Life Cycle Based CO₂ Emission Credits
Options for Improving the Efficiency and Effectiveness of Current Tailpipe Emissions Regulation in the Automotive Industry

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Summary

The current focus on the use phase in automotive carbon dioxide (CO₂) legislation bares a risk of unintended consequences as often reductions in the use phase come along with increasing CO₂ emissions in other life cycle (LC) phases. This study presents voluntary policy options in form of LC-based CO₂ emission credits. They were developed by desk research considering existing applications of LCA in practice (e.g., environmental reports) and feedback obtained in a structured stakeholder dialogue. A variety of credit options were identified, including rather simple ones based on life cycle thinking (LCT) and more advanced options which rely on quantitative LCA: LCT options that reward innovations leading to CO₂ reductions, for example, in the production phase. LCA-based options reward CO₂ reductions along the LC (credits for an International Organization for Standardization [ISO] 14044 conforming externally reviewed LCA showing a continuous improvement) or reductions of other environmental impacts. It was shown that the credit options can be implemented throughout a simplified and robust methodology, for example, with defined rules for conducting the LCA based on international standards and established industry practice, and for calculating the credits (e.g., a credit of 1 gram [g] of CO₂/km [kilometer] for savings of 10 g of CO₂/km). Voluntary credit options as a complementary modality to the current automotive tailpipe-based CO₂ regulations would help to improve its efficiency and effectiveness and support and reward efforts on achieving real net CO₂ emission reductions. The credit options were developed with a first focus on CO₂ and automotive industry, but can generally be transferred to other environmental impacts and sectors as well.

Introduction and Background

This section explains why a life cycle (LC) perspective is needed in automotive carbon dioxide (CO₂) legislation, provides examples why implementing an LC perspective is feasible and presents a framework of potential LC-based policy options, including a description of the potential role of credit systems. This introduction provides the necessary background for accomplishing the goal of this paper, that is, the development...
and presentation of credit-based policy options for an LC-based automotive CO₂ legislation.

The environmental profile and legislation of cars obviously affect a more comprehensive set of environmental impacts than climate change only. While methodologically, most of the policy options presented here can be used for a full set of environmental impacts as covered by life cycle assessment (LCA), just one of the credit options presented below addresses other impacts explicitly. The justification for the narrower scope on greenhouse gases (GHGs) emissions is twofold: first, this impact is the current focus and main business driver in automotive legislation. Second, relating the explanation of the policy options to one impact simplifies the demonstration of the intended mechanisms.

Why Is a Life Cycle Perspective Needed in Automotive Carbon Dioxide Legislation?

Climate change is presently one of the most important and widely discussed topics in science, the public, industry, and policy. Two recent and probably most prominent frameworks highlighting the necessity for decreasing CO₂ emissions are the Sustainable Development Goals (UN 2015b)—particularly goal 13: climate action—published in 2015 and the Paris Agreement (UN 2015a) ratified in November 2016. The transport sector plays a major role in tackling climate change as it is currently responsible for approximately 23% of energy-related CO₂ emissions and is expected to increase at a faster rate than emissions from the other energy end-use sectors if no substantial mitigation policies would be implemented (Sims et al. 2014). As one consequence, the automotive industry is confronted with increasingly stricter limit values for CO₂ emissions in different key markets (European Union [EU], United States, China, and Japan). However, current CO₂ legislation focuses on the use phase only, that is, on tailpipe CO₂ emissions. This bares a risk of unintended consequences as often reductions in the use-phase come along with increasing CO₂ emissions in other LC phases, such as production or end of life (EoL). These trade-offs are explained in the following example using a common metric to express automotive CO₂ emissions, that is, grams [g] of CO₂ emitted per kilometer (km) driven. A schematic illustration of this example can be found in section S1 in the supporting information available on the Journal’s website. Throughout this paper, we differentiate between tailpipe emissions expressed as CO₂/km and LC-based CO₂ emissions per km, that is, LC CO₂/km. The latter equals a product carbon footprint (Finkbeiner et al. 2006). While early use-phase optimization measures like engine efficiency improvements or downsizing lead to net CO₂ emissions close to the gross emission reduction (e.g., –1 g/km), this often holds no longer true for advanced CO₂ emissions reduction measures like some low-density materials and designs or electrification.

In the best case, still an overall reduction of CO₂/GHG along the whole LC can be achieved by such technologies (e.g., –0.5 g/km) (e.g. Nealer et al. 2015; Hawkins et al. 2012, Aguirre et al. 2012; Kim et al. 2011), but in the worst case the net LC GHG emissions may even increase (+x.x g/km) despite reduced use-phase emissions (e.g., Daimler AG 2014; Kendall and Price 2012; PE International 2013). It should be highlighted here that measures to reduce CO₂ emissions in the use phase are relevant and needed, and that lower fuel consumption values within a specific vehicle class compared to the competitors may also be very important from a competitive perspective. However, due to the potential carbon leakage effects, outlined above, that is, burden shifts to other regions or LC phases, without achieving an overall reduction of CO₂ emissions, a pure focus on the use phase is not sustainable anymore. Therefore, CO₂ measures and policies considering the whole LC, that is, including embedded CO₂ emissions, are needed to avoid the unintended consequences of current legislation (e.g., WorldAutoSteel 2013; Lehmann et al. 2015; EPSC 2016).²

An LC-based CO₂ legislation also offers higher flexibility for the automotive industry, that is, the OEMs (original equipment manufacturers), to meet CO₂ reduction targets as those can be achieved, for example, in the production phase.³ This will also help to increase the eco-efficiency of both the policy measures and the investments of the OEMs by helping to identify those technologies and solutions that have the highest CO₂ reduction return per US$ or euro (£) invested.

As a starting point, tailpipe-related CO₂ emission reduction legislation was necessary, efficient, and successful. In other words, early reduction measures to meet the legal requirements of the legislation were economically feasible and achieved tangible CO₂ reductions. However, the stricter CO₂ emission reduction legislation comes along with significant economic burdens for OEMs. In other words, for the future, OEMs and policy makers are confronted with the dilemma that the net efficiency of advanced CO₂ reduction measures is getting smaller and smaller while the associated investment and production costs for these measures are getting (exponentially) higher—and in worst case these efforts will not even lead to environmental benefits. An LC-based automotive CO₂ legislation could offer a way out and would be beneficial for all stakeholders: Policy makers can avoid unintended consequences of their legislation and actually achieve a better overall CO₂ reduction in the transport sector while buffering increased economic burdens for OEMs, that is, their industry.

Why Is It Feasible to Implement a Life Cycle Perspective in Automotive Carbon Dioxide Legislation?

Life cycle thinking (LCT), LC-based single-issue metrics like carbon footprints and/or LCA are already known and acknowledged by many policy makers (Inaba et al. 2003; Reimann et al. 2010; Sala et al. 2016) and are already directly or indirectly considered in some legislations. An example for an existing legislation in Europe directly based on single-issue LCA is the Renewable Energy Directive, which includes the calculation of LC GHG emissions of biofuels (EU 2009b). Similarly, an LCA of GHG emissions is required in the United States under the current Renewable Fuel Standard (US EPA 2010). An example for a legislation which is based on LCT and indirectly on
multicriteria LCA is the so-called Ecodesign Directive (EU 2009a). Conducting an LCA is not required from companies when applying the Directive, but LCA studies are mandatory during the development of the so-called implementation measures, that is, for defining eco-design requirements for energy-related products. Moreover, the relevance of an LC perspective for both policy and market is reflected by the recent developments on the European level, that is, the European Commission’s (EC) Product Environmental Footprint (PEF) method (EU 2003; Finkbeiner 2014; Galatola and Pant 2014) and its ongoing pilot phase. Besides this, LCA has been acknowledged and widely applied in practice for many years, and several companies, for example, OEMs (e.g., Warsen and Krinke 2012; Chanaron 2007; Nissan 2015; Toyota Motor Corporation 2016; Daimler 2015; Morel et al. 2011; Finkbeiner et al. 2006; BMW 2017), and materials associations are actively using and developing LCA approaches (e.g., WorldAutoSteel 2011; European Copper Institute 2017; PlasticsEurope 2011; EAA 2013).

Therefore, an implementation of an LC perspective in automotive CO₂ emission legislation seems feasible as there are proven LCA methods and LCA practitioners and developers raised objectives and concerns with regard to using LCA in a regulatory frame, for example, because of missing accuracy and preciseness of data. However, this is also a challenge in the current CO₂ legislation. Moreover, the authors believe that uncertainties resulting from LCA could be handled by robust settings of the credit options.

Framework of Policy Options for Life Cycle-Based Carbon Dioxide Emission Regulation and Potential Role of Credit Systems

Against the background outlined above and because the authors of this paper think that it is in substance “right” to base environmental legislation on LCA, they developed a framework of policy options for LC-based CO₂ emission regulation in the automotive industry. This framework includes both mandatory and voluntary policy options, options with the direct requirement of full LCAs and indirect solutions not requiring the provision of LCA data, options which are performance based, that is, may require a product redesign, and process-based options, defining requirements on company level without leading to a product redesign as well as options addressing different legislative targets like restricting market access or providing market incentives. A detailed analysis of the policy options also revealed that technical requirements of the policy options (e.g., methodology, data, and LCA models) can be clearly fulfilled, as many solutions are already available in practice. The challenge is rather to find a consensus or rule. A detailed description of the policy options developed is provided in Lehmann and colleagues (2015).

Since their publication, these policy options were communicated to stakeholders in the automotive key markets the EU, the United States, Japan, and China, including some ten OEMs, some 15 policy-making bodies, scientists (presentations at LCM2015, Ecolalance 2014 and 2016, Indian LCM 2015, and SETAC Europe 2015), and several material associations. According to the feedback obtained, the voluntary policy options were identified as the most realistic and promising options from a short-/mid-term perspective—particularly when combined with a credit system. Taking into account this feedback, the focus of this work was then based on further developing the voluntary policy options combined with credit options. Such a policy option seems preferable, because it does support the existing regulations and does not require the development of a separate set of legislation. In addition, credits—even though not yet LC based—are already an existing policy element in both the EU and the United States: As part of EU policy, credits are provided on a voluntary basis as incentives for “eco-innovations,” which are a specific category of technologies providing a confirmed contribution in terms of reducing CO₂ emissions (UPI 2011). With the eco-innovation system, OEMs can benefit from credits up to a maximum of 7 g of CO₂/km by adopting approved and certified eco-innovations on each vehicle. An example for such an eco-innovation is a light-emitting diode low-beam module (“E-light”), which ensures significant energy savings allowing OEMs to obtain a credit of 1 g of CO₂/km for every vehicle that fits this module in its headlamps (Magneti Marelli 2014) and use this credit to meet the OEM’s specific CO₂ emissions targets. In the United States, credit systems exist, for example, as part of the “zero-emission-vehicles” (ZEVs) regulation, which requires manufacturers to produce specific numbers/percentages (e.g., 14% for 2015–2017) of car technologies like battery electric, fuel cell, and plug-in-hybrid vehicles (CARB 2016). Moreover, credits for flexible fueled vehicles are provided under the Corporate Average Fuel Economy standards (US EPA 2012).

The existing credits systems outlined above aim at reducing automotive tailpipe emissions. Adopting an LC perspective regarding CO₂ emissions can contribute to an overall reduction of CO₂ emissions. Thus, OEMs which implement and use LCA for measuring and reducing LC CO₂ emissions could be rewarded with credits to complement their reductions of the car’s use-phase CO₂ emissions (and increase their flexibility in meeting fleet targets).

The goal of this paper is to introduce and describe LC-based CO₂ emission credits as voluntary policy options for improving the efficiency and effectiveness of current tailpipe emissions regulation in the automotive industry. The Methods section gives an overview about how the credit options were developed. The section that follows presents and discusses the developed options and potential implementation requirements. Finally, a conclusion and outlook are provided.

Methods

For identifying a broad range of potential credit options, the following approach was chosen: It was differentiated between rather simple options based on LC thinking (called LCT...
options) and more advanced options based on LCA (called LCA options). The idea of the LCT options is to consider and reward innovations and measures which lead to CO\textsubscript{2} reductions in other LC phases than the use phase, that is, the production phase, or additional measures for CO\textsubscript{2} reductions in the use phase.\textsuperscript{7} These options do not require a full quantitative LCA to be performed, but expand the view beyond current tailpipe CO\textsubscript{2} regulations. The more advanced LCA options are based on quantitative global warming potential (GWP) reductions along the LC or consider additional environmental impacts beyond climate change. The LCT and LCA credit options were developed by desk research and structured stakeholder input taking into account existing applications of LCA in practice (e.g., environmental reports) as well as existing credit systems. After having identified potential options, all of them were described in detail. For each option, theoretical examples for measures, which could be rewarded with a credit as well as numerical examples for calculating the credits, were provided. Wherever it was possible, the theoretical examples were complemented by examples from practice. Moreover, potential benefits of the individual credit options were specified for the key stakeholder policy makers and OEMs. Last, but not least, methodological and technical requirements for implementing the credit options were elaborated, including examples for technical solutions. In this context also, some potential (relative) disadvantages of the credit options are addressed. The requirements and proposals for calculating the credits were further specified in a so-called illustrative example, which gives concrete solutions for these requirements. Again, this was done based on desk research, literature, as well as feedback obtained from stakeholder discussion. Meetings with stakeholders (policy makers, OEMs, academia, and material associations) in the EU, the United States, Japan, and China took place at least once, mostly twice, sometimes even more. During these meetings, the credit options were presented and discussed. The feedback obtained was used for fine-tuning the credit options.

**Results and Discussion**

Figure 1 gives an overview about the developed credit options: In total, nine options were identified—three LCT options, which reward innovative measures in the production and the use phase of a car and six LCA options, which reward the consideration and improvement of LC CO\textsubscript{2} emissions only or CO\textsubscript{2} emissions and other environmental impacts. It is shown that a broad variety of credit options exists, ranging from relatively simple to more advanced options. Moreover, the credit options can be considered as technology neutral, meaning that they do not favor a specific material or a specific technology.\textsuperscript{5}

All LCT and LCA credit options are described in detail in the two sections that follow. The methodological and technical requirements for implementing the credit options are then presented. A list with all credit options, including several numerical examples, can be found in section S2 on “List of credit options including numerical examples” in the Supporting Information on the Web.

**Life Cycle Thinking-Based Credit Options**

The LCT credit options can be applied without conducting an LCA study and reward innovative measures resulting from an expanded view beyond current tailpipe CO\textsubscript{2} regulations. A description of the three LCT credit options (options 1 to 3) is provided below, including numerical examples how a credit could be obtained and calculated\textsuperscript{6} (see also section S2 on “List of credit options including numerical examples” in the Supporting Information on the Web) and an outline of potential benefits for policy makers and OEMs. Potential (relative) disadvantages of the credit options are similar for all options and are therefore presented together in the section Requirements for Implementing the Credit Options.

**Option 1: Credits for Improvements in the Production Phase**

In LCA studies of conventional cars with internal combustion engines, the production phase contributes only 15% to 25% to the total GWP of a car (Finkbeiner et al. 2006). Even though lightweight materials and alternative power trains can reduce CO\textsubscript{2} emissions during the use phase, they often increase the total and relative contribution of the production phase. Innovative concepts for reducing CO\textsubscript{2} emissions in the production phase (e.g., innovative production technologies) can be rewarded by allowing for a fixed or percentage credit in the use-phase CO\textsubscript{2} emissions. For example: An “old” manufacturing technology may need 2,000 megajoules of energy (assumed to equal 400 kilograms [kg] of CO\textsubscript{2} per car based on a given emission factor), while an innovative manufacturing technology may need only 1,000 MJ of energy (200 kg CO\textsubscript{2} per car). Assuming a defined reduction target for CO\textsubscript{2} emissions in the production phase of, for example, 150 kg of CO\textsubscript{2} per car, an OEM could obtain a credit of, for example, 1 g of CO\textsubscript{2}/km by replacing the old manufacturing technology by the innovative one, which would lead to a saving of 200 kg of CO\textsubscript{2} per car (i.e., 1.3 g of CO\textsubscript{2}/km when assuming a lifetime driving distance of 150,000 km). Table 1 shows some further examples for this credit options and potential benefits for policy makers and OEMs.

**Option 2: Credits for Measures Aiming at Influencing User Behavior**

As mentioned earlier, the use phase typically dominates the GHG emissions along the LC of a conventional car. While the reported amount of CO\textsubscript{2} emitted during the use phase has been determined based on a standardized driving cycle, the actual emissions are usually higher and greatly depend on the driving behavior of the user. Therefore, a fixed or percentage credit in the use-phase CO\textsubscript{2} emissions could be allowed if the OEMs provide technical features or user guidance that can lead to reduced fuel consumption and thus reduced CO\textsubscript{2} emissions in practice. For example: If a new car includes a technical feature (e.g., a maximum/minimum temperature setting), which leads to a reduction of CO\textsubscript{2} emissions, for example, by 2 g of CO\textsubscript{2}/km, the OEM could be rewarded, for example, with...
Figure 1  Overview of options for crediting a car’s use-phase CO\textsubscript{2} emissions, differentiated between (1) options based on implementation of life cycle thinking (LCT) leading to innovations in the production and/or use phase and (2) options requiring an LCA study to be conducted considering CO\textsubscript{2} emissions only or CO\textsubscript{2} emissions only or CO\textsubscript{2} emissions and other additional environmental impacts. CO\textsubscript{2} = carbon dioxide; GHG = greenhouse gas; ISO = International Organization for Standardization; LC = life cycle; LCA = life cycle assessment.

Table 1  Credits for improvements in the production phase

| Exemplary measures to obtain a credit | Benefits for policy | Benefits for original equipment manufacturers |
|--------------------------------------|---------------------|-----------------------------------------------|
| • Technologies and concepts for reducing CO\textsubscript{2} emissions in the production of materials | • Easy to implement | • Provides incentives to improve production processes |
| • Technologies reducing material losses during manufacturing | • Promotes development of CO\textsubscript{2} efficient material production and manufacturing processes | • Provides incentives for using materials from innovative CO\textsubcript{2} reducing production processes |
| • Reducing “stand by” electricity consumption of robots during manufacturing | | |

Note: CO\textsubscript{2} = carbon dioxide.

a fixed credit of, for example, 1 g of CO\textsubscript{2}/km. Table 2 shows some examples for this credit option and potential benefits for policy makers and OEMs.

Option 3: Credits for Use of Low-Carbon Fuels

Another option to allow for a reduction of CO\textsubscript{2} emissions during the use phase comprises the consideration of low-carbon fuels. The credit can be given in two ways.

Option 3a: Credit for Use of Low-Carbon Fuels

Here, a credit is allowed for cars which can be run with a share of biofuels which is beyond current legal shares. For example, car A can be run with a legal share of biofuels (e.g., 10% biodiesel) and emits 100 g of CO\textsubscript{2}/km, while car B can be run with a higher share of biofuels (e.g., 20% biodiesel) and also emits 100 g of CO\textsubscript{2}/km. The OEM which produces car B could obtain a fixed credit, for example, 1 g of CO\textsubscript{2}/km for using more biofuels and therefore causing less LC CO\textsubscript{2} emissions.

Option 3b: Credit for Biogenic Carbon Emission

Here, in this more advanced version, the tailpipe emissions could be distinguished into fossil and biogenic carbon emissions resulting from biofuel components. Subsequently, biogenic CO\textsubscript{2} emissions could be directly subtracted from the total CO\textsubscript{2} emissions or total emissions could be reduced by a fixed amount/percentage, if biogenic CO\textsubscript{2} emissions reach a certain threshold. For example, a car is run with (a share of) biofuels and emits, for example, 100 g of CO\textsubscript{2}/km (90% fossil, 10% biogenic). The OEM could obtain a credit based on difference to reference, for example, the savings of fossil CO\textsubscript{2} emissions (10 g/km) could be rewarded with 10 g of CO\textsubscript{2}/km, or with a fixed amount (e.g., 1 g of CO\textsubscript{2}/km), if biogenic emission
Table 2  Credits for measures aiming at influencing user’s behavior

| Exemplary measures to obtain a credit | Benefits | for policy                                                                 | for original equipment manufacturers |
|---------------------------------------|----------|-----------------------------------------------------------------------------|---------------------------------------|
| • Providing a guideline on driving behavior which reduces fuel consumption (e.g., optimum tire pressure) as well as on recommended maintenance and service intervals (e.g., cleaning of fuel filter, maintenance of ignition plugs) | • Easy to implement | • Low efforts |
| • Technical features that limit real driving emissions, that is, maximum heating temperature setting for an electric vehicle | • Education and motivation for consumers | |
| • Offering fuel-efficient driving training | | |
| • An upshifting assistance which guides the driver when the next gear should be taken | | |

Table 3  Credits for use of low-carbon fuels

| Exemplary measures to obtain a credit | Benefits | for policy | for original equipment manufacturers |
|---------------------------------------|----------|------------|---------------------------------------|
| • Cars, which are compatible to use low-carbon fuels | • Promotes use of low-carbon fuels | • Low efforts |
| • Accounting of biogenic carbon according to renewable share in fuel mix | • Quick to implement, since Directive 2009/28/EC already exists | |

reaches a threshold, for example, 10% of the total CO₂ emissions. It should be noted that the production of biofuels can cause substantial GHG emissions as well. This burden should obviously be considered in the calculation of credits. Table 3 shows some examples for this credit option and potential benefits for policy makers and OEMs.

**Life Cycle Assessment–Based Credit Options**

The LCA options reward the consideration and reduction of LC GHG emissions or additional environmental impacts beyond climate change. They rely on a quantitative single-issue or multicriteria LCA. Depending on the intended level of implementation, this can be either a comprehensive LCA according to ISO 14040/44 or a simplified LCA based on the bill of materials and emission factors. A description of the six LCA credit options (options 4 to 9) is provided below, including numerical examples how a credit could be obtained and calculated⁹ (see also section S2 in the supporting information on the Web) and an outline of potential benefits for policy makers and OEMs. Potential (relative) disadvantages of the credit options are similar for all options and are therefore presented together in the section Requirements for Implementing the Credit Options.

**Option 4: Credits for Low Greenhouse Gas Emissions in the Production Phase**

This credit option intends to avoid problem shifting from the use to the production phase: A credit can be obtained, if the GWP of the production phase remains below a certain threshold or baseline. This threshold could be, for example, the average GWP of the current market mix of vehicles consisting of respective shares of e.g. the steel, aluminum and carbon fiber reinforced polymer. For example, if the GWP of the production phase of a car made by OEM A is, for example, 20 g of CO₂/km, while the GWP of an average production is, for example, 30 g of CO₂/km, OEM A could be rewarded, for example with a fixed obtainment of 1 g of CO₂/km. Table 4 shows an example for this credit option and potential benefits for policy makers and OEMs.

**Option 5: Credits for ISO Conforming Life Cycle Assessment Studies**

This credit option is based on the provision of an ISO 14040/44 conforming LCA study. Accordingly, the OEM and the policy makers will gain knowledge and data on the LC performance of the car and the net LC reduction achieved compared to the gross use-phase CO₂ emissions. In this way, the OEM shows that it addresses GHG emissions not only during the car’s use phase, but also along the entire LC. This option provides a low entry barrier for LC-based legislation as it does not yet relate to product performance, that is, does not require an immediate product redesign. However, it provides LCA capability and data development and serves as an enabler for stricter performance-based options. OEMs who conduct an LCA study can be rewarded, for example, with a fixed credit of 1 g of CO₂/km. Table 5 shows some examples for this credit option and potential benefits for policy makers and OEMs.
Table 4  Credits for low GHG emissions in the production phase

| Exemplary measures to obtain a credit | Benefits for policy | Benefits for original equipment manufacturers |
|--------------------------------------|---------------------|-----------------------------------------------|
| • GHG production threshold based on market mix of aluminum, steel, and carbon fiber reinforced polymer cars | • Easy to implement | • Provides incentives to improve production processes |
|                                       | • Promotes development of CO₂-efficient material production and manufacturing processes | • Provides incentives to use materials from innovative CO₂-reducing production processes |

Note: GHG = greenhouse gas; CO₂ = carbon dioxide.

Table 5  Credits for ISO conforming life cycle assessment (LCA) studies

| Exemplary measures to obtain a credit | Benefits for policy | Benefits for original equipment manufacturers |
|--------------------------------------|---------------------|-----------------------------------------------|
| • Publication of environmental reports and declarations, e.g.: | • Promotes life cycle thinking | • Rewards innovative OEMs which implemented LCA |
|  - Environmental commendation (Volkswagen) | • Provides LCA information and data | |
|  - Environmental certificate (Daimler) | • Provides basis for methodological and data settings for advanced policies | |
| • Report as part of type approval | • Easy to implement | |

Note: ISO = International Organization for Standardization.

Table 6  Credits for ISO conforming life cycle assessment (LCA) studies and continuous improvement

| Exemplary measures to obtain a credit | Benefits for policy | Benefits for original equipment manufacturers |
|--------------------------------------|---------------------|-----------------------------------------------|
| • Proof of continuous improvement as provided, e.g., in: | • Promotes life cycle thinking | • Rewards innovative OEMs which implemented LCA and reaches continuous improvement |
|  - Environmental commendation (Volkswagen) | • Promotes continuous environmental improvement and avoids problem shifting | |
|  - Environmental certificate (Daimler) | | • Offers flexible opportunities for reduction of CO₂ emissions |

Note: ISO = International Organization for Standardization; CO₂ = carbon dioxide.

**Option 6: Credits for ISO Conforming Life Cycle Assessment Studies and Continuous Improvement**

This credit option can be regarded as an extended version of option 5. Credits may be granted based on the existence of ISO 14040/44 conforming LCA studies and the commitment of continuous improvement, that is, reduction of GHG emissions along the LC. Hence, a CO₂ emission credit can be granted as a fixed percentage/amount, if the LC-based GWP of a car model is lower compared to the predecessor model. In order to promote LCT, the credit is given regardless of whether this reduction is achieved due to improvements in the production, use, or recycling phase. For example: The GWP of an old car (predecessor model) is 130 g of LC CO₂/km, while the GWP of a new car (successor model) is only 120 g of LC CO₂/km. Thus, the OEM achieved savings of 10 g of LC CO₂/km. A robust implementation of such a credit can consider the inherent value choices and uncertainties of the underlying LCA by a robust “exchange rate” between demonstrated reduction and credit granted. For example: The 10 g of LC CO₂/km savings would be rewarded with a credit for use-phase CO₂ emissions in full, but with, for example, 1 or 2 g of CO₂/km only. Table 6 shows some examples for these credit options and potential benefits for policy makers and OEMs.

**Option 7: Credits Based on Life Cycle Share of the Use Phase**

This option allows for crediting the use-phase emissions based on the LC share of the use phase to the overall LC CO₂ emissions, as the cars that still have a high share of use-phase burdens are effectively governed by the underlying tailpipe legislation and lead to less problem shifting. The credit can be given in two ways.
Credits based on life cycle share of the use phase

| Exemplary measures to obtain a credit | Benefits for policy | Benefits for original equipment manufacturers |
|---------------------------------------|---------------------|-------------------------------------------------|
| • Special types of cars for which the use phase is the significant life cycle stage | • Promotes life cycle thinking | • Relatively easy to implement; a reference car or market mix does not need to be defined, relative shares of CO₂ emissions with regard to the own vehicle are sufficient. |
| • Technology and material choices that do not increase the emissions in production/end of life significantly | • Directly addresses the potential problem shifting | |

Note: CO₂ = carbon dioxide.

**Option 7a: Credit for High Share of Use Phase**
Here, a fixed or percentage credit can be given, if the use phase contributes significantly (e.g., more than 75%) to the overall LC-based emissions. In this way, cars made of materials with low contributions in the production and EoL phases can obtain a credit for use-phase CO₂ emissions as these emissions are similar to the LC emission. Vice versa, cars made of materials with low use phase but relatively high LC emissions typically would not qualify to be credited as their use-phase advantage, which is fully accounted in the underlying tailpipe fleet consumption anyway, is caused by a shifting of emissions to other LC phases. For example: An OEM that produces a new car which emits 95 g of CO₂/km in the use phase, contributing to 80% to the overall LC CO₂ emissions, could be rewarded with a credit of, for example, 1 g of CO₂/km. This credit option would need to be constructed in a way that there is no unintended incentive to increase the use-phase emissions in order to arrive at a credit. However, as long as the potential credits are smaller than the potential use-phase reductions, this risk is theoretical only.

**Option 7b: Credit for a Small Leakage Rate**
Here, a credit could be obtained for cars with a small “leakage rate to rest of LC” of, for example, <20%. That would mean that a new car with a use-phase reduction compared to a predecessor of, for example, 10 g/km could be rewarded with a credit in addition to this reduction of, for example, 1 g of CO₂/km, if the rest of the LC does not increase more than, for example, 2 g/km (i.e., 20% of 10 g/km). If implemented in this way, the credit option directly addresses the issue of problem shifting from the use to the other LC phases.

Table 7 shows some examples for these credit options and potential benefits for policy makers and OEMs.

**Option 8: Credits Based on Life Cycle Greenhouse Gas Emissions**
In this option, the GWP of a car caused along its LC is determined based on an ISO conforming LCA study. Subsequently, the result is compared to a reference which represents the LC-based GWP of either the predecessor car model, the market mix, or the version with the lowest possible use-phase emission. The credit can be given in two ways.

**Option 8a: Credit Based on Life Cycle Efficiency**
Here, the “LC efficiency,” that is, the GWP of the car in relation to the GWP of the reference, is determined. Subsequently, a credit for use-phase CO₂ emissions is allowed if the LC efficiency is above, for example, 110%. In this way, a reduction of GHG emission is rewarded regardless of the LC phase in which it occurs. This option is similar to option 6, but a fixed reduction target (e.g., 10%) needs to be achieved. For example: If the GWP of a reference car (e.g., market mix) is 130 g of CO₂/km and the GWP of a new car is 120 g of CO₂/km, the LC efficiency would be 108% (130 divided by 120). Thus an LC improvement of 8% was achieved and the OEM would obtain a credit (e.g., 1 g of CO₂/km), if the LC efficiency target was set to 5%, but not if it was set to 10%.

**Option 8b: Credit Based on Difference to Reference**
Here, the GWP of the car is compared to the reference, and the difference is directly subtracted from the car’s use-phase CO₂ emission. Hence, cars which cause a lower GWP than the reference benefit from a use-phase credit which equals the LC-based savings. Compared to options 1 to 7, the use-phase reductions are not given as a fixed percentage/amount, but are determined quantitatively based on an LCA study. For example: If the GWP of a reference car (e.g., the predecessor car model) is 130 g of CO₂/km and the GWP of a new car is 120 g of CO₂/km, the OEM would have achieved savings of 10 g of CO₂/km, which would be rewarded with a credit for use-phase CO₂ emissions of 10 g of CO₂/km.

Table 8 shows some examples for this credit options and potential benefits for policy makers and OEMs.

**Option 9: Credits for Reducing Other Environmental Impacts**
Despite the policy and industry focus on CO₂ emissions and the environmental impact of global warming only, there are many other environmental impact categories, such as acidification, human toxicity, eutrophication, or water depletion, which are relevant for cars and therefore considered by full LCA studies. As mentioned above, this particular credit option presents an approach on how reductions in other environmental impacts could be rewarded in the GHG tailpipe legislation of cars. Other impact categories can be quantified and compared to the impact category results of a reference (e.g., market mix or predecessor model). The credit can then be given in two ways.
Table 8 Credits based on life cycle GHG emissions

| Exemplary measures to obtain a credit | Benefits for policy | Benefits for original equipment manufacturers |
|--------------------------------------|---------------------|-----------------------------------------------|
| • Calculation of life cycle (LC) efficiency, e.g., as part of an environmental commendation/certification using the predecessor car model as a reference and showing a reduction of LC GWP | • Promotes life cycle thinking • Promotes continuous environmental improvement and avoids problem shifting | • Innovative OEMs which implemented life cycle assessment and reach continuous improvement will be rewarded. • Offers flexible opportunities for reduction of CO₂ emissions |

Note: GHG = greenhouse gas; GWP = global warming potential; CO₂ = carbon dioxide.

Option 9a: Default Credit
If other environmental impacts are below the reference threshold, the car's use-phase CO₂ emissions might be reduced by a fixed amount or percentage. As an example: A car achieves a very low emission level well below the legal limits for particles or nitrogen oxide; this could be incentivized by a credit of, for example, 1 g of CO₂/km.

Option 9b: Credit Based on Difference to Reference
By means of LCA endpoint characterization models (e.g., by Goedkoop et al. 2009), for example, damages to human health (expressed by the indicator, the disability-adjusted life year [DALY]) resulting from GHG emissions and other environmental interferences, such as toxic emissions or freshwater consumption, can be determined. If the car’s results in other impact categories (e.g., particulate matter) are below the reference thresholds, the difference can be transferred into DALYs. Subsequently, an equivalent amount of CO₂ emissions, which would lead to the same amount of DALYs, could be reduced from the car’s use phase CO₂ emissions. For example: An old car emits 120 g LC CO₂ equivalents (CO₂-eq)/km and 40 milligrams (mg) of LC particle/km. A new car also emits 120 g of LC CO₂-eq/km, but only 20 mg of LC particle/km. The savings of 20 mg of LC particles/km equals 5.2 × 10⁻⁹ DALYs, which equals 3.6 g of CO₂-eq. Hence, an OEM can obtain a credit of 3.6 g of CO₂/km. Table 9 shows some examples for this credit options and potential benefits for policy makers and OEMs.

Requirements for Implementing the Credit Options
Implementing a credit option will provide a new modality to consider embedded emissions under the current scope of CO₂ legislation in order to buffer unintended consequences of the existing tailpipe focus. In order to integrate voluntary credit options into legislation, several methodological and technical requirements would need to be addressed and specified: For LCA options, this refers, for example, to LCA requirements, such as methodology, data, functional unit, and allocation, and other technical settings, such as lifetime driving distance (Weymar and Finkbeiner 2016), driving cycle, as well as the calculation and magnitude of the credit. Different options may have different requirements and therefore potential (relative) advantages/disadvantages. For instance, for some options (e.g., option 8), additional requirements would need to be defined, for example, a reference car, which may not needed for other options (e.g., option 7). Defined requirements would ensure that automotive LCAs would be conducted based on the same assumptions, thus leading to comparable results. Solutions for these requirements as well as a solid harmonization level based on international standards and established industry practice are already available and can serve as a starting point for the required specification—the challenge is rather to find a consensus (see also the discussion of a framework of policy options for LC-based CO₂ emission regulation and potential role of credit systems below and Lehmann et al. [2015]). It is also worth noting that, for policy implementation, the robustness of the LCA implementation is more important than the precision or level of detail. This notion is based on the experience of the implementation of the recycling legislation for cars. There, a simplified recyclability calculation based on ISO 22628 was used for policy implementation while a proper recycling planning or design for recycling of the products requires much more detailed analysis. Similarly, the policy implementation of LCAs can be conducted in a simplified and robust way on the level of the complete car and high-end automotive LCAs as applied in product development are not necessarily required. For the LCT options, the calculation and magnitude of the credit would need to be specified along with defining rules for measuring GHG emissions in the production phase (for credit option 1). To ensure (1) comparable and fair results/credits and (2) that reduced CO₂ emissions in the production phase are actually reached by, for example, the innovative technology, reference scenarios need to be defined, such as: conducting direct CO₂ measurements under the same conditions (e.g., during running operation, using the same measurement point). Moreover, if green energy was used to reduce CO₂ emissions in the production phase, robust green certificates should be required in order to avoid double counting. In order to demonstrate that an implementation of voluntary credit options is feasible, several illustrative examples for the individual credit options were developed. “Illustrative” means that concrete solutions for the LCA requirements and required other settings as well as concrete examples on how to calculate and to reward credits were proposed. The solutions were chosen taking into account existing approaches for LCA modeling from practice (e.g., from OEMs, material associations, policy, and academia) and
examples from existing legislation. For example, LCA could be conducted based on different approaches, such as the existing ISO 14040/44 standard, but with an additional car-specific specification, either as an additional ISO or European Committee for Standardization (CEN) standard or a product category rule (PCR). All these requirements need to be defined by the policy makers (following scientific advice, stakeholder consultations, and proper impact assessment). For example, all LCA requirements/settings could be fixed in an “automotive PCR”—either one, which is valid for all regions (potentially with regional specifications) or in different regional ones. A detailed illustrative example for LCA-based credit options can be found in section S3 of the supporting information on the Web. The illustrative example shows that the implementation of an LC-based credit option can be realized through a simplified and robust methodology, with defined rules for conducting the LCA (or, with regard to LCT option 1: for measuring GHG emissions in the production phase) and for calculating the credit. This will entail the use of simplified high-level calculations (similar to those under the existing EU End of Life Vehicles-Directive) and a robust “threshold or exchange rate” for the credit to account for remaining uncertainties in the calculation (e.g., 1 g of credit for 10 g of savings). Thus, even if the uncertainty range of an LCA, for example, caused by inaccurate or missing LCI data, would be 200%, the savings along the LC would still be higher than the credit obtained for the use phase (also see section S2 of the supporting information on the Web). Consequently, the overall target of CO₂ reduction in road transport will not be weakened. One feasible way to operationalize an LCA-based credit option is to integrate it into the type approval process and to use data already handled in this process as a baseline for the implementation: OEMs would conduct an LCA study in a standardized way (e.g., based on an automotive PCR). The LCA model and data would then be verified and validated in analogy to the type approval process by external and independent reviewers. This will leave OEMs with very little room to be fraudulent and ensure that the reductions in LC emissions are real. The credit option will be on top of a stringent tailpipe emissions test which will also follow a strict verification process. Transparency of reporting will help ensure that credibility is maintained.

### Conclusions and Outlook

Current CO₂ legislation focuses on tailpipe CO₂ emissions only, which suffers from an increasing risk of unintended consequences and unfair market conditions. For example: A car A may emit 95 g of CO₂/km tailpipe emissions and 130 g of LC CO₂/km emissions when considering the whole LC. Its successor car model A⁺ may still have 95 g of CO₂/km tailpipe emissions, but fewer LC CO₂ emissions, for example, 120 g of LC CO₂/km. In current tailpipe legislation, the efforts of the OEM to reduce the total CO₂ emissions of the successor car would not be rewarded. Moreover, unfair conditions and unintended consequences can occur as another car B with lower tailpipe emissions (e.g., 80 g of CO₂/km) than car A⁺ would be advantaged, even though it may have higher total LC CO₂ emission (e.g., 130 g of CO₂/km). In this example, car model A⁺ will not be rewarded in the current tailpipe regulation as there is no use-phase improvement even though its total LC CO₂ emissions are 10 g of LC CO₂/km lower than those of car B. Car B, despite being environmentally worse than car A⁺, would be rewarded with the 10 g of CO₂/km reduction of use-phase emissions. While it is not realistic in the short and mid-term that this unjustified bias toward use-phase emissions is removed as legislative baseline, the credit options proposed here are intended to buffer some of these negative effects by introducing the option for the environmentally preferable car A⁺ to earn at least a 1- or 2-g/km credit based on its better LC performance, that is, savings of 10 g of CO₂. Such voluntary credit options as a complementary modality to tailpipe-based CO₂ regulations would help to improve the efficiency and effectiveness of current automotive regulation and to support and reward efforts on achieving real net CO₂ emission reductions. The credits could help the OEM to meet the emission targets of current tailpipe regulation. In this way, LC-based

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**Table 9** Credits for reducing other environmental impacts

| Examples | Benefits |
|----------|----------|
| • Additional environmental impacts (besides CO₂) are already considered in existing environmental declarations, such as environmental commendation (Volkswagen AG) and environmental certificate (Daimler AG), and are compared to the predecessors car model (option 9a) | • Comprehensive information on potential environmental impacts |
| • Comparison of different environmental impacts at end point level is common in life cycle assessment studies (option 9b) | • Avoids problem shifting |
| | • Promotes multicriteria assessment |
| | • Can tackle local air pollution issues (e.g., in China) |
| | • OEMs which focus on the reduction of environmental impacts beyond global warming will be rewarded. |
| | • Offers flexible opportunities for reduction of CO₂ emissions |

Note: CO₂ = carbon dioxide.
credits can be used to get an “extra reduction” of the fleet value, for example, if there is a 2-g/km credit for 50% of the fleet, the fleet value is reduced by 1 g/km.

In this study, nine potential LC-based CO₂ emission credit options were introduced and described, ranging from simple options not requiring an LCA to more advanced options, which are based on LCAs. All options can be considered as being overall technology neutral, that is, they do not favor certain materials or technologies per se. However, as the credit options differ with regard to their award criteria and the calculation procedures an OEM may obtain credits with the credit options X and Y, but not with the credit option Z. Moreover, the study shows that an implementation of credit options is possible in a feasible and robust way—feasible because solutions for most of the methodological and technical requirements are already available and robust because (1) LCAs (or GHG measurements) would be done in a standardized way and (2) the credits would be given in a conservative way considering the existing uncertainties of LCA results, for example, for a saving of 10 g of LC GHG, a credit of “only” 1 g of CO₂/km would be provided. Such robust and well-considered target values will ensure that credits are only obtained if an actual reduction along the LC is achieved and the overall target of CO₂ reduction in road transport is supported. As an LC perspective gains increasing importance in policy, including automotive legislation, voluntary credit options, which complement the existing legislation, seems a feasible and promising option from a short- and mid-term perspective. When implemented in a robust and simple way, they help to buffer unintended consequences of the existing tailpipe-only focus and be effective to support and reward efforts on achieving real net emission savings for the environment. Moreover, they also will help to develop the understanding, data, and confidence needed for potential future mandatory LC-based policies considering a comprehensive set of environmental impacts.

The policy options presented in this paper will be further evaluated in terms of their effectiveness, viability, and support from various stakeholders and fine-tuned based on the outcomes of the ongoing stakeholder dialogues.

As a future paradigm shift in (automotive) legislation toward a more fact- and science-based policy approach is needed to achieve a sustainable development, the consideration of the LC approach is indispensable. The work presented here is not the ultimate solution, but rather a low-entry-barrier approach for a specific field of legislation that intends to deprive the responsible policy makers of their usual, yet unsound, excuses to implement LCA into their policies. In that sense, we do hope to see LC-based credits implemented in the currently debated, next version of automotive CO₂ legislation, and we do hope that this will help in paving the way for more comprehensive solutions in future revisions as well as other policy fields.

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Notes

1. Note, lightweight design leads, in many cases, to an increase of CO₂ emissions in the production phase, while some advanced solution such as hot-formed steel applications can lead to a CO₂ reduction in the production phase compared to conventional steel construction (Broch et al. 2015).

2. The need for further consideration of embedded emissions from vehicle manufacturers was also noted in the Inception Impact Assessment report released in connection with the EC Communication “A European Strategy for Low-Emission Mobility,” published in July 2016 (EC 2016).

3. Still, OEMs may first develop cars in such a way that they will be better than the competitors in terms of fuel consumption; however, they additionally have the opportunity to achieve reductions in other phases than the use phase.

4. This was done within an ongoing project initiated by WorldAutoSteel, the automotive group of the World Steel Association, which commissioned the Technical University of Berlin to explore and develop policy options for integrating LCA into automotive legislation.

5. Methods: for example, International Organization for Standardization (ISO) 14040/44 (ISO 2006a, 2006b), PEF (EU 2013); databases for background data: for example, Environmental Life Cycle Database (ELCD) from the EC (EC 2015; ecoinvent 2015; thinkstep 2016); data collection formats, for example, by Finkbeiner and colleagues (2003); customized LCA software and models: for example, University of California at Santa Barbara (UCSB) model by WorldAutoSteel (UCSB 2013) or the model from the European Aluminium Association (EAA) (Hill and Kirsch 2015); and communication formats: for example, environmental reports.

6. European and Japanese car manufacturers, for example, asked for the eco-innovation credits when the CO₂ legislation was being formulated, and the European Automobile Manufacturers Association declared that it is working on a series of initiatives that could tap the eco-innovation credit (UPI 2011).

7. In theory, a credit option which would reward a reduction of CO₂ emissions in the EoL phase is also possible. However, due to the existing challenges/discussions on how to allocate EoL emissions (e.g., avoided burden vs. cut-off approach) and thus a missing direction for an EoL credit option (Mengarelli et al. 2017; Zampori et al. 2016), such an option has not yet been explored.

8. Contrarily, the existing tailpipe CO₂ legislation cannot be considered as technology neutral as it incentivizes electric vehicles (which are considered as ZEVs, but, in fact, are “elsewhere emission vehicles”), for example, by providing “supercredits” (i.e., counting vehicles emitting less than 50 g/km as up to 3.5 vehicles).

9. Please note that all numbers/percentages provided in some of the examples are examples chosen by the authors and hence can be different. If a credit option (or a subset of credit options) would...
be implemented, those numbers would need to be defined by the policy makers based on scientific advice and a proper impact assessment.

10. Following conversion factors were taken from the ReCiPe model report, table 2.9 (hierarchist perspective): 1 kg of particles equals 2.6 × 10^4 DALYs; 1 kg of CO₂-eq equals 1.4 × 10^6 DALYs (Goedkoop et al. 2009).

11. Please note that option 5 would allow more flexibility in terms of LCA requirements used by individual OEMs.

12. It should be emphasized here that such a robust approach also addresses one of the existing challenges in the current legislation, that is, the gap between real world and lab emissions, which are determined based on a standardized driving cycle and actually much lower than the actual emissions. As the LCA credit will be more robustly designed than current measurement methods, inaccuracies, which will occur, will have less of an impact than inaccuracies resulting from current measurement methods.

13. The same principles also apply for the LCT options, for example, measurements of GHGs in the production phase will be done based on defined rules and verified by independent reviewers.

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**Supporting Information**

Supporting information is linked to this article on the JIE website:

**Supporting Information S1:** This supporting information includes one figure and two tables. Figure S1 shows trade-offs when considering use phase CO₂/GHG emissions only instead of life cycle CO₂/GHG emissions, Table S1 shows a list of credit options including numerical examples, and Table S2 is an illustrative example for an LCA-based credit option in a European context.