate melt transfers will add greatly to the improvement of the structural quality. Finally, air and surface entrainment during casting production can and should be minimized though process development and engineering.

## 6. Conclusions

Today, a common practice to reduce the $CO_2$-footprint is to mix secondary aluminum with primary aluminum alloy ingots in the melt or to switch to secondary alloy solutions. The current study demonstrated that producing better quality material with reduced levels of damage to the melt during handling and casting offers an additional route to reducing the $CO_2$ footprint.

It was concluded [3] that weight reduction was possibly more important than electrification of the driveline in the transition from fossil-fuel based electricity to sources with no $CO_2$ emissions. This is confirmed by the currently performed analysis. The current study clearly illustrates the means to achieve this weight reduction with relatively simples means including.

Increase of the foundries melt handling capabilities to reduce and minimize the entrainment damage made to the melt in the melting and casting process chain.

Ensure that weight reduction using increased requirements on elongation to secure a reduced $CO_2$-footprint in the designs, materials usage and life cycle of cars.

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