European Commission

11th adaptation to scientific and technical progress of exemptions 2(c)(i), 3 and 5(b) of Annex II to Directive 2000/53/EC (ELV)

Final Report

5 November 2021

LEGAL NOTICE

This document has been prepared for the European Commission however, it reflects the views only of the authors, and the European Commission is not liable for any consequence stemming from the reuse of this publication. More information on the European Union is available on the Internet (http://www.europa.eu).

Bio Innovation Services, Fraunhofer IZM and UNITAR have taken due care in the preparation of this report to ensure that all facts and analysis presented are as accurate as possible within the scope of the project. However, no guarantee is provided in respect of the information presented, and Bio Innovation Services, Fraunhofer IZM and UNITAR are not responsible for decisions or actions taken based on the content of this report.

EUROPEAN COMMISSION

Directorate-General for Environment
Directorate B — Circular Economy and Green Growth
Unit B.3 — Waste Management and Secondary Materials

Contact: Christian Wimmer

E-mail: *christian.wimmer@ec.europa.eu*

European Commission
B-1049 Brussels

11th adaptation to scientific and technical progress of exemptions 2(c)(i), 3 and 5(b) of Annex II to Directive 2000/53/EC (ELV)

Final Report

Report prepared by Fraunhofer-Institute for Reliability and Microintegration (IZM), the United Nations Institute for Training and Research (UNITAR), and Bio Innovation Service (BioIS)

Dr. Otmar Deubzer, Fraunhofer IZM and UNITAR

Christian Clemm, UNITAR

Shailendra Mudgal, BioIS

5 November 2021

United Nations Institute for Training and Research (UNITAR) Bonn Office
UN Campus, Platz der Vereinten Nationen 1, 53113 Bonn, Germany
Tel: +49-30-417 258 33
Web: https://unitar.org/about/offices-training-centres-around-world/bonn

Fraunhofer IZM
Gustav-Meyer-Allee 25
13355 Berlin, Germany
Tel.: +49 (0)30 / 46403-157
Fax: +49 (0)30 / 46403-131
Web: www.fraunhofer.de

Bio Innovation Service
7 rue Oberkampf
75011 Paris, France
Tel.: +33 952398787
Web: www.biois.eu

Acknowledgements

We would like to express our gratitude towards stakeholders who contributed information concerning the requests for exemptions handled in the course of this project.

Table of Contents

List of Figures

List of Tables

1 Executive summary – English

The consortium for the Framework Contract "Assistance to the Commission on technological, socio-economic and cost benefit assessments related to the implementation and further development of EU waste legislation" (ENV.B.3/FRA/2019/0017) coordinated by Bio Innovation Service was requested by DG Environment of the European Commission to provide technical and scientific support for the evaluation of exemption requests under the "11th Adaptation to scientific and technical progress of exemptions 2(c)(i), 3 and 5(b) of Annex II to Directive 2000/53/EC (ELV)". The work has been undertaken by Fraunhofer Institute IZM, UNITAR and Bio Innovation Service.

1.1 Background and objectives

Directive 2000/53/EC on end-life-vehicles ("ELV" Directive) restricts the use of certain hazardous substances in vehicles. The Directive includes a list of exemptions to these use restrictions, which is adapted regularly to scientific and technical progress according to the respective provisions in the Directive.

Following the requirements of Article 4(2)(a) of Directive 2000/53/EC on end-of-life vehicles, Member States of the European Union have to ensure that materials and components of vehicles put on the market since 1 July 2003 do not contain lead, mercury, hexavalent chromium and cadmium. A limited number of applications exempted from the provision of this article are listed in Annex II to the Directive as well as the scope and the expiry date of the exemption and the labelling requirement according to Article 4(2)(b)(iv)[1] (if applicable).

Based on Article 4(2)(b), Annex II is to be adapted to scientific and technical progress by the Commission on a regular basis. This is done in order to check whether existing exemptions are still justified with regard to the requirements laid down in Article 4(2)(b)(ii), whether additional exemptions have been proposed on the basis of the same article and whether exemptions are no longer justified and need to be deleted from the Annex with regard to Article 4(2)(b)(iii). Furthermore, the adaptation procedure has to – as necessary – establish maximum concentration values up to which the restricted substances shall be tolerated (Article 4(2)(b)(i)) and designate those materials and components that need to be labelled.

All non-confidential stakeholder comments submitted during the consultation were made available on the EU CIRCABC website (Communication and Information Resource Centre for Administrations, Businesses and Citizens):

[1] Article 4(2)(b)(iv) provides that designated materials and components of vehicles that can be stripped before further treatment have to be labelled or made identifiable by other appropriate means.

https://circabc.europa.eu (Browse categories > European Commission > Environment > ELV exemptions, at top left, click on "Library").

1.2 Key findings – Overview of the evaluation results

The exemption request covered in this project and the applicant concerned, as well as the final recommendation and proposed expiry date are depicted in Table 1-1. The reader is referred to the corresponding section of this report for more details on the evaluation result.

Table 1-1: Overview of the exemption requests, associated recommendations and expiry dates

Ex. No.	Current exemption wording	Applicant	Recommendation	Expiry date and scope
2(c)(i)	*Aluminium alloys for machining purposes with a lead content up to 0,4 % by weight*	*ACEA et al., European Aluminium*	*Continue exemption with current wording*	*Vehicles type-approved before 1 January 2028 and spare parts for these vehicles*
3	*Copper alloys containing up to 4 % lead by weight*	*ACEA et al., Mitsubishi Materials Corporation*	*Continue exemption with current wording for three years, max. 4 years*	*Review in 2024*
5	*Lead in batteries for battery applications not included in entry 5(a)*	*ACEA et al, EGARA, Bosch*	*Continue exemption with restricted scope, review in 2025*	*Vehicles type approved before 1 January 2024 and spare parts for these vehicles*

2 Executive Summary: French - Note De Synthèse: Français

Le consortium pour le contrat cadre « Assistance en faveur de la Commission sur les évaluations techniques, socio-économiques, environnementales et coûts-avantages liées à l'exécution et au développement ultérieur de la législation UE sur les déchets » (ENV.B.3/FRA/2019/0017) coordonné par Bio Innovation Service a été mandaté par DG Environnement de la Commission Européenne pour fournir une assistance technique et scientifique pour l'évaluation des demandes d'exemptions suivant la « 11ème Adaptation aux progrès techniques et scientifiques des exemptions 2(c)(i), 3 et 5(b) de l'Annexe II à la Directive 2000/53/EC (ELV) ». Les travaux ont été réalisés par Fraunhofer Institute IZM, UNITAR et Bio Innovation Service.

2.1 Contexte et objectifs

La directive 2000/53/CE relative aux véhicules hors d'usage (directive "VHU") restreint l'utilisation de certaines substances dangereuses dans les véhicules. La directive comprend une liste de dérogations à ces restrictions d'utilisation, qui est régulièrement adaptée au progrès scientifique et technique conformément aux dispositions respectives de la directive.

Conformément aux exigences de l'article 4(2)(a) de la directive 2000/53/CE relative aux véhicules hors d'usage, les États membres de l'Union européenne doivent s'assurer que les matériaux et les composants des véhicules mis sur le marché depuis le 1er juillet 2003 ne contiennent pas de plomb, de mercure, de chrome hexavalent et de cadmium. Un nombre limité d'applications exemptées des dispositions de cet article sont énumérées à l'annexe II de la directive, ainsi que le champ d'application et la date d'expiration de l'exemption et l'exigence d'étiquetage conformément à l'article 4, paragraphe 2, point b) iv) (le cas échéant).

En vertu de l'article 4, paragraphe 2, point b), l'annexe II doit être régulièrement adaptée au progrès scientifique et technique par la Commission. Cela permet de vérifier si les exemptions existantes sont toujours justifiées au regard des exigences fixées à l'article 4, paragraphe 2, point b) ii), si des exemptions supplémentaires ont été proposées sur la base du même article et si des exemptions ne sont plus justifiées et doivent être supprimées de l'annexe au regard de l'article 4, paragraphe 2, point b) iii). En outre, la procédure d'adaptation doit - si nécessaire - établir des valeurs de concentration maximales jusqu'auxquelles les substances faisant l'objet de restrictions sont tolérées (article 4, paragraphe 2, point b) i)) et désigner les matériaux et composants qui doivent être étiquetés.

Tous les commentaires non confidentiels des parties prenantes soumis au cours de la consultation ont été mis à disposition sur le site web de l'UE CIRCABC (Communication and Information Resource Centre for Administrations, Businesses and Citizens) :

https://circabc.europa.eu (Naviguez) (Catégories > Commission européenne > Environnement > ELV exemptions, en haut à gauche, cliquez sur "Library").

2.2 Les principales conclusions – Synthèse des résultats de l'évaluation

La demande d'exemption couverte par ce projet, le demandeur concerné, ainsi que la recommandation finale et la date d'expiration proposée sont présentés dans le tableau 2-1. Le lecteur est invité à se reporter à la section correspondante du présent rapport pour plus de détails sur le résultat de l'évaluation.

Tableau 2-1 : Récapitulatif des demandes d'exemption, des recommandations associées et des dates d'expiration

Traduction en français fournie par souci de commodité. En cas de contradictions entre la traduction française et la version originale anglaise, cette dernière fait foi.

Dem. ex. n°	Libellé actuel de l'exemption	Demandeur	Recommandation	Date d'expiration et champ d'application
2(c)(i)	*Alliages d'aluminium pour usinage avec une teneur en plomb allant jusqu'à 0,4 % en poids*	*ACEA et al., European Aluminium*	*Maintenir l'exemption avec le libellé actuel*	*Véhicules réceptionnés avant le 1er janvier 2028 et pièces détachées pour ces véhicules*
3	*Alliages de cuivre avec une teneur en plombe allant jusqu'à 0,4 % en poids.*	*ACEA et al., Mitsubishi Materials Corporation*	*Maintenir l'exemption avec le libellé actuel pour trois ans, max. 4 ans*	*Révision en 2024*
5	*Le plomb dans les batteries pour des applications de batteries non incluses dans la section 5(a)*	*ACEA et al, EGARA, Bosch*	*Maintenir l'exemption avec un champ d'application restreint, révision en 2025*	*Véhicules réceptionnés avant le 1er janvier 2024 et pièces détachées pour ces véhicules*

3 Introduction

3.1 Background

The EU Directive 2000/53/EC on end-of-life vehicles ("ELV" Directive, hereafter referred to as "the Directive") bans the use of certain substances in vehicles. According to Article 4(2)(a), “Member States shall ensure that materials and components of vehicles put on the market after 1 July 2003 do not contain lead, mercury, cadmium or hexavalent chromium other than in cases listed in Annex II under the conditions specified therein.” Article 4(2)(b) provides a basis for excluding certain materials and components in Annex II and specifies the criteria on which such exemptions can be justified:

“Annex II shall be amended on a regular basis, according to technical and scientific progress, in order to:

(i) as necessary, establish maximum concentration values up to which the existence of the substances referred to in subparagraph (a) in specific materials and components of vehicles shall be tolerated;

(ii) exempt certain materials and components of vehicles from the provisions of subparagraph (a) if the use of these substances is unavoidable;

(iii) delete materials and components of vehicles from Annex II if the use of these substances is avoidable;”

(iv) under points (i) and (ii) designate those materials and components of vehicles that can be stripped before further treatment; they shall be labelled or made identifiable by other appropriate means.”

Annex II to the Directive that has so far been adapted to scientific and technical progress ten times; the last amendment of Annex II to the Directive is dated 5 March 2020. Annex II also provides review dates for a number of exemptions.

3.2 Project scope and methodology

Following the requirements of Article 4(2)(a) of Directive 2000/53/EC on end-of-life vehicles, Member States of the European Union have to ensure that materials and components of vehicles put on the market since 1 July 2003 do not contain lead, mercury, hexavalent chromium and cadmium. A limited number of applications exempted from the provision of this article are listed in Annex II to the Directive as well as the scope and the expiry date of the exemption and the labelling requirement according to Article 4(2)(b)(iv) (if applicable).

Based on Article 4(2)(b), Annex II is to be adapted to scientific and technical progress by the Commission on a regular basis. This is done in order to check whether the current exemptions are still justified with regard to the requirements laid down in Article 4(2)(b)(ii), whether additional exemptions have been proposed on the basis of the same article and whether exemptions are not anymore justified and need to be deleted from the Annex with regard to Article 4(2)(b)(iii). Furthermore, the adaptation procedure has to – as necessary – establish maximum concentration values up to which the restricted substances shall be tolerated (Article 4(2)(b)(i)) and designate those materials and components that need to be labelled.

Against this background, this study reviewed the following three exemptions of Annex II of the Directive, which approach their mandatory review date in 2021.

- 2(c)(i) Aluminium alloys for machining purposes with a lead content up to 0.4 % by weight
- Copper alloys containing up to 4 % lead by weight
- 5(b) Lead in batteries for battery applications not included in entry 5(a)

In the course of the study, a stakeholder consultation was performed, following the EC guidelines for consultation of interested parties. The stakeholder consultation was launched on the 15th of September 2020 and ended on the 8th of December 2020. A dedicated website (https://elv.biois.eu) for the study was developed where all relevant documents related to the consultation were stored. It was also used as a channel to inform the stakeholders on the progress and provided links to the webpage of the public consultation. Stakeholders were also provided the opportunity to register, and registered stakeholders were kept informed through email. The clarification questionnaires and consultation responses were made available at the study website.

Following the stakeholder consultations, an in-depth evaluation of the exemption was conducted.

The evaluation of the exemption appears in sections 4, 4 and 6 of this report. The information provided by the applicants and by stakeholders is summarised in the first sections of the respective sections. This includes a general description of the application and requested exemption, a summary of the arguments made for justifying the exemption, information provided concerning possible alternatives and additional aspects raised by the applicants and other stakeholders. In the Critical Review part, the submitted information is discussed, to clarify how the consultants evaluate the various information and what conclusions and recommendations have been made. The general requirements for the evaluation of exemption requests as set by the European Commission may be found in the technical specifications of the project.[2]

[2] Cf. https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_18/Technical_Specification_RoHS_Pack18.pdf

4 Exemption 2(c)(i) of ELV Annex II: Lead in aluminium for machining

The exact wording of the current exemption 2(c)-I is as follows:

Aluminium alloys for machining purposes with a lead content up to 0,4 % by weight

Declaration

The sections preceding the "Critical review", the phrasings and wordings of applicants' and stakeholders' explanations and arguments have been adopted from the documents they provided as far as required and reasonable in the context of the evaluation at hand. Formulations were only altered or completed in cases where it was necessary to maintain the readability and comprehensibility of the text.

Acronyms and definitions

Al	aluminium
Bi	bismuth
Cu	copper
EA	European Aluminium
Pb	lead
Sn	tin

4.1 Background and Technical Information

The above exemption has become due for review. Two contributions to the stakeholder consultation were received:

1) European Aluminium (2020) (EA) claim that lead free wrought aluminium alloys for machining are available, they have been tested and approved in all applications where led-containing alloys were used by major automotive brands worldwide. Lead-free wrought aluminium alloys are already used for many automotive parts. Aluminium industry is able to support a phase-off of lead-containing wrought aluminium alloys already now. How fast the phase-off could be, depends only on the downstream.
2) ACEA et al. (2020) request an extension of exemption 2(c)(i) for seven years for vehicles type-approved before 1 January 2028, as well as for spare parts for these vehicles, and ending the exemption for new vehicles type-approved after 1 January 2028.

4.1.1 Summary of the requested exemption

ACEA et al. (2020) have substituted most of the uses with intentional lead addition. However, in a small amount of quite challenging parts, the specific properties of lead are important for the function (e.g. anti-friction effect) and therefore the phase out could not yet be realized. They request an extension of exemption 2(c)(i). for seven years and then ending for new vehicles type-approved after 1 January 2028, as well as for spare parts for these vehicles.

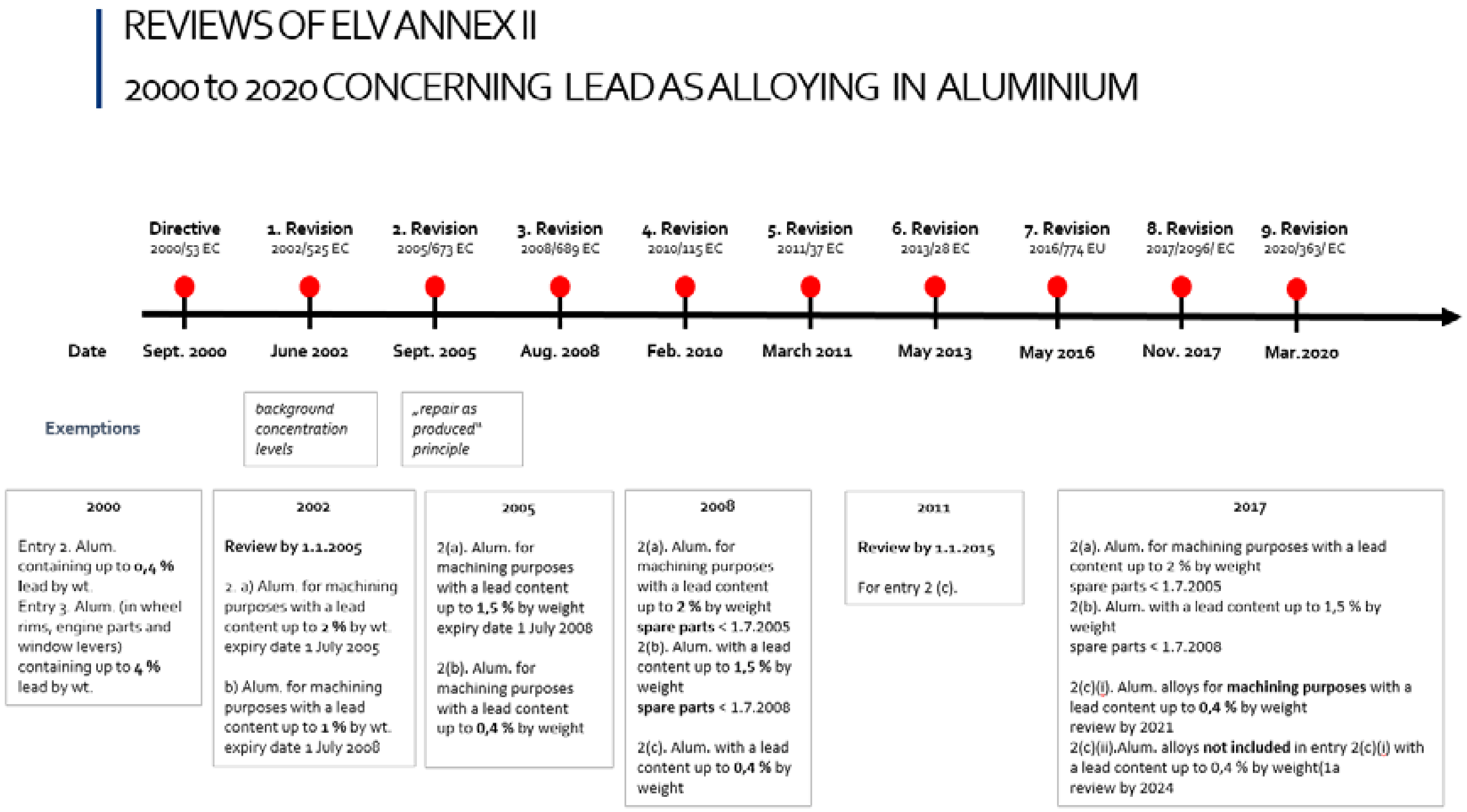
European Aluminium (2020) state that lead-free wrought aluminium alloys for machining purposes are globally available and aluminium producers have developed lead-free alternatives with properties compatible with lead-containing alloys in use for any applications. Aluminium extruders started back in 1996 to develop alloys with high machinability which could replace the lead-containing ones. Now, thanks to the big experience accumulated during decades, there are in the market all possible lead-free alloys which could replace any kind of lead-containing alloy, for any end-use application, for all kind of families of alloys from 2000 series (Al-Cu based) to 6000 series (Al-Cu-Mg series). These alloys have been tested and approved by several major automotive brands worldwide, in all applications from brake parts and pistons, transmission valves, safety parts and components, whether used in high or low temperature environments, whether in contact with fluids, lubricants, coolants, whether anodized or not. All parts passed all the requirements also in terms of respecting tight tolerances, surface roughness, superficial aspect, anodizing response, mechanical properties. The aluminium industry is immediately able to supply any quantity needed of lead-free alloys.

European Aluminium (2020) acknowledge that the car industry needs time to adapt and qualify these new alloys. They say that they are not experts in the details of the development cycles, which is why they prefer not to give a timeline.

4.1.2 History of the Exemption

A first version of the exemption was published in the first amendment of the Directive, for “Aluminium for machining purposes”. The exemption scope and wording changed a few times since publication of this first version. In the third revision of Annex II in 2008, the exemption wording was adapted based on request of the Organisation of European Aluminium Refiners and Remelters (OEA) and the European Aluminium Association (EAA) who claimed a general exemption of up to 0.4 % for the unintentional content of lead in aluminium alloys was needed, whereupon the restriction to machining purposes was removed from the exemption scope resulting in the following formulation: “Aluminium with a lead content up to 0.4% by weight”, which thereby inherently allows unintentionally present lead within the scope of the exemption. Exemption 2(c) in its current wording was published in the third revision of Annex II in 2008 and reviewed in 2009/2010. The Commission set a review date within five years as industry had not provided substantiated evidence to prove that reduction of lead concentrations in aluminium alloys was not feasible, despite the general availability of lead-free alternatives. In consequence, exemption 2(c) was reviewed again in 2015 resulting in the current exemption 2(c)-I, which has become due for review in 2021. Figure 4-1 gives a more detailed overview of the development of the aluminium exemptions.

Figure 4-1: Lead limits in aluminium materials defined in Annex II of ELV Directive



Source: ACEA et al. (2020)

4.1.3 Technical description of the exemption and use of restricted substance

According to ACEA et al. (2020), there are about ten different lead containing alloys for machining purposes with a content of up to 0.4 % weight of lead applied. This is to enable fulfilment of component specific requirements and their interacting function in complex assemblies under mechanical load, temperature and with fluids impact with different compositions. ACEA et al. (2020) list the below examples.

- Valves, valve tappets, valve pins, valve, plungers, valve bushings,
- Pistons, pistons in automated gearbox systems,
- Special adjusting screws,
- Pumps,
- Cylinders,
- Compressor elements,
- Sensor elements,
- Motor bearing cages,
- Separating cylinders rollover system,
- Safety belt systems,
- Squib holders,
- Piston brake systems,
- Turbo chargers,
- Shock absorber elements and bearings,
- Cylinder sleeves,
- HVAC systems,
- Axles,
- Magnet brake power multipliers (brake boosters),
- Closing bolts.

ACEA et al. (2020) point out the specific characteristics of these components to be that they are mainly small moving parts, like in valves or pistons where light weight and emergency dry running properties as well as some ductility are important. Small means small size of component, but accuracy of dimensions and wear resistance is important as well as corrosion resistance. There is no major difference to be observed between vehicles with internal combustion engines and battery electric vehicles concerning relevant lead uses. This sounds reasonable as brake systems or safety belt applications are in use in both variants. According to ACEA et al. (2020), most relevant properties for such sliding or moving elements are:

- Fatigue strength (Ability of bearing of permanent mechanical load);
- Good resistance to fatigue crack growth and damage tolerance even at elevated temperatures;
- Erosion resistance (wear by critical flow of media turbulence);
- Elution/leaching by fluids /oils;
- Cavitation pitting;
- Resistance against abrasive wear;
- Tolerance against fretting;
- Corrosion resistance;
- Resistance against chemicals.

ACEA et al. (2020) explain that the quality of the surface respectively the fatigue life of the relevant vehicle components depends on the material properties which are highly influenced by the machinability of the alloy, the machining process parameters and cutting tools used for the procedures. Based on different combinations of required properties mentioned above different grades of Aluminium alloys are used as time tested materials.

The choice of the material is done to component case specific use profiles e.g. like ductility, surface quality or dry run emergency lubrication ability etc., including materials containing up to 0.4 % Pb.

4.1.4 Amount of lead used under the exemption

Based on 18.0 Mio vehicles (M1/N1) put on the EU market in 2019, ACEA et al. (2020) estimate a total lead amount for alloys covered by exemption 2(c)(i) of about 10 tonnes to 15 tonnes per year.

ACEA et al. (2020) substantiate their above estimate as follows:

In 2019, 18.003 571 vehicles in categories M1/N1 were newly registered in the EU. Calculated lead volumes are related to this figure. Depending primarily on the use of recycled aluminium in a vehicle we estimate a lead content in the range of 25 g to 200 g in aluminium materials per car, with an average quantity of 73 g/car. Most of this lead (≈ 99%) is contained in cast alloys for which secondary Aluminium is used. lead intentionally added for machining applications represents 0.6 g to 0.7 g per vehicle in total (i.e. 0.9%), resulting in the above 10 tonnes to 15 tonne of lead per year.

ACEA et al. (2020) state not to have sufficiently detailed data to calculate the worldwide use of lead in aluminium alloys in the scope of exemption 2(c)(i)

4.2 Justification for the requested exemption

4.2.1 Substitution of lead and roadmap towards substitution (ACEA et al. (2020))

ACEA et al. (2020) inform that some innovations regarding substitutes for “conventional” hard alloys containing lead (over 0.1 %) have been put on the market in the recent years. New alloy formulations for machining of Aluminium need to keep a low melting element. Tin (Sn) is commonly known as substitute. Bismuth (Bi) is also often mentioned but, in fact, its content stays in the same range as “non-Lead-free” alloys. Lead-free aluminium alloys are globally available and aluminium producers have developed lead-free alternatives with the aim of obtaining property ranges compatible with lead-containing alloys in use for any applications.

ACEA et al. (2020) point out that actual substitution requires that these lead-free alternatives meet the technical requirements for the specific automotive parts currently produced from alloys with higher lead content (0.1 – 0.4 %). The actual performances of substituting alloys need to be validated, not only in terms of intrinsic properties but also in functional behaviour, to ensure among others:

- machining properties;
- heat treatment options;
- corrosion resistance;
- strength;
- necessary material properties in the final product (e.g. durability / low friction);
- high safety standard (e.g. linked to part precision or corrosion resistance).

This need for validation, according to ACEA et al. (2020), is demonstrated by the number of parts used in car applications which are still based on aluminium alloys containing between 0.1 and 0.4 % lead. Moreover, some alloys have been developed more recently and need to be thoroughly evaluated by individual users against requirements for the specific parts (data cannot be shared for obvious confidentiality issues and evaluation needs to be realized for specific applications).

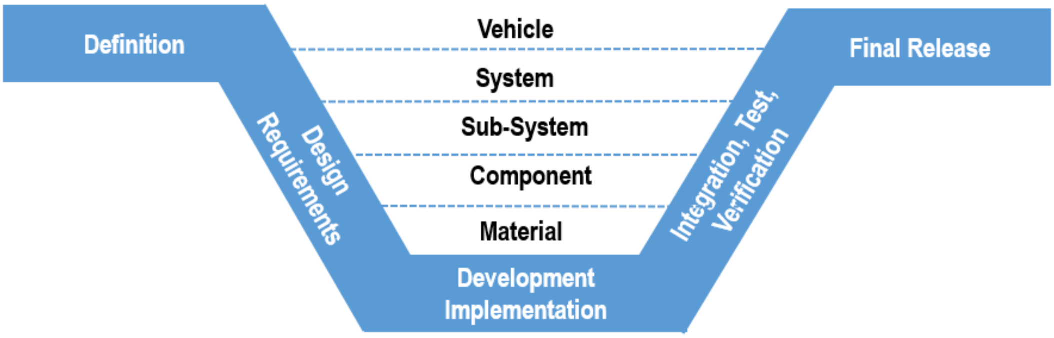
ACEA et al. (2020) describe that the starting point for the evaluation is the identification and confirmation for availability of a new material in samples from the material manufacturer (material sourcing with potential multi-sourcing requirements) and it ends at transition of the whole production to the new material. The usual steps include

- Materials characterization at coupon level (including ageing tests);
- Machining tests (mechanical behaviour, compatibility with machining fluids, durability of tools etc.);
- Product design (potential modifications to match properties of the alloy);

- Product validation (including bench testing at part or sub-assembly level as well as field testing).

ACEA et al. (2020) illustrate the above evaluation procedure in the figure below.

Figure 4-2: Development stages and levels from material to vehicle



ACEA et al. (2020) claim that the overall time to pass all development stages takes about 7 years, if using validated materials. This is only possible in case no general design loops are necessary, sufficient qualification capacity is available, and no new machining tools need to be bought. Depending on the tool complexity, lead time is up to two years delivery time which needs to be added to the total time frame.

Based on the above, ACEA et al. (2020) request the continuation of exemption 3 until end of 2027.

4.2.2 Substitution of lead (European Aluminium (2020))

European Aluminium (2020) state that lead-free aluminium alloys are readily available globally. The aluminium industry is ready to give any support its customers need to replace the lead-containing wrought aluminium alloys. However, to enable necessary validation and parts' development regarding functional and safety requirements, they understand that the automotive industry needs a phase out time and can support this if the objective is to completely phase out the lead-containing wrought aluminium alloys. They concede that they are not experts in the details of the development cycles and therefore prefer not to give a timeline.

They recommend, if the future goal is to reduce lead to a maximum of 0.1 % w/w for wrought alloys for machining purposes, to forego an intermediate step of 0.3 % because this would only double the costs of developments, as it would be necessary to start tests for new alloys. As modified old alloys are scientifically new alloys, new tests, and time would not be enough. So, from the wrought alloys for machining purposes producers' point of view, a reduction to 0.3 % in the 2(c)(i) exemption is pointless, and they suggest reducing directly to 0.1 %.

4.2.3 Elimination of lead

ACEA et al. (2020) mention that electronic functions or devices can replace mechanical systems and thus aluminium alloys in the scope of exemption 2(c)-I. Use of machining steel and copper alloys can also be used in some cases instead of aluminium alloys.

4.2.4 Environmental arguments

ACEA et al. (2020) are not in favour of substitution of lead with bismuth since it would not result in clear environmental benefit.

4.3 Critical review

4.3.1 Substitution of lead and roadmap towards substitution

The consultants understand that the use of lead in aluminium in the scope of exemption 2(c)-I is no longer unavoidable and that the exemption can expire. ACEA et al. state that seven years would be required once materials are validated, which, according to European Aluminium (2021), is finalized around two years after registration of an alloy. To obtain better insights into when these periods could have begun, EA was asked when the last lead-free aluminium alloys relevant for this exemption became available.

European Aluminium (2021) reference the Aluminium Teal Sheet which lists the year of registration for each alloy. Between 1993 and 1999, four alloys only were registered. From 2000 to 2006, 17 new alloys were registered. Four new alloys were registered from 2016 to 2020.

Both ACEA et al. and EA had highlighted that the new alloys had become available recently which pave the way to lead phase out. The last ones of the four registered since the last review of this exemption became available in 2017 and 2020.

Table 4-1: Year of registration of lead-free aluminium alloys

Alloy No.	Date
2012	1993
2111	1993
6020	1995
6012A	1999
6021	2000
2007A	2001
2111A	2001
2111B	2001
6023	2001
6033	2002
6040	2002

Alloy No.	Date
2007B	2006
2028C	2006
2041	2006
2044	2006
2045	2006
6028	2006
6041	2006
6043	2006
6026LF	2016
6050	2016
2033	2017

6065	2005	2077	2020
6262A	2005		

Source: Aluminium Teal Sheet in European Aluminium (2021)

Taking into account the provided information and in the light of the above registration dates of lead-free alloys since the last revision of exemption 2(c)-I, it is plausible that the validation of the possibly crucial lead-free alloys could only be started in 2017 and 2020. The expiry of the exemption end of 2027 would then be in line with these dates.

In principle, the scope of exemption 3 could be restricted prior to its expiry end of 2027, either by reducing the maximum lead content of the aluminium alloys in the scope of the exemption, or by trying to exclude parts from the exemption scope for which substitution of lead was already successful.

EA request to avoid interim reduction steps, and ACEA et al. put forward that the alloys up to 0.4 % of lead are used in parts which are not yet converted to lead-free ones. Taking into account these pieces of information, and the perspective that the exemption expires instead of setting a new review date, the consultants recommend following EA's request.

4.3.2 Elimination of lead

ACEA et al. (2020) mention that electronic functions or devices can replace mechanical systems and thus aluminium alloys in the scope of exemption 2(c)-I. Machining steel and copper alloys can also be used in some cases instead of aluminium alloys.

Machining steel and copper alloys contain lead as well. These uses of lead are exempted in exemptions 1(c) and 3 of ELV Annex II. They are thus no alternative to speed up the avoidance of lead in aluminium alloys so that an earlier expiry of exemption 2(c)-I could be realistic. The latter also applies to the dematerialization approach. It cannot be applied to make obsolete so that the need for aluminium alloys persists, even though in lower volumes.

4.3.3 Environmental arguments and socioeconomic impacts

ACEA et al. (2020) do not see environmental benefits from the use of bismuth and therefore do not prefer bismuth-containing lead-free aluminium alloys. They do not explain how they arrive at this statement concerning the environmental side of bismuth but mention that in the context of new aluminium alloy exemptions, *"[…] Bismuth (Bi) is also often mentioned but, in fact, its content stays in the same range as "non-Lead-free" alloys."*

ACEA et al. do not raise the above or other environmental arguments related to bismuth as a reason to maintain exemption 2(c)-I. Overall, it seems that bismuth is used anyway. For these reasons, the consultants did not follow up these aspects.

4.3.4 Conclusions

Article 4(2)(b)(II) provides that an exemption can be justified if the use of a restricted substance is unavoidable.

ACCEA et al. state that they still require leaded aluminium alloys until end of 2027 to allow the various vehicle manufacturers to test and qualify lead-free alloys for remaining parts which could not yet be produced with lead-free aluminium alloys.

The last lead-free alloys which are relevant to avoid lead in aluminium completely have become available in 2019 and 2020. In the absence of contradictory information and experiences and given the support of EA as a stakeholder for this transition, the consultants recommend to continue the exemption 2(c)-I until end of 2027. A restriction of the lead content to less than 0.4 % prior to the exemption expiry is technically impracticable and, according to EA, not advisable. They plead for a single reduction step down to 0.1 % of maximum lead content.

4.4 Recommendation

ACEA et al. are on the way to avoid the use of lead completely until end of 2027. In the light of the available information, and in the absence of contradictory information, this transition period seems plausible. In the parts still to be produced from lead-free alloys until 2028, aluminium alloys with 0.4 % of lead are still used. Granting the exemption as requested in the consultants' view would thus be in line with the stipulations of exemption 4(2)(b)(II). The consultants recommend to continue the exemption with the current wording and the below scope and expiry date:

	Materials and components	Scope and expiry date of the exemption	
2(c)(i)	*Aluminium alloys for machining purposes with a lead content up to 0,4 % by weight*	*Vehicles type-approved before 1 January 2028 and spare parts for these vehicles*	

4.5 References

ACEA et al. (2020): Request for continuation of exemption 2(c)-I of Annex II of the ELV Directive. Answers to the consultation questionnaire. Unter Mitarbeit von ACEA, CLEPA, JAMA, KAMA. Online verfügbar unter http://www.elv.biois.eu/ACEA_2ci.pdf.

European Aluminium (2020): Answers to the consultation questionnaire. Online verfügbar unter http://www.elv.biois.eu/European_Aluminium.pdf.

European Aluminium (2021): Answers to questionnaire 2, sent via e-mail by Eva Tormo, European Aluminium, to Dr. Otmar Deubzer, UNITAR.

5 Exemption 3 of ELV Annex II: Lead in copper alloys

The exact wording of this exemption is as follows:

Copper alloys containing up to 4 % lead by weight

Declaration

The sections preceding the "Critical review", the phrasings and wordings of applicants' and stakeholders' explanations and arguments have been adopted from the documents they provided as far as required and reasonable in the context of the evaluation at hand. Formulations were only altered or completed in cases where it was necessary to maintain the readability and comprehensibility of the text.

Acronyms and definitions

Bi	bismuth
C36000	CuZn39Pb3
Cu	copper
Eco Brass	CuZn21Si3P (JIS C6931, C6932, CAC804; CDA C69300, C69310, C87850, C87870; EN CW724R, CB768S)
ECV	electronic control valve
MMC	Mitsubishi Materials Corporation
Pb	lead
Sn	tin
Zn	zinc

5.1 Background and technical Information

The above exemption has become due for review. Two answers were received to the consultation questionnaire:

3) ACEA et al. (2020) claim that the unlimited exemption concerning leaded copper alloys is still required and that the maximum lead content in these alloys must remain at 4 % by weight. Moreover, they a review time for this exemption in eight years.
4) MMC (2020) claim that they have developed two types of lead-free copper alloys and present automotive application examples for one of them. They admit that as material makers they do not know all automotive applications of leaded copper alloys. Therefore, MMC (2021b) request the exemption to be continued for limited applications only where substitution is truly impracticable.

5.1.1 Summary of the stakeholder contributions to the consultation

ACEA et al.

According to ACEA et al. (2020), leaded copper alloys are still widely used in the automotive industry, mainly for the manufacturing of very small parts, e.g. electrical and electronic equipment, valve elements, joint elements, bushing, etc. In particular, the high machinability, associated to the optimal chip breaker effect of lead, the high conductivity and the intrinsic lubricant effect from lead, are some of the main reasons why leaded-copper alloys are used.

ACEA et al. (2020) report that several promising lead-free copper alloys have been recently developed, and in some cases even commercialized. Based on the current knowledge, it is not possible to identify a lead-free copper alloy or a group of lead-free copper alloys that could potentially substitute leaded-brasses and copper alloys in all their applications fields. For example, some new alloys might be able in the future to substitute copper alloys with relatively low amount of lead (e.g. up to 0.8 % by weight) for what concerns the machinability and the mechanical and corrosion properties, but no alternative currently exists for emulating the internal lubricant effect of leaded alloys. Also, a very limited number of literature studies have so far taken into account the recyclability aspects of new-developed lead-free copper alloys and their overall environmental and circular economy-related impacts. From this point of view leaded-copper alloys, having a very good “acceptance” in the copper recycling loop, not requiring a dedicated recycling stream and being produced with very high fraction of secondary material, are difficult to replace obtaining lower environmental impacts.

ACEA et al. (2020) state that if new lead-free copper alloys able to fully substitute leaded-alloys will be available on the market, many years will still be needed by the automotive industry to re-design, test, validate and produce new components made of these alloys and therefore claims that exemption 3 is still required in its current scope and wording. ACEA et al. (2020) request a review time for this exemption of 8 years.

Mitsubishi Materials Corporation (MMC)

MMC (2020) has developed two different lead-free copper alloys, GloBrass and ECO BRASS. ECO BRASS has been processed into approximately 15 billion components that have been installed in approximately 100 million cars by now, and about half of them have been used for five or more years under various environments allowing ECO BRASS to earn high reliability as a material in terms of strength, corrosion resistance, durability and some other characteristics. ECO BRASS exhibits higher strength, better wear resistance, creep properties, and corrosion resistance than the conventional material containing 3 % of lead so that MMC (2020) presumes that thickness and weight of components can be reduced with ECO BRASS. MMC (2020) believes that lead-free and lighter components can reduce various loads imposed on the environment. ECO BRASS scraps are separated and managed, then collected for recycling without confusion.

By selecting appropriate machining methods and conditions, MMC (2020) says, ECO BRASS provides almost the same level of productivity, tool life, dimensional precision, and surface quality as C36000. MMC (2020) further on developed, a new, lead-free free-cutting brass called GloBrass, which has different composition, metal structure, and properties from of ECO BRASS so that MMC (2020) is certain that the range of applications of Pb-free alloys will expand now that GloBrass is available in addition to ECO BRASS.

Although MMC (2021b) wishes the revocation of the exemption, it requests a partial continuation, i.e., continuation of the exemption for limited applications. As a material maker, we MMC (2021b) thinks that it is possible to replace leaded copper alloys with lead-free counterparts in many applications in the automobile field admitting, however that it does not know about all the existing auto parts. Therefore, if the exemption is to continue, it is reasonable to allow application of the exemption only where substitution is truly impracticable.

5.1.2 History of the Exemption

Since the publication of the ELV Directive, exemption 3 has been listed in Annex II with the above mentioned wording. It was reviewed in 2009/2010 and 2015/2016 by Zangl et al. (2010) and Gensch et al. (2016) respectively. Zangl et al. (2010) had recommended the continuation of the exemption for five years to leave industry time to further develop lead-free solutions, among others one of the materials which MMC presents now as well.

In the last review in 2015/2016, ACEA et al. claimed that none of the tested lead-free machining alloys was able to fulfil the diverse set of minimum requirements. Gensch et al. (2016) concluded that the use of up to 4 % lead in copper alloys is still unavoidable in a number of components but starting points for substitution exist especially for components with an already low lead content. The overall picture where substitution efforts are promising was, however, not clear enough to narrow the exemption scope. Thus, Gensch et al. (2016) recommended the continuation of the exemption with the current scope and wording and another review in five years to allow monitoring developments in the potential for substitution and to clarify that the increased use of electrical applications within vehicles does not lead to an unjustified increase in the use of leaded copper alloys, and to identify lists of components or categories of applications for lead reduction or substitution. Exemption 3 was actually continued with the same wording and became due for review in 2021.

5.1.3 Technical description of the exemption and use of restricted substance

ACEA et al. (2020) report that leaded copper alloys are still widely used in the automotive industry, mainly for the manufacturing of very small parts (e.g. electrical and electronic equipment, valve elements, joint elements, bushing, etc.) that require very particular properties. In particular, the high machinability, associated to the optimal chip breaker effect of lead, the high conductivity and the intrinsic lubricant effect caused by lead, are some of the main reasons why leaded-copper alloys are used. In the last years, the use of leaded copper alloys has been strictly limited to the applications where no other technically viable solution could be found. As demonstrated by the revised 2020 leaded-copper inventory, also the number of automotive parts and the amount of lead per car included in copper alloys has appreciably decreased since 2014.

ACEA et al. (2020) explain that lead as an alloy element is usually added to copper and copper alloys for the following reasons:

- It improves their machinability, with regards to excellent chip breakage, low tool wear and high applicable cutting parameters;
- It improves their castability;
- It improves the surface quality of the parts being machined[5];
- It increases their electrochemical stability and thus their resistance to harsh corrosive environments:
- It improves the surface adaptability of components made of copper and its alloys, due to the superficial plastic deformation of its nodules. This results in a better contact and adhesion between different components, fundamental for example in the field of electrical connectors.

According to ACEA et al. (2020), by far the most used leaded copper alloys are leaded brasses (copper-zinc alloys). Other leaded copper alloys are leaded nickel-silver alloys, leaded bronzes[3] and some special alloys.

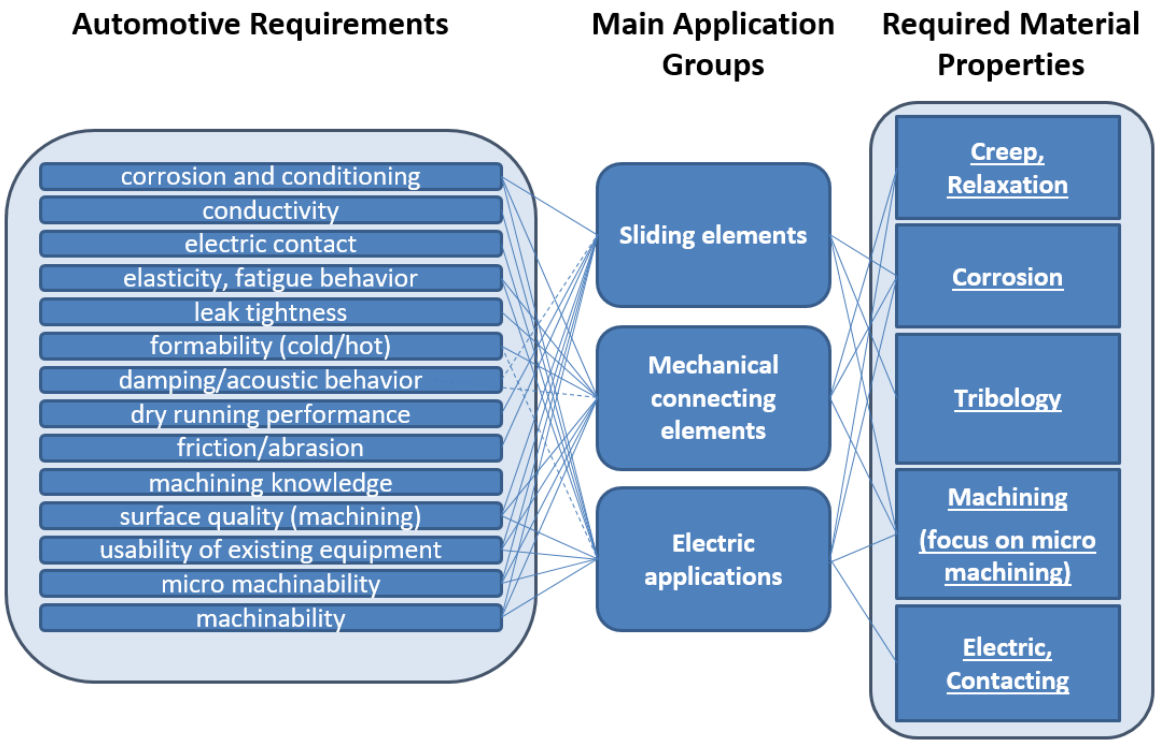
ACEA et al. (2020) describe the main applications of leaded brass in the automotive industry divided in following groups:

- Sliding elements, such as valve guides, bearing shells, clutch, door locks, etc.;
- Mechanical connecting elements, such as fittings for fuel feed injection systems, bearings, etc.;
- Electric applications, that include battery clamps, connectors pins, cables, etc.

Figure 5-1 illustrates the correlation of these three groups with automotive requirements and required material properties.

[3] e.g. copper-tin

Figure 5-1: Correlation between main application groups of leaded copper brasses and automotive and material requirements



Source: ACEA et al. (2020)

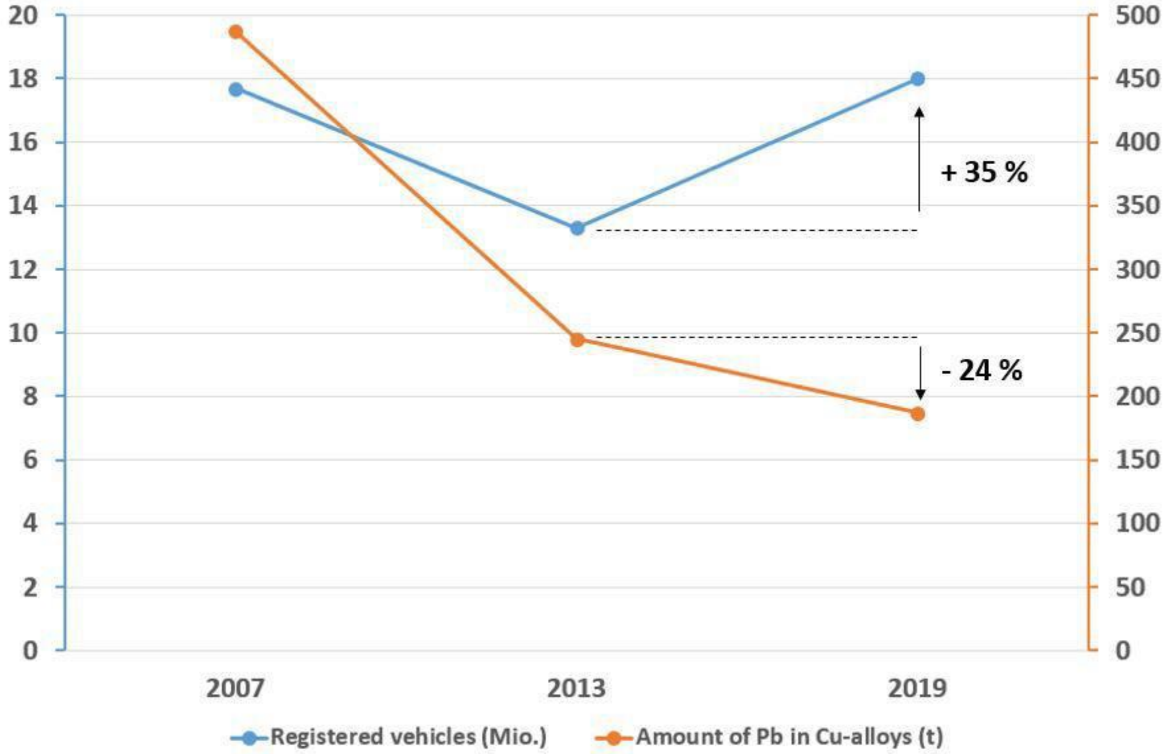
Further technical details are described by Zangl et al. (2010) and Gensch et al. (2016).

5.1.4 Amount of lead used under the exemption

ACEA et al. (2020) present the below Figure 5-2 and state that 187 t of lead were used under exemption 3 in the EU28 + EFTA[4] in 2019.

[4] European Free Trade Association: Iceland, Liechtenstein, Norway, Switzerland

Figure 5-2: Number of vehicles and amounts lead used under exemption 3 in the EU28+EFTA



Source: *ACEA et al. (2020)*

ACEA et al. (2020) substantiate this figure stating that 18,003,571 new cars and light commercial vehicles (categories M1 and N1) were registered within the EU28+EFTA, from which 3.0 % were electric. Taking into account the consumer demands per segment, similarly to what was done in 2014, ACEA et al. (2020) declare 80 % of these vehicles to be considered as standard models, whereas 20 % can be assimilated into fully equipped models. ACEA et al. (2020) combine that above vehicle market share with the outcome of the 2020 European copper inventory.[5]

ACEA et al. (2020) point out that although the number of vehicles sold in the EU in 2019 is higher than in 2013 and 2009, the corresponding total amount of lead brought on the market through the vehicles and included in copper alloys has significantly decreased in the last few years. ACEA et al. (2020) do not have sufficiently accurate data to calculate or estimate the worldwide volumes of lead in copper alloys used in vehicles.

[5] According to ACEA et al. 2020, an assessment among ACEA and joint automotive associations members to calculate average amounts of leaded-copper alloys in three car models: a best-selling standard model, a fully equipped high-end model, an electric model, if available. ACEA et al. followed a similar approach in 2014 so that the figures should be comparable.

5.2 Justification of the requested exemption by ACEA et al.

5.2.1 Decreasing volumes of lead from copper alloys in vehicles

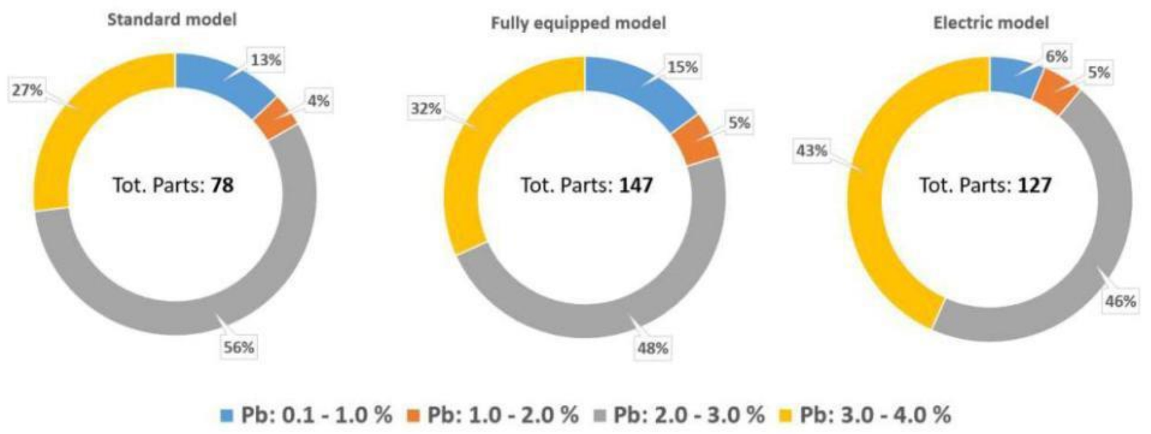
ACEA et al. (2020) invested a high amount of money and resources in looking for solutions to possibly substitute or at least reduce the amount of lead in copper alloys. These activities include the analysis of the most recent literature studies on lead-free copper alloys, the characterization of new promising lead-free copper alloys, still ongoing, the testing of components made of lead-free copper alloys and the generation of a new inventory evaluating the current use of leaded copper in the European automotive industry.

ACEA et al. (2020) report that the 2020 leaded-copper inventory is the result of an assessment among ACEA and the joint automotive associations members and aimed to calculate the average amount of leaded-copper alloys in the following three car models:

- a best-selling standard model;
- a fully equipped high-end model;
- an electric model, if available.

In addition, ACEA et al. (2020) want to use the inventory to identify the automotive parts that contribute the most to the total amount of lead as part of copper alloys and to find out how this amount changed in comparison with the results of the last automotive leaded-copper alloys inventory carried out in 2014. ACEA et al. (2020) interpret Figure 5-3 stating that the average number of parts made of leaded-copper alloys per car resulted higher in fully equipped models (147) than in electric models (127) and in standard best-selling models (78).

Figure 5-3: Number of leaded-copper alloy parts and their split based on lead-content for each of the three vehicle models taken into account

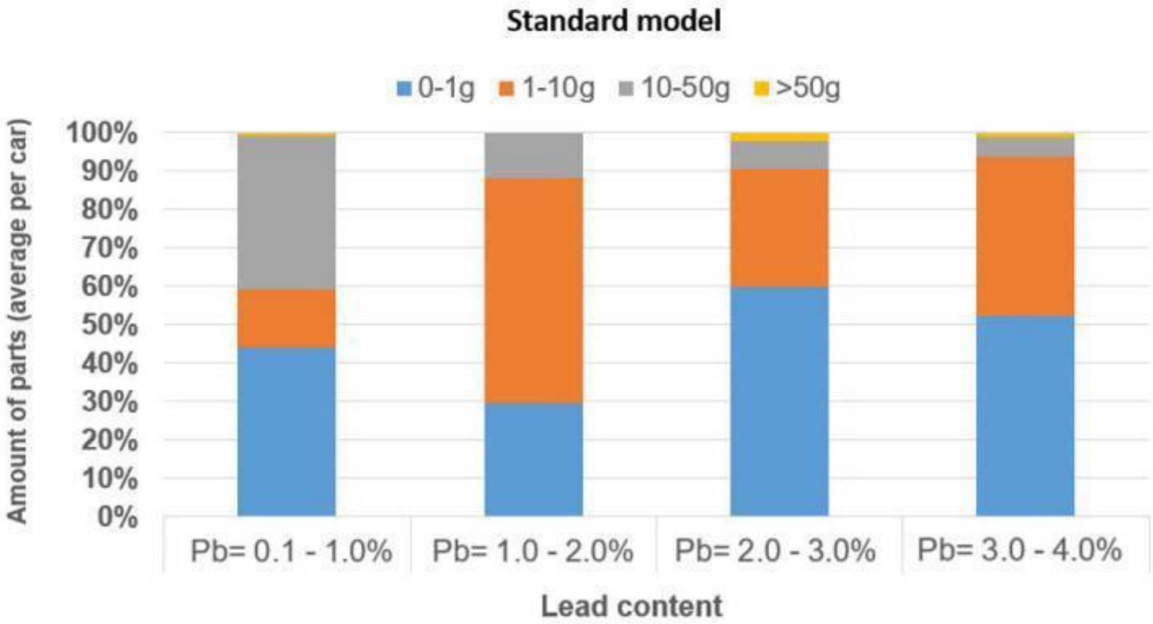


Source: ACEA et al. (2020)

For all three model types, ACEA et al. (2020) indicate that more than 80 % of the leaded-copper alloy parts (and almost 90 % in case of the electric models) contain an amount of lead between 2.0 % and 4.0 % by weight.

Furthermore, ACEA et al. (2020) explain, Figure 5-4 shows for the standard models, confirmed by the findings related to the high-end and electric models, that roughly 90 % of the parts with a lead content between 2.0 % and 4.0 % by weight have a weight lower than 10 g.

Figure 5-4: Average amount of leaded-copper alloy parts, expressed in percentage, in standard vehicle models and their split based on lead-content and weight

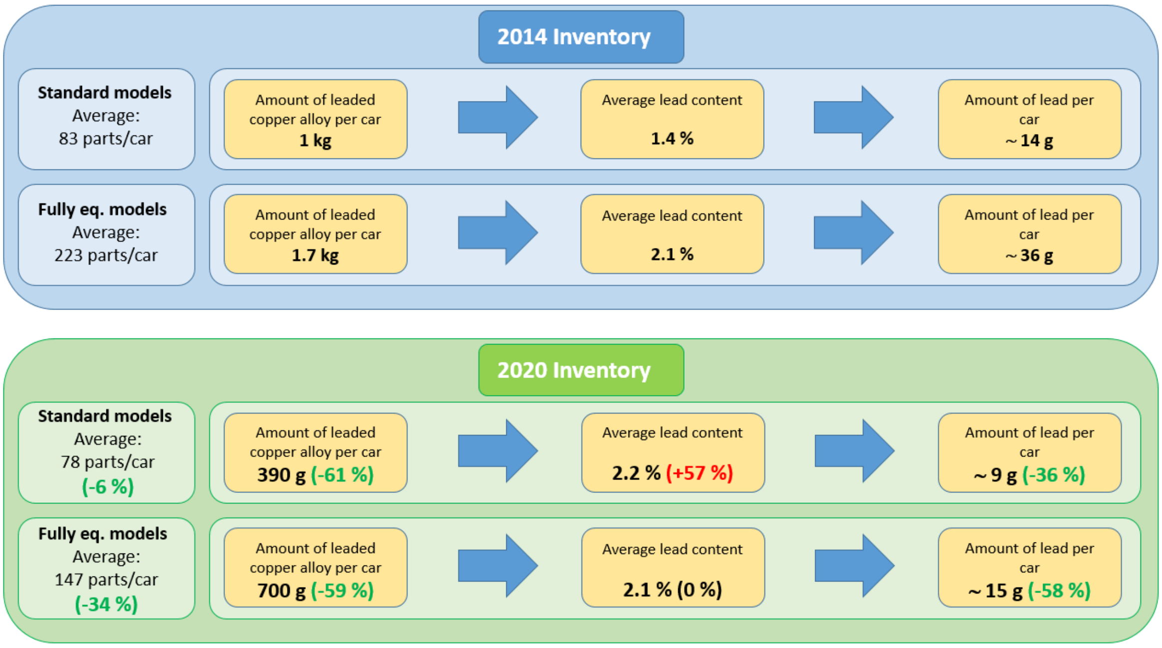


Source: ACEA et al. (2020)

ACEA et al. (2020) see this as confirmation that the smallest parts, which require a high dimensional accuracy and therefore a high machinability, still need a relatively high amount of lead to make this happen.

Referring to Table 5-1, ACEA et al. (2020) state that compared to 2014, in 2020 the average number of components containing leaded-copper alloys per car has decreased for both the standard best-selling models and the fully equipped ones (electric models were not taken into account in 2014). Similarly, the average total amount of leaded copper alloys per car has substantially decreased, of about 60 %, for both standard and equipped models. The same trend has been observed for the total amount of lead included in copper alloys per car, which showed an average reduction of 36 % for standard vehicle models and of 58 % for fully equipped models.

Table 5-1: Comparison between the outcome of the 2014 and the 2020 leaded-copper alloys inventory



Source: ACEA et al. (2020)

ACEA et al. (2020) point out the fact that the average number of leaded-copper components has decreased at a lower rate than the amount in grams of leaded copper alloys per car suggests that relatively big/heavy components have been removed from 2014 to 2020. The absence of these components, together with the large number of very small parts containing a relatively high amount of lead, caused the average lead content per part to increase from 1.4 % in 2014 to 2.1 % in 2020.

Finally, ACEA et al. (2020) point out that although its many excellent physical and chemical properties, copper has a high specific gravity, approximately 230 % higher than that of aluminium, and it is much more expensive than aluminium and steel. For these reasons, and especially in the automotive sector where costs and weight are particularly important, copper and its alloys are selected and used only when it is strictly necessary.

5.2.2 Substitution of lead

Characterization and machinability of lead-free copper alloys

ACEA et al. (2020) say that currently, there are only a few standardized lead-free copper alloys, whose composition is regulated by the following four European Standards. Table 5-2lists both the lead-free the standardized copper-zinc alloys and those that are commercially available with a lead content lower that 0.1 % w/w.

- EN 12163:2016 - Copper and copper alloys - Rod for general purposes
- EN 12164:2016 - Copper and copper alloys - Rod for free machining purposes
- EN 12165:2016 - Copper and copper alloys - Wrought and unwrought forging stock

- EN 1982:2017 - Copper and copper alloys - Ingots and castings

Table 5-2: Nomenclature and types of lead-free European standardized brasses and of brasses commercially available in a lead-free version

Standard	Material designation		Lead amount (% by weight)		Remarks
	Symbol	Number	Limit	Value	
EN 12163:2016	CuZn5 CuZn10 CuZn15 etc.	CW500L CW501L CW502L etc	-	-	Not machinable
EN 12163:2016 EN 12164:2016 EN 12165:2016	CuZn40	CW509L	Min. Max.	- 0.20	commercially available also with a lead content below 0.1% w/w
	CuZn42	CW510L	Min. Max.	- 0.20	
	CuZn38S	CW511L	Min. Max.	- 0.20	
EN 12163:2016 EN 12164:2016	CuZn21Si3P	CW724R	Min. Max.	- 0.10	
EN 12165:2016	CuZn37	CW508L	Min. Max.	- 0.10	
EN 1982:2017	CuZn38Al-B	CB767S	Min. Max.	- 0.10	
	CuZn38Al-C	CC767S			
	CuZn42Al-B	CB773S			
	CuZn42Al-C	CC773S			
	CuZn21Si3P-B	CB768S			
	CuZn21Si3P-C	CC768S			

Source: ACEA et al. (2020) CuZn21Si3P: Eco Brass

ACEA et al. (2020) mention several studies showing that lead-free copper alloys are more difficult to machine than lead-free ones. They reference, for example, Nobel et al.[6], who analysed the effect of microstructure and silicon as alternative alloying element of commercially available lead-free brass alloys, and they investigated various approaches for machinability enhancement in order to enable high performance cutting operations, particularly for mass production. The machinability of lead-free brass alloys CW508L, CW511L and CW510L as well as silicon alloyed special brass CW724R were investigated and compared to the machinability of leaded brass CW614N. Table 5-3 shows their chemical composition.

6 Christoph Nobel, Fritz Klocke, Dieter Lung, Sebastian Wolf, Machinability Enhancement of Lead-Free Brass Alloys, 6th CIRP International Conference on High Performance Cutting, HPC2014, 2014; source as referenced by ACEA et al. 2020

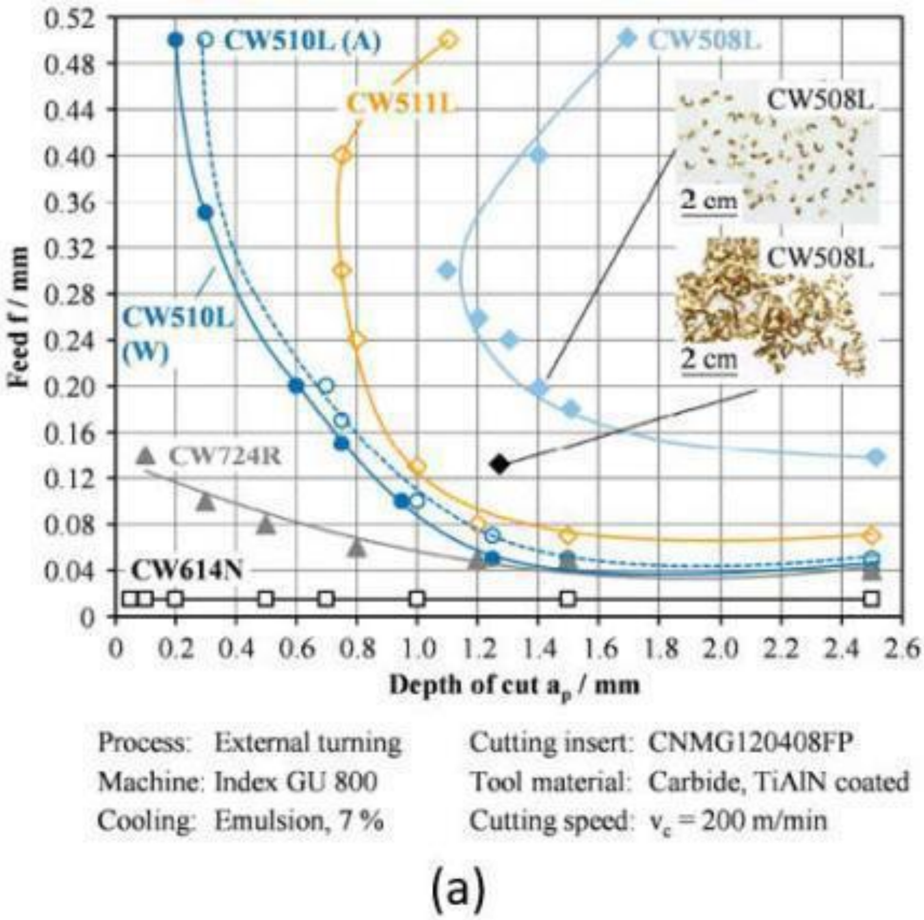
Table 5-3: Chemical composition of assessed copper alloys

Material	Cu	Zn	Pb	Si	As	P
CW724R	75.86	≈ 21	0.02	3.4	-	0.05
CW508L	62.97	≈ 37	0.01	-	-	-
CW511L	≈ 62	≈ 38	≈ 0.18	-	≈ 0.07	-
CW510L (A)	57.38	≈ 42	0.07	-	-	-
CW510L (W)	57.76	≈ 42	0.18	-	-	-
CW614N	57.61	≈ 39	3.32	-	-	-

Source: ACEA et al. (2020)

According to ACEA et al. (2020), the study showed that, in comparison to the leaded brass CW614N, longer chips were formed, as shown in the below Figure 5-5, higher cutting forces and temperatures were generated and higher abrasive and adhesive tool wear was caused.

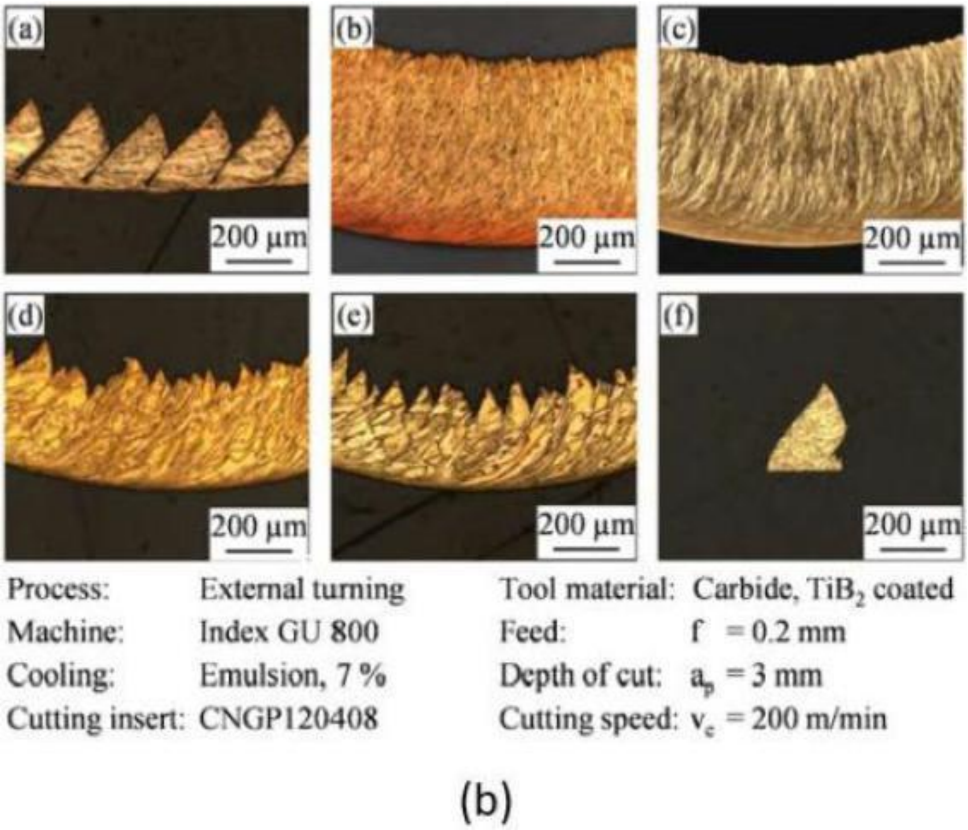
Figure 5-5 a: Chip breakage of brass alloys depending on feed and depth of cut (also see Figure 5-5 b)



Source: ACEA et al. (2020)

ACEA et al. (2020) state that in comparison to lead-free brasses, silicon alloyed special brass CW724R showed an improved machinability in terms of better chip breakage and lower thermo- mechanical tool load, however, it caused higher flank wear due to its abrasive κ-phase. ACEA et al. (2020) add that analogous results were found also during a study performed by the RWTH University of Aachen.

Figure 5-5 b: Mechanisms of chip formation when turning (a) CW724R; (b) CW508L; (c) CW511L; (d) CW510L (A); (e) CW510L (W); (f) CW614N



Source: ACEA et al. (2020)

ACEA et al. (2020) compared several mechanical, chemical, electrical conductivity, and machinability-related properties of three commercial lead-free brass alloys (EcoBrass (Cu724R), CuZn42, CuZn38As) with those of the free-cutting leaded brass CuZn39Pb3 (CW614N). From the results of this analysis, summarized in Table 5-4, they conclude that that clearly none of the considered lead-free brasses can completely replace leaded-brass alloys for any of their main automotive applications groups (c.f. Figure 5-1 on page 31).

Table 5-4: Summary of the analysis of several properties of lead-free brass alloys in comparison with a reference free-cutting leaded brass CuZn39Pb3

	compared to CuZn39Pb3		
material requirements	**CuZn21Si3 EcoBrass®**	**CuZn42**	**CuZn38As**
tensile strength at 150°C	M	M	M
relaxation fittings (130°C)	M	M	M
wear of copper disc	S	S	S
adhesion	M, S	M, S	M, S
friction coefficient	M, S	M, S	M, S
relaxation el. contacts	E	E	E
machinability (incl. surface quality)	M, S, E	M, S, E	M, S, E
el. conductivity	E	E	E
galvanic corrosion	M, S, E	M, S, E	M, S, E
stress corrosion cracking	M, E	M, E	M, E
+ additional for small parts (micro machining)			
drilling time	M, S, E	M, S, E	M, S, E
tool life	M, S, E	M, S, E	M, S, E
tool force	M, S, E	M, S, E	M, S, E

	relevant for:
S	sliding elements
M	mechanical connecting elements
E	electric applications

better	(green)
similar	(yellow)
worse	(red)
not tested	(white)

Source: ACEA et al. (2020)

ACEA et al. (2020) report that in addition to the analysis of the behaviour and the machinability of commercially available lead-free brass alloys, efforts have been also made for developing and characterizing new lead-free alloys.

ACEA et al. (2020) mention as one example the recently developed AquaNordic▫ lead-free copper alloy from which report good anticorrosion properties and machinability with significantly improved environmental performance and lower price levels than competing products. The machinability of the AquaNordic alloy has been recently characterized and compared with that of a standardized leaded-brass, CW625N (1.5 % Pb), and that of standardized lead-free brass, CW511L. The AquaNordic brass has the same composition as the CW511L alloy but it contains ceramic inclusions in its microstructure.

According to ACEA et al. (2020), the analysis demonstrated that the CW625N alloy generates significantly lower cutting forces during the turning test than the other two alloys, CW511L, and AquaNordic due to the lubricating effect of lead globules in the cutting zones. Although the cutting forces are significantly higher compared to those of the leaded alloy, the author of the respective study claims that the chip formation of the AquaNordic brass showed promising character compared to CW511L and that the AquaNordic alloy might be a substitute of leaded brass from the point of view of the machinability. There were, however, indications suggesting that lead-free brass alloys are more sensitive to changes in cutting parameters (e.g. cutting speed) than leaded brasses.

ACEA et al. (2020) regard as another example the recent development of novel lead-free copper alloys for oil-hydraulic applications as bushings, slippers or distributor plates, carried out by the company Otto-Fuchs[7]. According to the study that Otto-Fuchs published, these alloys showed a good machinability behaviour as well as good mechanical properties and compatibility with biolubricants (e.g. esters, PAOs, PAGs) that would allow them to be good candidates for substituting leaded-copper alloys in hydraulic applications. It shall be however noted, that the alloys described in the study aim to substitute leaded-alloys with a relatively low lead-content, not exceeding 0.8 % by weight.

ACEA et al. (2020) report about another lead-free brass which the American company Aviva Metals has recently developed mainly for plumbing and drinking-water-related applications. According to its developer, this Aviva Model 3™ free machining alloy, containing less than 15 % by weight of zinc and tellurium in an amount between 0.3 and 0.9 % by weight, offers very good machinability, high conductivity and excellent dezincification-resistant properties. ACEA et al. (2020) do not currently have specific experience or knowledge about this alloy and are not aware of any automotive applications for which the Aviva Model 3 alloy is in use or for which its use has been considered. Even though some tests performed by Aviva Metals revealed that the Aviva Model 3 does not negatively contaminate leaded brasses during their recycling and production, the possible negative embrittlement effect of tellurium and its overall environmental impact have still not been completely analysed.

ACEA et al. (2020) themselves characterized another two lead-free copper alloys:

- CuSi4Zn9MnP (wrought alloy)
- CuSn4Zn2PS-C (casting alloy)

ACEA et al. (2020) did an initial screening where their tribology, stress corrosion cracking, galvanic corrosion and electrical conductivity were analysed and compared with those of the CuZn39Pb3 alloy (CW614N) as reference. They summarize the overall results as follows:

- The reference alloy CuZn39Pb3 has higher electrical conductivity than CuSi4Zn9MnP and CuSn4Zn2PS-C. This is due to the chemical composition of the materials: Si, Mn, P and Sn produce a higher decrease of the electrical conductivity of the copper than lead.
- The stress corrosion cracking test, performed according to the DIN 50916-1 in an ammonia solution (concentration 12,5 %; temperature 23 °C) for 24 hours, showed that the two lead-free copper alloys, in contrast to reference leaded alloy, are not sensitive to this type of corrosion. This is due to their chemical composition and to the fact that their microstructure is free from any zinc-rich phase.

[7] B. Reetz, T. Münch, Challenges for novel lead-free alloys in hydraulics, 12th International Fluid Power Conference, Dresden, 2020.

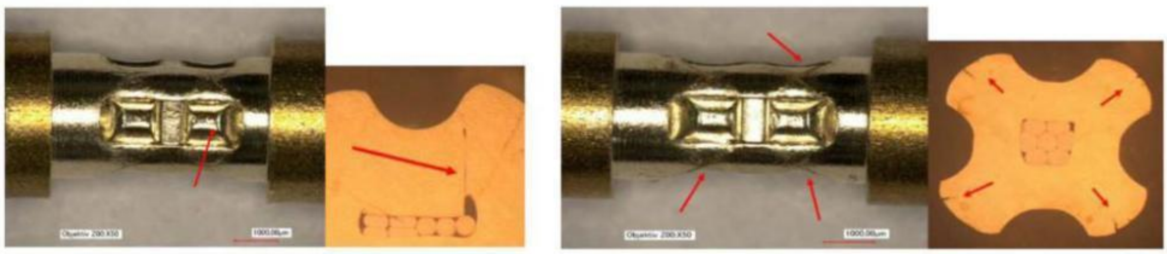
- In general, all three alloys provoked the galvanic corrosion of the Al-based anode, but the galvanic corrosion performances of the two lead-free copper alloys, evaluated against an AlSi9Cu3 alloy and in 5 % NaCl at room temperature, were slightly better than those of the reference leaded-alloy, probably due to the positive effect of Si, Sn and Mn.
- During the tribology characterization, the reference leaded-alloy copper alloy showed a coefficient of friction similar to that of CuSi4Zn9MnP and significantly lower than that of CuSn4Zn2PS at both loads of 5 N and 15 N.
- Nevertheless, the wear behaviour of the lead-free copper alloys resulted significantly better than that of the reference leaded alloy (Figure 11).

ACEA et al. (2020) conclude that, due to the promising first laboratory results showed by the two selected lead-free copper alloys during this first screening, ACEA et al. (2020) planned to further analyse them, evaluating in particular their corrosion behaviour, their warm forming performances and their ability to be machined and drilled.

Testing of component samples manufactured from lead-free copper alloys

ACEA et al. (2020) report several attempts aiming to substitute leaded-copper alloys in real components in the last few years by different stakeholders of the automotive and of the electric and electronic industry. In all the known cases where lead-free copper alloys were evaluated as potential substitutes of leaded-copper alloys, the produced components failed in fulfilling the needed requirements. They present several examples of such failed components.

Figure 5-6: Crimp connection made of CuZn42 with cracks



Source: ACEA et al. (2020)

Figure 5-7: Knurl made from CuZn42 with sharp edges and broken material

Source: *ACEA et al. (2020)*

Figure 5-8: Knurl pressed on a component made of CuZn39Pb3 (left) and two knurls pressed on CuZn21Si3P* with loose particles (right)

Source: *ACEA et al. (2020)* *ECO Brass

ACEA et al. (2020) further report a recent investigation aiming to substitute a leaded-brass JIS C3604 currently used for a tire valve. The lead-free alloys taken into account were three different bismuth-based alloys, named BZ-5U, BZ-5A and BZ-3N.[8] In the first part of the

[8] San-Etsu Metals, BZ series of bismuth-based lead-free brass rod with full compliance with ELV/RoHS, https://www.sanetu.co.jp/en/products/; source investigated by the consultants

study, the adhesion of the rubber part onto a stem made of BZ-5U alloy was evaluated. In the test, the bismuth-based lead-free brass performed worse than the leaded-brass. Figure 5-9 shows the details of the evaluated part and the pictures of the tire valve stems after the rubber adhesion test.

Figure 5-9: Tire valve with TPMS produced from leaded (C3604) and unleaded brass (BZ-5U) after rubber adhesion test

Material		n	Lead free brass BZ-5U (※1) (Bismuth alloy)	Judgment	Leaded brass C3604 (Current)
Adhesion	Chemical Resistance ($10\%CaCl_2 \times 80°C \times 168h$ →Test)	5	27% Min. 	×	47% Min. 
	Acid Resistance ($0.2\%H_2SO_4 \times 168h$ →Test)	5	65% Min. 	×	83% Min. 

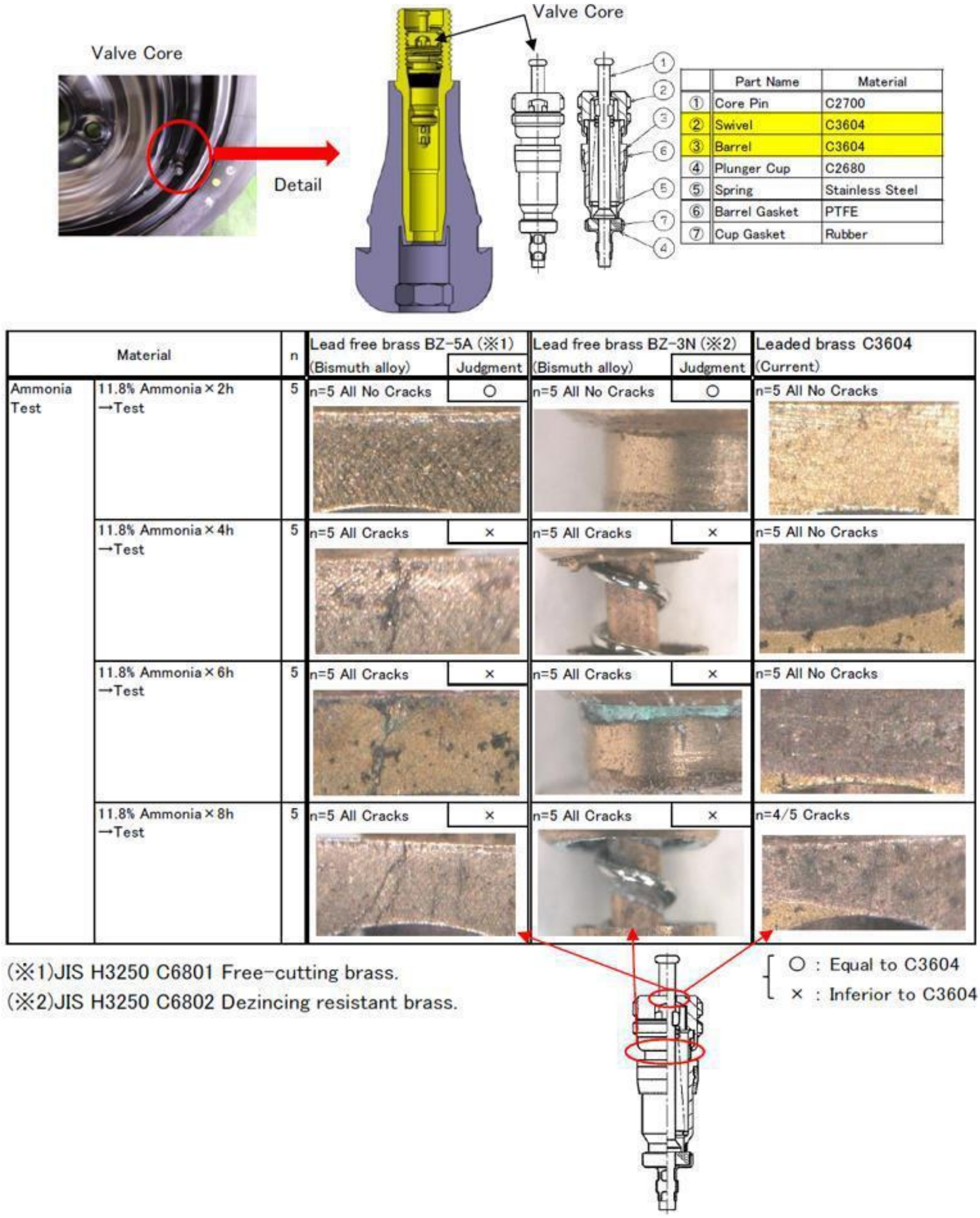
Material		n	Lead free brass BZ-5U (※1) (Bismuth alloy)	Judgment	Leaded brass C3604 (Current)
Adhesion	Chemical Resistance ($10\%CaCl_2 \times 80°C \times 168h$ →Test)	5	27% Min. 	×	47% Min. 
	Acid Resistance ($0.2\%H_2SO_4 \times 168h$ →Test)	5	65% Min. 	×	83% Min. 

Source: *ACEA et al. (2020)*; TPMS: Tire pressure monitoring system

In the second part ACEA et al. (2020) evaluated valve cores made of the reference leaded brass and of the bismuth-based lead free brasses BZ-5A and BZ-3N. The parts underwent a stress-corrosion cracking test in which they were initially exposed to an ammonia solution (concentration: 11.8 % by weight) and then washed with sulfuric acid (concentration: 10.0 % by weight).

Also in this case, ACEA et al. (2020) state, both bismuth-based alloys showed a stress-cracking behaviour much worse than that of the reference alloy, as illustrated in Figure 5-10.

Figure 5-10: Valve core produced from leaded brass (C3604) and from bismuth-based brasses BZ-5A and BZ-3N after ammonia tests



Source: ACEA et al. (2020)

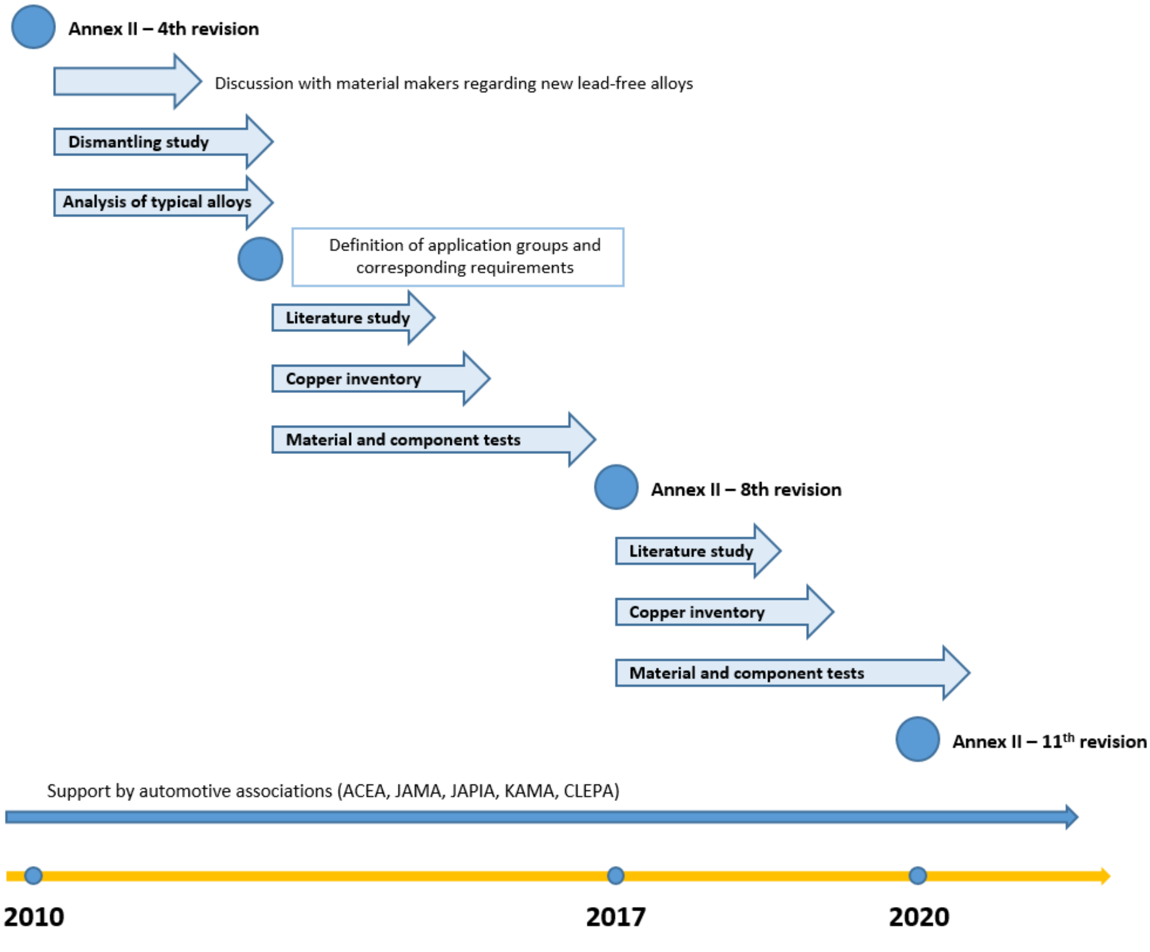
ACEA et al. (2020) conclude that the described results convinced the company not to substitute the leaded brass used for the tire valve.

ACEA et al. (2020) summarize that several promising lead-free copper alloys have been recently developed and in some cases even commercialized. Based on the current knowledge, it is not possible to identify a lead-free copper alloy or a group of lead-free copper alloys that could potentially substitute leaded-brasses and copper alloys in all their application fields. For example, some new alloys might be able in the future to substitute copper alloys with relatively low amount of lead (e.g. up to 0.8 % by weight) for what concerns the machinability and the mechanical and corrosion properties, but no alternative currently exists for emulating the internal lubricant effect of leaded alloys.

5.2.3 Roadmap towards substitution or elimination lead

ACEA et al. (2020) present the below Table 5-5 to illustrate their approach towards the substitution or elimination of lead.

Table 5-5: Summary of the activities carried out by the automotive industry for substitution of leaded copper alloys



Source: ACEA et al. (2020)

Once and if new lead-free copper alloys able to fully substitute leaded-alloys will be available on the market, ACEA et al. (2020) will still need many years to re-design, test, validate and produce new components made of these alloys. Therefore, the associations involved in answering this questionnaire, ACEA, JAMA, JAPIA, KAMA, CLEPA and the European Copper Institute, ACEA et al. (2020) claim that the unlimited exemption concerning leaded copper alloys is still required and that the maximum lead content in these alloys must remain at 4 % by weight. Moreover, they propose a review time for this exemption of 8 years.

5.2.4 Environmental arguments

ACEA et al. (2020) inform that the production of lead-copper alloys is carried out using close to 100 % of recycled material that allow material producers to save costs and resources. In the consultants understanding, this means that leaded alloys are produced more or less directly from leaded copper alloys instead of mixing them from the refined metals, i.e. the copper and alloying elements including lead.

This loop system may apply to the residues from the machining processes, but not for automitive parts. Copper alloy components are not removed from ELVs prior to further treatment steps, which include shredding followed by a mechanical separation process resulting in different fractions. ACEA et al. (2021c) explain that "*Copper alloys from automobiles end up in the shredder heavy fraction and will be transferred to metallurgical processes. Recycling of lead-containing copper is possible and widely used in copper recycling plants."*

During the shredding process, the highest share of copper and copper alloys should be directed into the non-iron fraction together with precious metals, copper, lead, and other metals besides iron and aluminium. This non-iron fraction in the end is treated in copper or copper-type smelters, e.g. Aurubis in Hamburg and Lünen (Germany), Boliden (Sweden), or Umicore (Belgium). In the mechanical separation process following shredding, parts of the non-iron metals end up in other than the non-iron metal fraction from which they are not necessarily recycled.

In the light of the above information that leaded copper alloys form an own material cycle, it must be considered that automotive uses of leaded copper alloys open this cycle towards the metallurgic treatment in copper smelters, which, according to ACEA et al. (2020), *"[…] requires much more energy than the recycling of leaded copper alloys […]*." The automotive industry thus benefits from the leaded-copper alloy cycle, but at least with the parts used in vehicles does not contribute to it. Automotive uses of leaded copper alloys remove leaded copper alloys from the leaded copper alloy cycle. The removed copper alloys have to be replenished with metals coming from metallurgic refining processes as long as the market for leaded copper alloys does not shrink.

In this system perspective, each life cycle of a vehicle implies metallurgic refining processeses for copper and lead, and other alloying elements, regardless whether leaded copper alloys or lead-free alloys are used. This will happen in principle as long as leaded copper alloys are used in the economy outside the automotive industry. The argument that use of leaded copper alloys saves energy compared to lead-free copper alloy use must therefore be put into this system perspective where no clear advantage can be identified for the use of leaded copper alloys. At the same time, it is important to see that the production of copper from secondary sources like non-iron fractions from shredding and mechanical separation processes is still an environmental benefit compared to primary metal production from ores. In this way, the sound end-of-life treatment of ELVs is important to reduce environmental burdens. It should be noted that the above considerations only apply to the volumes of leaded copper alloys used as parts in vehicles.

ACEA et al. are also afraid that due to their high global demand, lead-containing copper scraps might be exported, used and/or disposed outside EU, potentially contradicting the principles of the circular economy. Exports are actually linked to transports consuming energy and causing emissions. Processing of copper alloy scraps generated in the EU is therefore preferable. Beyond this, copper is traded on the world market so that copper exported and treated outside the EU reduces the demand on the world market. Due to their high prices, copper and copper alloys are not disposed as an alternative to processing in the EU. Adding to this, the volumes of leaded copper alloys used in vehicles in the scope of the ELV Directive are only a minor share of their total use. ACEA et al. (2020) point out that in 2018 around 13 % of copper and copper alloys were used in the transportation sector, and in this share around 25 % are leaded copper alloys, resulting in around 3 % of copper alloy use. These 3 % include applications in trucks, ships, trains, aircrafts and other vehicles which are out of the ELV Directive's scope. The share of leaded copper alloys used in vehicles under the ELV Directive can therefore be assumed to be well below 3 % of all uses of leaded copper alloys. Adverse system impacts disbalancing offer and demand of leaded copper alloys are thus not very likely to occur if lead-free copper alloys replace leaded ones in vehicles in the scope of the ELV Directive.

5.3 Justification of MMC for the (partial) revocation of the exemption

5.3.1 Substitution of lead

MMC (2020) present their two lead-free copper alloys ECO Brass and GloBrass with the below compositions.

Table 5-6: Compositions of ECO Brass and GloBrass

Type	Shape	Standard number			Cu	Si	P	Sn	Pb*1	Cd*1	Zn
		CDA	JIS	EN							
ECO BRASS	Bar	C69300	C6932	CW724R	75.5	3.0	0.08	<0.1	<0.09	<0.0075	Rem.*2
	Casting	C87850	CAC804	CB768S	76.0	3.0	0.08	<0.1	<0.09	<0.0075	Rem.*2
GloBrass	Bar	-	-	-	62.5	1.0	0.07	<0.2	<0.1	<0.0075	Rem.*2

Source: MMC[9]

MMC (2020) present examples from which they claim to be demonstrated cases of successful substitution of lead in copper alloys of vehicles with their lead-free ECO Brass alloy. The below Table 5-7 presents the properties of a lead-containing copper alloy –

[9] Mitsubishi Materials Corporation, http://www.mitsubishi-copper.com/en/products/materials/ECO Brass/

C36000, ECO Brass and GloBrass, both lead-free copper alloys. The GloBrass material was introduced later into the market than ECO Brass and MMC did not present automotive application examples for it.

Table 5-7: Properties of GloBrass, C36000*, and ECO BRASS

	Unit	GloBrass	C36000	ECOBRASS
Specific Gravity	g cm^{-3}	8.3	8.5	8.3
Thermal Conductivity	W/m·K	73	114	35
Electrical Conductivity	%IACS	16	26	8
Coefficient of Thermal Expansion	10^{-6}/K	19	21	20
Melting Point – Liquidus	℃	880	900	890
Melting Point – Solidus	℃	865	885	855
HV(ϕ20)		180	145	190
Tensile Strength(ϕ20)	MPa	600	475	670
0.2% Proof Stress (ϕ20)	MPa	465	355	510
Elongation(ϕ20)	%	20	25	30
Hot Deformation Resistance at 650℃	MPa	15	30	50
Tensile Strength(at 150℃)	MPa	550	410	670
Creep Strength, Stress at 0.5% Creep Strain(MPa)	100h at 90℃	about 430	about 330	–
	100h at 120℃	about 420	about 260	≦570
	100h at 150℃	about 370	about 200	about 490
Cutting Force of Turning	N	120	100	115

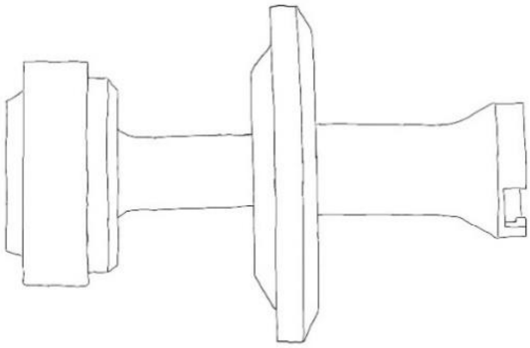
Source: MMC (2021a) *Leaded copper alloy CuZnPb

MMC (2020) claim that a multiple number of ECO BRASS parts have been installed in approximately 100 million cars by now. Several of them, which include knurling in their production process, have been installed in over five million automobiles. They meet customers' quality-related demands such as forming of complicated shapes or high dimensional precision. MMC (2020) introduces four specific parts produced from its lead-free alloys as representative examples for uses of ECO BRASS.

Small Component A for Car Air-Conditioner –Check Valve

Figure 5-11 shows check valve for a car air-conditioner placed near the engine room of an automobile. MMC (2020)

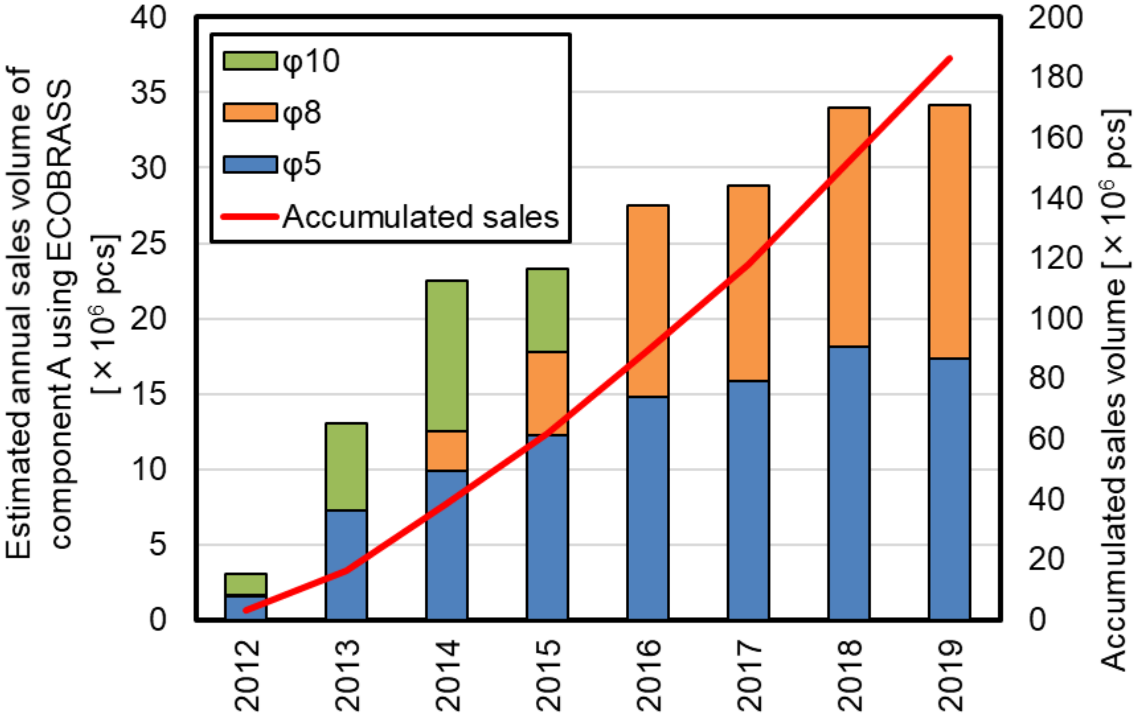
Figure 5-11: Check Valve for Car Air-Conditioners



Source: MMC (2021e)

MMC (2020) describe that component A consists of two parts which are made of ECO BRASS rods of 10 mm diameter, currently downsized to 8 mm, and 5 mm respectively. The parts weigh 0.42 g and 0.66 g respectively and are classified as small parts. MMC (2020) state that the sales volume has been approximately 60 tonnes annually since 2014, and the accumulated sales volume through to the end of September 2020 reached 440 tonnes. Figure 5-12 illustrates the estimated annual sales of the components broken down to the different diameter rods.

Figure 5-12: Estimated sales volumes of component A (in million pieces)



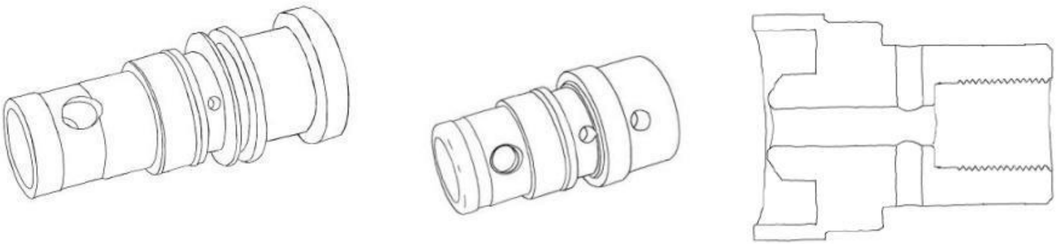
Source: *MMC (2020)*

MMC (2020) estimate the total sales with around 90 million pieces for each of the the smaller diameter rods in 2018 and 2019 respectively, while the 10 mm parts were no longer sold after 2015.

Small Component B for car air-conditioner – control valve for variable capacity compressors

MMC (2020) present three types of another car air-conditioner component B weighing 36.8 g, and34.3 g, and 23.7 g respectively from left to right in the below Figure 5-13.

Figure 5-13: Control valve for variable capacity compressors



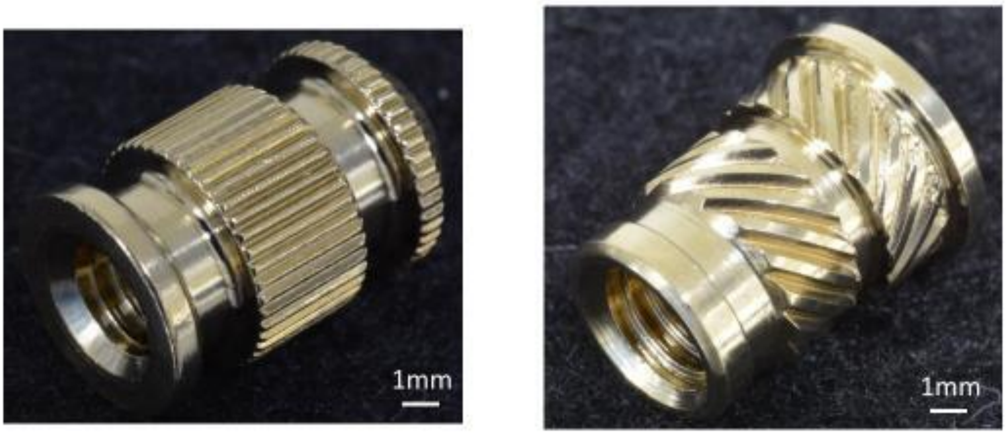
Source: MMC (2020)

MMC (2020) highlights that these components require particularly high dimensional precision of 2 µm and indicates a steady growth from 2007 on to around 1,600 t of ECO Brass sold in 2019 to produce an estimated 16 millions of these three components in that same year. A total of around nine million units have been installed in vehicles demonstrating that there was no problem in their durability or reliability.

Insert Nuts

The third type of small car components are the insert nuts presented in Figure 5-14.

Figure 5-14: Insert nuts produced from ECO Brass



Insert nut C（2.0g）　Insert nut D（1.1g）

Source: MMC (2020)

MMC (2020) report nut C to be manufactured in large quantities in 2016 using φ7 to 10 mm rods. By September 2020, a total of 50 t of materials were used for mass production and use of about five million pieces. Insert Nut D has been manufactured since 2015 using φ7 to 9 mm rods, and 95 t of such materials were used for the production of an estimated more than 20 million components by August 2020.

According to MMC (2020), the surface quality of these components is good. In particular, no fibrous foreign matter or cracks are observed on the product surface which is processed by rolling a knurl piece. The component's machined surface is in good condition proving that knurling conditions for mass production have been established.

5.3.2 Manufacturing of parts from lead-free copper alloys

Since lead affects the manufacturability of brass parts, MMC (2020) present several examples which show that parts can be successfully manufactured with the lead-free ECO Brass and the GloBrass alloys. The wear of the tools is in general higher than in processing of lead-containing brass. MMC (2020) claim that this effect can be reduced by choosing the machining processes and tools with respect to the lead-free alloys' specific properties as well as optimizing new tools for these materials. Detailed information about these manufacturing processes and the results are presented in the document which MMC (2020) submitted to the stakeholder consultation. According to MMC (2020), in mass machining of ECO BRASS, the productivity was at least 90 % that of C36000 (leaded copper alloy) and tool life was at least 80 % that of C36000.

Further on, MMC (2020) present machined parts to show the practicability of their manufacturing from MMC's lead-free alloy also for small parts. The test machining was performed with the cooperation of some machining companies using their machining facilities normally used for manufacturing commercial products. Details of the test machining are:

1) Machining small diameter rods to produce parts assumed to be used as auto parts or electrical/electronic parts (Example 1);
2) Machining with an automatic 6-spindle lathe (a mass production facility; example 2); and
3) Machining with a multi-purpose NC lathe (example 3).

1) Machining example of small diameter rods (Example 1)

MMC (2020) show examples of machining small diameter rods of 3 mm to 12 mm in diameter in Figure 5-15. At a machining company, 100 to 200 pieces of each part were manufactured. An NC lathe was used for the test production of eight kinds of small parts weighing from 0.4 g to 10 g assumed to be used as auto parts or electrical/electronic parts.

Figure 5-15: Machining small-diameter Rods [rod diameter (mm)/component weight]

Source: MMC (2020)

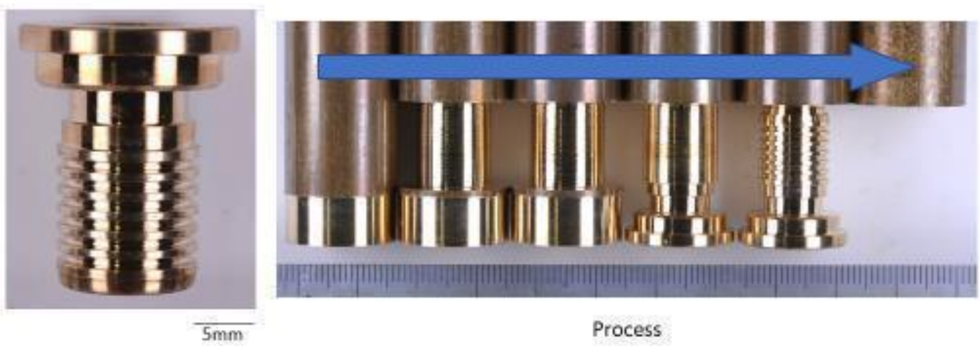
MMC (2020) summarize that turning, small/hole drilling (drilling φ0.7 mm holes), side drilling, threading (inside and outside), and knurling were well done, and product quality was equivalent to when C36000 was used. The applied machining conditions are the same as those applied toC36000. Unfortunately, MMC (2020) inform, they are unable to disclose them though. MMC (2020) conclude that machining rods of small diameters went well, too, demonstrating that small parts can be manufactured with ECO BRASS rods.

2) Machining examples using a 6-spindle lathe (Example 2)

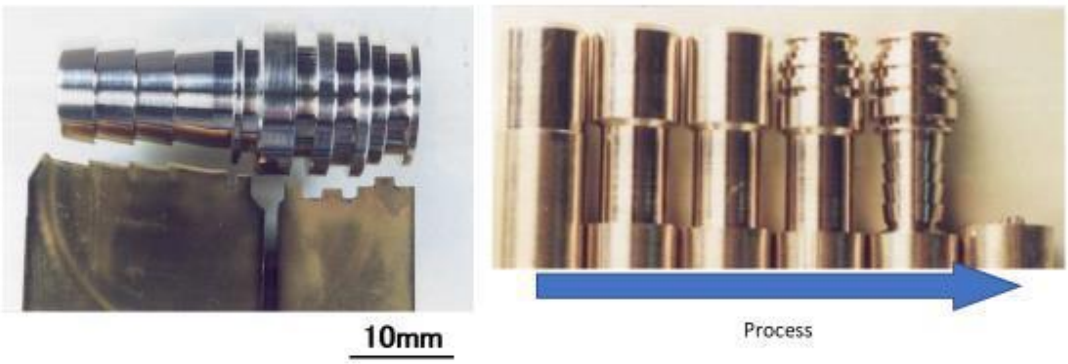
MMC (2020) describe automatic 6-spindle lathes as the most productive machines since they can work on six different locations at the same time. However, the shapes of workpiece sit can handle are limited, and dimensional precision is moderate. Using such mass production facilities, the machinability of MMC's ECO BRASS was evaluated in mass production at two other machining companies than the one in example 1.

For the test machining, MMC (2020) report that two kinds of parts actually mass-produced with C36000 by a process including drilling were selected. Then, 23,000 pcs and 12,000 pcs respectively of the selected parts were produced continuously by machining on the same conditions as when C36000 was used.

Figure 5-16: Machining with automatic6-spindle lathe



- Cycle：10sec
- Condition : Wet
- Material : ϕ19 × 3000
- Pieces : 23,380



- Cycle：10sec
- Condition : Wet
- Material : ϕ18 × 3000
- Pieces : 12,000
- Machining Condition :
  ϕ8.0 Drilling(2000rpm, 0.15mm/rev.), Forming tool(2000rpm, 0.03mm/rev.)

Source: MMC (2020)

MMC (2020) say that it takes only about 10 seconds to finish machining one component with a 6-spindle automatic lathe. As productivity is prioritized, the load imposed on cutting tools is heavy.

- Somewhere around 10,000 pcs of each part were able to be machined continuously.
- There were no irregularities such as chips getting bulky or tangling the tools. There were no problems like components' dimensions getting out of allowable tolerance or poor surface conditions.

As a result, MMC (2020) consider that their lead-free ECO BRASS can be used for mass production without modifying the machining conditions applied to C36000 since no problem was found in machining productivity or quality during the test machining with the 6-spindle automatic lathes.

3) Machining examples using a 6-spindle lathe (Example 3)

MMC (2020) report a continuous machining of 1,000 pcs of valve parts was performed at yet another machining company for four days in a row (during daytime operation hours only though) using ø20-mm ECO BRASS rods and an NC lathe which was normally used for mass production of commercial products.

Figure 5-17: Appearances of a part after machining and generated chips (top), and the appearances of the cutting tools after machining 1,000 pieces (bottom)

Source: MMC (2020)

According to MMC (2020), after machining 1,000 pieces no change in the quality of machined surface or product dimensions was observed. There was no occurrence of problem like product being tangled with chips and damaged. MMC (2020) interpret that

Figure 5-17 (top) indicates that the chips generated during the machining were easy to dispose of, and Figure 5-17 (bottom) shows that no visible wear was observed in any of the tools used for turning, grooving, threading, or severing. It is considered that further continuation of machining was possible. MMC (2020), assume that if it takes 3 minutes to complete machining of one workpiece (20 pcs/h), 480 pcs per day could be produced if operated around the clock. An alloy can be considered to have good machinability if it has machinability equivalent to that of C36000. Specifically, continuous machining needs to be possible for 24 hours without human assistance or presence, quality issue in the product, problem with disposal of the chips, or necessity of tool replacement. Therefore, it is true that the longer the tool life is, the better, but there would be no substantial problem if disposal of chips and replacement of tools could be done at a timing when the NC lathe is stopped to perform inspection or the like.

MMC (2020) present more examples similar to the above ones to show the machinability of their lead-free copper alloy under industrial production conditions. They sum up and conclude that with the cooperation of five companies including four machining companies having several dozen employees and capitalized at somewhere around 100,000 euros, test machining of components having various shapes was performed using ECO BRASS at their commercial mass production facilities. The outcome was that the test machining went well and without problems at all of the companies. With the consent of the machining companies, we MMC (2020) were able to disclose a lot of information such as component shape and surface quality on 15 kinds of machined items including mass produced auto parts. It became possible to disclose how much the tools wear, conditions of generated chips, and machining process although such disclosure is not complete. From the results of the test machining in which turning, grooving, all sorts of threading, knurling, wall-thinning, and drilling of various holes are included, there is generally no serious problem in machining ECO BRASS materials on a commercial scale although the 15 kinds of the test-machined items do not cover all the existing auto parts and electrical/electronic parts.

MMC (2021b) admit that as a material maker they do not know about all the existing auto parts and request, with view to their two lead-free alloys, the continuation of the exemption for limited applications where substitution is truly impracticable.

5.4 Critical review

ACEA et al. (2020) state that "*[…]* it is not possible to identify a lead-free copper alloy or a group of lead-free copper alloys that could potentially substitute leaded-brasses and copper alloys in all their application. They claim that the unlimited exemption concerning leaded copper alloys is still required and that the maximum lead content in these alloys must remain at 4 % by weight."

ACEA et al. (2020) say that "*Most likely, the future substitution of leaded-copper alloys will not be achievable through only a single type of lead-free copper alloys. Rather, different varieties of lead-free alloys will be likely needed to cover the whole spectrum of properties and possible applications that leaded-copper alloys are able to offer.*"

The consultants share this point of view since the drop-in replacement approach has not yielded tangible results in the last 20 years as to the actual substitution of lead in copper alloys. Adding to this, given the variety of applications, machining processes and processors with different levels of knowledge as to the processing of lead-free copper alloys, the examples of failing components produced from lead-free copper alloys presented by ACEA et al. (2020) are no evidence that the substitution of lead in copper alloys is still generally unavoidable. The failures as presented can have different causes:

- The substitution of lead actually is still impossible in these specific cases with specific requirements as to shapes and mechanical and/or electrical properties;
- Substitution might be possible, but the selected lead-free copper alloy was inadequate for the aspired shapes and properties; actually each of the presented failure samples was produced only from a single lead-free alternative material or a single type of lead-free materials, e.g. only from different bismuth-containing lead-free alloys;
- Substitution of lead could potentially work with the tested lead-free material sample, but the respective machining processor was not able to produce the required quality with its process equipment and/or its knowledge about processing of lead-free copper alloys; it is either mentioned that the samples were produced by one manufacturer, or it is not further specified.

ACEA et al. were requested to provide the missing evidence addressing the above points. ACEA et al. (2021c) justify their approach claiming that "*The results that we showed in our last and previous contributions already referred to what in our opinion were the most promising lead-free copper-based alternatives and processing conditions. The strong and weak points of the different lead-free candidate materials have been assessed with scientific-based support and the results have been comprehensively outlined in our previous contributions.*"

ACEA et al. did not reveal which specific considerations and scientific-based results guided them to choose the respective materials and processing conditions specifically for the failed lead-free copper parts. ACEA et al. (2021c) "*[…]want to include for each sample a trial with different lead-free materials or material classes respectively and produced by more than one machining processor/with different technologies*" in the next working packages of industry research activities since as of today these information is not available.

For the tire valve components, ACEA et al. (2021c) reference their contribution to the last review where ACEA et al. (2014) based their tests for tire valves on a broader material selection than in the test provided by ACEA et al. (2020) (c.f. Figure 5-9 on page 44). In the 2014 test, they had included Eco Brass and a low lead copper alloy as displayed in Figure 5-18. The tested resistance against chemicals in the consultants' understanding is strongly related only to the copper alloy properties. It is not clear why ACEA et al. tested the tire valve components again in 2020 with the same tests but a smaller selection of the same lead-free copper alloys than in the 2014 test. If the material composition of the copper alloys is identical, the same results can be expected. Figure 5-18 confirms the test outcomes of the recent test, and for Eco Brass and low lead alloys.

Figure 5-18: Test of tire valve components (2014 review)

Material		n	BZ-5U	Judgment	Eco-Brass	Judgment	Pb0.2% brass	Judgment	C3601 (Current)
Adhesion	Non-treatment → Test	5	94 (80～100)	×	62 (40～80) %	×	All 100 %	○	All 100 %
	Heat Resistance (100℃×72h → Test)	5	91 (70～100)	×	70 (50～80) %	×	All 100 %	○	All 100 %
	Moisture Resistance (70℃×Moisture 90%×72h → Test)	5	96 (90～100)	○	61 (40～80) %	×	All 100 %	○	All 100 %
	Acid Resistance ($0.2\%H_2SO_4$×168h → Test)	5	65 (60～70)	×	34 (30～40) %	×	62 (60～65) %	×	83 (80～90) %
Ammonia Test	11.8%Ammonia×72h → Test	5	n=5 All Cracks	×	n=5 All No Cracks	○	n=5 All No Cracks	○	n=5 All No Cracks

Average. (Min.～Max.)

○ : Equal to C3601
× : Inferior to C3601

Material		n	BZ-5U	Judgment	Eco-Brass	Judgment	Pb0.2% brass	Judgment	C3601 (Current)
Adhesion	Non-treatment → Test	5	94 (80～100)	×	62 (40～80) %	×	All 100 %	○	All 100 %
	Heat Resistance (100℃×72h → Test)	5	91 (70～100)	×	70 (50～80) %	×	All 100 %	○	All 100 %
	Moisture Resistance (70℃×Moisture 90%×72h → Test)	5	96 (90～100)	○	61 (40～80) %	×	All 100 %	○	All 100 %
	Acid Resistance ($0.2\%H_2SO_4$×168h → Test)	5	65 (60～70)	×	34 (30～40) %	×	62 (60～65) %	×	83 (80～90) %
Ammonia Test	11.8%Ammonia×72h → Test	5	n=5 All Cracks	×	n=5 All No Cracks	○	n=5 All No Cracks	○	n=5 All No Cracks

Average. (Min.～Max.)

○ : Equal to C3601
× : Inferior to C3601

Source: ACEA et al. (2014)

Figure 5-18 confirms the test outcomes of the recent test, and additionally for Eco Brass and low lead alloys. The results show that the tested lead-containing copper alloys are not appropriate to substitute leaded copper alloys in tire valve components. Whether and how far adaptations of the rubber chemistry could influence the result, could not be discussed within the available time for the review.

The tested resistance against chemicals in the consultants' understanding is strongly related to the physical and chemical properties of the tested alloys. Surface roughness may also influence the results because rougher surfaces exhibit larger areas for the chemicals to react with. It also remains unclear why ACEA et al. tested the tire valve components again in 2020 with the same tests but a smaller selection of the same lead-free copper alloys than in the 2014 test. As the material composition of the alloys tested in 2020 is identical to copper alloys that were already tested in 2014, the same results achieved were to be expected.

The further review was focused to proven applications of lead-free copper alloys in vehicles in the scope of the ELV Directive. Only MMC (2020) presented application examples, two valves for air conditioners used in vehicles and two insertion nuts produced from their lead-free copper alloy (ECO Brass). In the absence of further information about lead-free copper alloys and their uses in vehicles in the scope of the ELV Directive, the review was focused on the question whether the use of lead in copper alloys is at least partially avoidable for the uses which MMC (2020) present in their submissions.

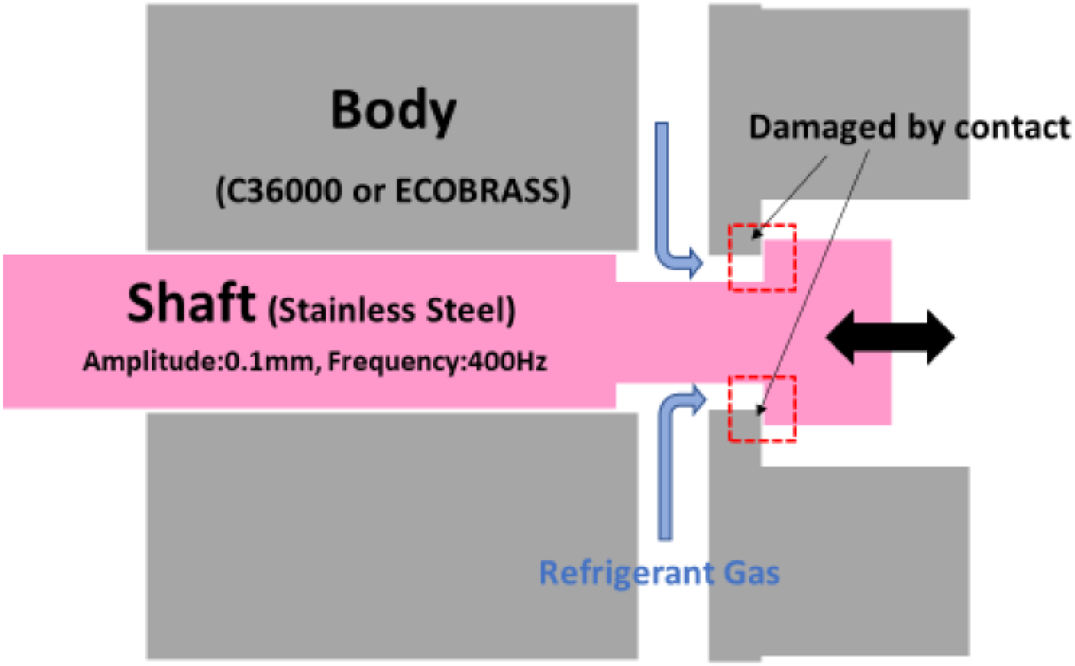
5.4.1 Substitution of lead in variable capacity air conditioners

MMC presented several examples of their lead-free copper alloy which has been used in vehicles in the scope of the ELV Directive. ACEA et al. (2021a) acknowledge that ECO Brass is currently used for several automotive parts but put forward that no member of ACEA or any other joint automotive associations has been able to provide examples of parts for which a successful substitution of leaded-copper alloys with ECO Brass had occurred in the last few years. They assume that the lead-free copper alloy parts presented by MMC (2020) replaced materials other than leaded-copper alloys. Their experience suggests that ECO Brass is a potential substitute for stainless steel rather than for leaded brass, which is also mentioned in Dr. Welter`s study[10] and supported by the associations involved in the RoHS Umbrella Industry Project.[11]

MMC was asked for further information whether in their presented applications the lead-free copper alloys replaced stainless steel or copper alloys with lead. MMC (2021c) "*[…] have confirmed with the machining company […] that they are still using both C36000 and ECO BRASS for the manufacture of the small car air-conditioner component* [component B; added by consultants]*. […] C36000 is used more than ECO BRASS.* […] *stainless steel is not a suitable material for Small Car Air-Conditioner Component (control valve) structure-wise. The shaft is made of stainless steel* [as illustrated by Figure 5-19]*, and use of the same kind of material, stainless steel, for the valve is not appropriate."* […] From this MMC (2021c) conclude *"[…] that most of the small car air-conditioner components manufactured would have been made of C36000 if ECO BRASS had not been used."*

[10] Dr. Welter, J.-M. Leaded copper alloys for automotive applications: a scrutiny. 2014; source as referenced by ACEA et al. 2021a.
[11] C.f. https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_22/Exemptions/6c/Application_UP_6_c__Exemption_Request_31Jan2020_final.pdf

Figure 5-19: Schematic diagram of a section of small car air-conditioner component B



Source: MMC (2021c)

ACEA et al. (2021b) concede that for the above specific example of the air conditioner component "*[…] it seems that Eco Brass replaced the leaded copper alloy C36000.*

From the above statements, the consultants conclude that at least in the case of the control valve for variable capacity air conditioners (component B, Figure 5-13 on page 52) operating with a steel shaft (Figure 5-14 on page 52), MMC's lead-free copper alloy substituted lead-containing copper alloys.

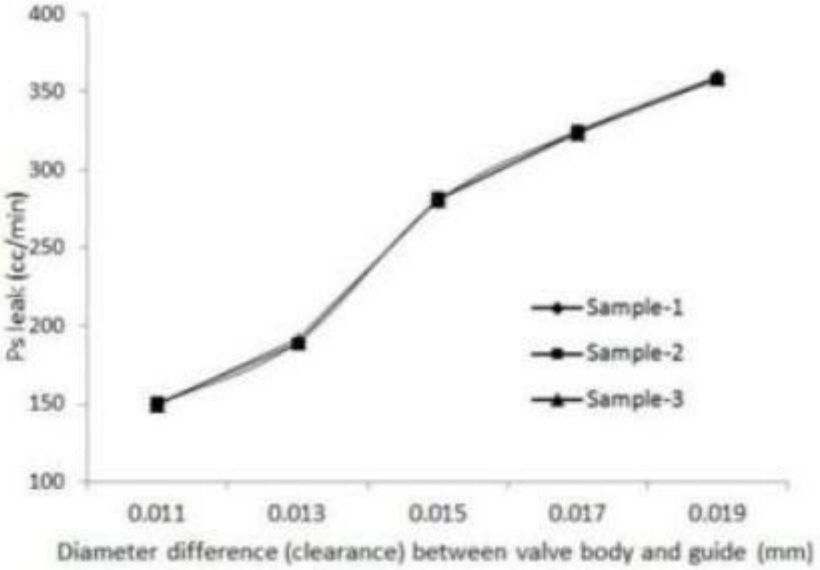
ACEA et al. (2021b) think that the above case of lead substitution in air conditioner component B "[...] *cannot be generalized to all or even part of other ECV*[12] *body components. A similar statement, even if not specific for air-conditioner ECV, is included in the […] 2010 report, that says: "[…] Furthermore, engine tests showed that lead free brasses like ECO BRASS or Diehl 474HT14 were suitable for valve-guide in some cases but failed in some other cases due to friction, wear, and fretting. ECV for automotive air conditioner systems differentiate in shape, dimensions and working conditions. We strongly believe that the substitution of a leaded-copper alloy that might have occurred for a single type of ECV, cannot be deemed as a sufficient proof for claiming that Eco Brass or any other silicon-based copper alloys can substitute leaded-copper alloys for further or possibly all ECV applications."*

ACEA et al. (2021b) further put forward that "*The design of these ECV valves needs to be very accurate and precise; generally, the tolerance for each of their component is ± 0.02 mm to ± 0.05 mm, but the tolerance for the assembly of components associated with the*

[12] ECV: electronic control valve

valve leakage performances, like the valve body and shaft, might be in the range of ± 0.002 mm or even ± 0.001 mm." ACEA et al. (2021b) present the below Figure 5-20 showing the correlation of dimensional aberrations and leakages of the refrigerant.

Figure 5-20: Ps leakage with respect to clearance between valve body and guide



Source: ACEA et al. (2021b)

ACEA et al. (2021b) claim that *"[…] control valves with bodies made of materials different from leaded-copper alloys have in general lower leakage performances […] compared to those including a leaded-copper alloy body."*

As to the dimensional accuracy of component B, MMC (2020) claim, confirmed by MMC (2021d), a precision of 2 µm (0.002 mm), which ACEA et al. point out as tolerance for the assembly of components associated with the valve leakage performances, like the valve body and shaft. Adding to this, the lead-free component B has been used for many years already in variable capacity air conditioners of vehicles as a substitute for lead-containing control valves in combination with the most commonly used steel shafts. This can be taken as evidence that the lead-free component B achieves the required leakage performance as otherwise it would not have been used for years.

ACEA et al. (2021b) also remark that *"[…] the substitution of a leaded-copper alloy valve body with one made of a silicon-copper alloy, likely requires either the addition of an external lubricating mean or the improvement of the existing lubricating system that acts in the area of contact between the valve body and the shaft. In case of malfunctioning of the lubricating system, the leaded-copper valve body would still ensure the valve functionality due to the material low friction coefficient and self-lubricating behavior. […] the missing or damaged lubrication of a valve made of Eco brass or any other lead-free copper alloy, would cause the failure of the system. In this sense, the use of leaded-copper alloys valve bodies can be seen as an additional safety feature for the correct functionality of the whole air conditioning system where the ECV is installed."*

MMC (2021d) consider wear resistance, cavitation resistance, and friction coefficient to be important. *"[…] ECO BRASS' friction coefficient is only slightly higher than that of C36000 when stainless steel is used as a material for the contacting component, but wear resistance and cavitation resistance of ECO BRASS are far better than those of C36000. Wear resistance and cavitation resistance are considered to be important since a stainless-steel shaft moves at a frequency of several hundreds of Hertz."*

The above discussion was not followed up further due to the limited time available. It can, however, be reasonably assumed, like in the case of the dimensional precision, that the variable capacity air conditioners equipped with component B have been operating reliably in the past years, even if additional lubrification would have been required. The use of the lead-free component B would have been stopped if lubrication issues or other failures had occurred with the variable capacity air conditioners which could have been solved with using valves produced from leaded copper alloy.

Summing up, the valves (component B) are a case of a successful substitution of lead in copper alloys in variable capacity air conditioners operating with a steel shaft. For component B, the lead-free alloy from which it is produced can be machined, the necessary precision is achieved, and its use for years in variable capacity air conditioners shows that it has operated in the air conditioner with a degree of reliability which caused the producer of the air conditioner not to switch back to leaded copper alloys.

Substitution of lead in insert nuts

Like for the valves in the air conditioner, ACEA et al. claimed that the lead-free copper alloy has replaced steel in the insert nuts, not leaded copper alloys. MMC was asked whether their lead-free alloy replaced leaded copper or steel in the insert nuts manufactured from their lead-free alloy (c.f. Figure 5-14 on page 52). MMC (2021c) stated that "*[…] these insert nuts have complicated shapes formed by machining even though they weigh as light as 2 g and 1 g respectively. This kind of work is difficult to accomplish on a commercial basis if stainless steel is used instead. MMC (2021c) have confirmed with the machining company that C36000 would still be used if ECO BRASS was not used instead.*"

ACEA et al. (2021b) agree "*[…] that stainless steel is much more difficult to machine than both leaded-copper and lead-free silicon-based copper alloys, it requires longer cycle times and it provokes much more damages on the tools, limiting severely their life.*" ACEA et al. do not provide any explanation why the lead-free nuts could have replaced steel nuts despite of the unfavourable machinability properties.

From the above statements, the consultants conclude that the insert nuts (Figure 5-14 on page 52), are a successful case of lead substitution in copper alloy.

ACEA et al. (2021b) commented that *"[…] these two examples cannot and shall not generalized for stating that nuts currently made of leaded-copper alloys could be produced using lead-free copper alloys. According to our experience with Eco Brass, and as showed in [*Figure 5-8 of page 43 (addition of the consultants*], this material is not always suitable for obtaining complicated shapes or profiles. […] leaded-copper alloys are often selected for producing insert nuts due to their high thermal conductivity, resulting in high positional accuracy and short cycle times, and not only for their ability to be machined in complicated shapes. Even assuming that complicated nut shapes might be obtained using silicon-based copper alloys, this would not solve the problem of their lower thermal conductivity.*

Furthermore, the undeniable better machinability of leaded-copper alloys compared to that of silicon-based lead-free copper alloys, might in some cases be required to obtain the most complicated and challenging nut shapes."

Since the insert nuts have been used successfully in vehicles for years, it can be reasonably assumed that the potential problems addressed above could be solved or, in the case of lower thermal conductivity, were not relevant in the specific application. They are an example for a successful substitution of lead in copper alloys.

Scope restriction of exemption 3

The available information suggests that substitution of lead in copper alloys has been practiced successfully for years with the valves in variable capacity air conditioners operating with a steel shaft and two types of insert nuts. It is also worth noting that that the lead-free copper alloy replaced the often-used C36000 alloy (CuZn39Pb3), a copper alloy containing 3 % of lead, not an exotic leaded copper alloy or a leaded copper alloy with very low lead content only.

The consultants nevertheless agree with ACEA et al. (2021b) that these examples cannot be generalized towards excluding valves and insert nuts from the exemption scope without further information. The properties, specific working conditions, performance requirements etc. related to their application need to be characterized further before any conclusions are possible as to the potential exclusion of such applications from the scope of exemption 3.

MMC (2021e) point out that MMC as *"[…] material manufacturers rarely deal with an auto maker or a large-scale auto parts maker directly. Most materials like ECO BRASS bars are supplied to machining companies via a wholesaler or a trade house. As a matter of fact, as car makers and large-scale auto parts makers rarely consult with a material maker regarding automotive component design, we are rarely involved in designing automotive component."*

More specific information could not be obtained in this exemption review since neither MMC nor the consultants have access to the automotive suppliers and/or the vehicle manufacturers producing and applying the variable capacity air conditioners and the insert nuts. Adding to this, information is impossible or difficult to access due to confidentiality agreements between vehicle manufacturers and suppliers. The successful cases of lead substitution in copper alloys can therefore not be reflected in the exemption scope.

Another principal possibility to restrict the exemption scope would be reducing the maximum content of lead in copper alloys in scope of exemption 3 down from the current 4 %. According to ACEA et al., more than 80 % of the leaded-copper alloy parts (and almost 90 % in case of the electric models) contain an amount of lead between 2.0 % and 4.0 % by weight, and the lead content has increased even though the number of components and the total lead content of vehicles has decreased. ACEA et al. argue that in particular the small components require higher lead contents.

Even though the lead-free copper parts discussed above substituted a leaded copper alloy with 3 % of lead content, showing that even lead-free copper alloys can in principle be used in this range of copper alloys with lead contents, the cases cannot be generalized to justify the reduction of the maximum lead content in the exemption scope. The consultants did not see promising starting points in the available information for such a reduction discussion and therefore invested the available time to prove or disprove that the application examples provided by MMC are actually cases of successful substitution of lead in copper.

Potential for further substitutions

ACEA et al. (2020) present 14 lead-free alloys which are already standardized and available on the market (Table 5-2 o page 36) and some test results including for MMC's lead-free alloy (Table 5-4 on page 40) which, like the others, is classified as inferior to lead-containing copper alloy. The successful substitution cases show that it could nevertheless replace leaded copper alloys, which in the consultants' opinion shows that lead-free copper alloys have a potential to substitute lead on an application-specific base even if they perform weaker in general tests.

The valves and insert nuts manufactured from lead-free copper alloy replaced parts which were otherwise produced from a standard lead alloy with 3 % of lead content. According to ACEA et al. (2020), more than 80 % of the leaded-copper alloy parts contain between 2.0 % and 4.0 % of lead by weight, and roughly 90 % of these parts weigh less than 10 g. ACEA et al. (2020) conclude from this that the smallest parts, which require a high dimensional accuracy and therefore a high machinability, still need a relatively high amount of lead to make this happen. The lead-free alloy used in the variable capacity air conditioners and the insert nuts thus substituted a copper alloy from which more than 80 % of components containing leaded copper alloys are produced. Additionally, the lead-free insert nuts weigh far less than 10 g. The lead substitution in these nuts thus happened in the area of the small parts, in which 90 % are produced from lead alloys with lead content between 2 % and 4 %, corresponding to more than 72 % of the parts using leaded copper alloys with 2 % to 4 % lead content.

Even though the cases of successful lead substitution in copper cannot be used to restrict the exemption scope due to lacking application-specific information, they show that substitution is possible even in the high lead content area. In the case of the insert nuts, substitution could even be achieved in the segment of small components, which according to ACEA et al. are manufactured from copper alloys with the highest amounts of lead to achieve the required machinability. In the light of these considerations, it can be assumed that lead-free copper alloys should at least have the potential for further substitutions of lead.

Besides the 14 lead-free copper alloys already standardized, ACEA et al. (2020) present several new ones, two of which, CuSi4Zn9MnP (wrought alloy) and CuSn4Zn2PS-C (casting alloy) they have started to test with promising results. ACEA et al. (2021c) explain that they will start producing trial components from these lead-free alloys upon successful finalization of the material characterization. If this is successful, the introduction of new materials in the automotive industry, even if fully characterized, requires several years according to ACEA et al. (2021c).

Further lead-free copper alloys include one for oil-hydraulic applications as bushings, slippers or distributor plates by the company Otto-Fuchs13, a lead-free alloy of Aviva

[13] B. Reetz, T. Münch, Challenges for novel lead-free alloys in hydraulics, 12th International Fluid Power Conference, Dresden, 2020.

Metals, and from AquaNord. ACEA et al. (2021c) upon request explained that they did not yet produce any trial components from any of these alloys as these alloys have recently become available so that they could not yet test and characterize them but will include them in their future investigations.

Overall, the consultants think that the examples of successful applications of lead-free copper alloys, and the of almost 20 lead-free alloys mentioned in the exemption request form a base with good potentials for further substitutions of lead in copper alloys in specific applications. ACEA et al. should not only characterize materials, but also the various applications of leaded copper alloys for parts, to enable a specific selection of copper alloys for application-specific testing. This would also form a systematic approach to testing of lead-free alloys rather than the anecdotal and in parts inconclusive samples presented as evidence that lead-free copper alloys cannot be used.

5.4.2 Elimination of lead by 3D printing

Machinability of lead-free alloys is pointed out as one potential obstacle justifying for the addition of lead. 3D printing is an alternative technology to produce parts so that this manufacturing technology might have the potential to avoid the use of lead.

ACEA et al. (2020) point out that leaded-copper alloys require high production volumes, and, among other attributes, good and predictable mechanical properties and a very high surface quality. Compared to conventional, subtractive production processes, the production of metal parts by additive manufacturing is usually slower and more expensive and thus more indicated for high value and low volumes parts. In many cases, post-processing operations on the 3D printed parts might be needed. Other challenges pertaining to additive manufacturing products are surface finish, part size, variations in product quality from machine to machine and between batches of productions, and a lack of fundamental understanding of the impact of operational variables on part quality.

ACEA et al. (2020) conclude that additive manufacturing techniques, in spite of many advantages that allow their use to spread in an increasing number of fields, have still some limitations that prevent them to be a suitable mean for producing copper-alloy-based components for the automotive industry. ACEA et al. (2020) provide more details and insights into 3D printing in their answers to the consultation questionnaire.

5.4.3 Environmental arguments

ACEA et al. (2020) inform that the production of lead-copper alloys is carried out using close to 100 % of recycled material that allow material producers to save costs and resources. In the consultants understanding, this means that leaded alloys are produced more or less directly from leaded copper alloys instead of mixing them from the refined metals, i.e. the copper and alloying elements including lead.

This loop system may apply to the residues from the machining processes, but not for automotive parts. Copper alloy components are not removed from ELVs prior to further treatment steps, which include shredding followed by a mechanical separation process resulting in different fractions. ACEA et al. (2021c) explain that "*Copper alloys from automobiles end up in the shredder heavy fraction and will be transferred to metallurgical processes. Recycling of lead-containing copper is possible and widely used in copper recycling plants.*"

During the shredding process, the highest share of copper and copper alloys should be directed into the non-iron fraction together with precious metals, copper, lead, and other metals besides iron and aluminium. This non-iron fraction in the end is treated in copper or copper-type smelters, e.g. Aurubis in Hamburg and Lünen (Germany), Boliden (Sweden), or Umicore (Belgium). In the mechanical separation process following shredding, parts of the non-iron metals end up in other than the non-iron metal fraction from which they are not necessarily recycled.

In the light of the above information that leaded copper alloys form an own material cycle, it must be considered that automotive uses of leaded copper alloys open this cycle towards the metallurgic treatment in copper smelters, which, according to ACEA et al. (2020), *"[…] requires much more energy than the recycling of leaded copper alloys […]*." The automotive industry thus benefits from the leaded-copper alloy cycle, but at least with the parts used in vehicles does not contribute to it. Automotive uses of leaded copper alloys remove leaded copper alloys from the leaded copper alloy cycle. The removed copper alloys have to be replenished with metals coming from metallurgic refining processes as long as the market for leaded copper alloys does not shrink.

In this system perspective, each life cycle of a vehicle implies metallurgic refining processes for copper and lead, and other alloying elements regardless whether leaded copper alloys or lead-free alloys are used. This will happen in principle as long as leaded copper alloys are used in the economy outside the automotive industry. The argument that use of leaded copper alloys saves energy compared to lead-free copper alloy use must therefore be put into this system perspective where no clear advantage can be identified for the use of leaded copper alloys. At the same time, it is important to see that the production of copper from secondary sources like non-iron fractions from shredding and mechanical separation processes is still an environmental benefit compared to primary metal production from ores. In this way, the sound end-of-life treatment of ELVs is important to reduce environmental burdens. It should be noted that the above considerations only apply to the volumes of leaded copper alloys used as parts in vehicles.

ACEA et al. are also afraid that due to their high global demand, lead-containing copper scraps might be exported, used and/or disposed outside EU, potentially contradicting the principles of the circular economy. Exports are actually linked to transports consuming energy and causing emissions. Processing of copper alloy scraps generated in the EU is therefore preferable. Beyond this, copper is traded on the world market so that copper exported and treated outside the EU reduces the demand on the world market. Due to their high prices, copper and copper alloys are not disposed as an alternative to processing in the EU. Adding to this, the volumes of leaded copper alloys used in vehicles in the scope of the ELV Directive are only a minor share of their total use. ACEA et al. (2020) point out that in 2018 around 13 % of copper and copper alloys were used in the transportation sector, and in this share around 25 % are leaded copper alloys, resulting in around 3 % of copper alloy use. These 3 % include applications in trucks, ships, trains, aircrafts and other vehicles which are out of the ELV Directive's scope. The share of leaded copper alloys used in vehicles under the ELV Directive can therefore be assumed to be well below 3 % of all uses of leaded copper alloys. Adverse system impacts disbalancing offer and demand of leaded copper alloys are thus not very likely to occur if lead-free copper alloys replace leaded ones in vehicles in the scope of the ELV Directive.

5.4.4 Summary and conclusions

Article 4(2)(b)(II) provides that an exemption can be justified if the use of a restricted substance is unavoidable. ACEA et al. claim that lead cannot be avoided in copper alloys and request the continuation of exemption 3 for eight more years while MMC present examples of uses of their lead-free copper alloy, where ACEA et al. claim that the lead-free copper alloy substituted steel rather than leaded copper alloys. No other stakeholder contributions were received.

The available information suggests that the current maximum lead content of 4 % in exemption 3 should be maintained. As to the substitution of lead, valves in variable capacity air conditioners operating with steel shafts, and two insert nuts could be demonstrated to be cases where a lead-free alloy successfully replaced the standard copper alloy C36000, which contains 3 % of lead. Since the technical details of the air conditioners and the exact uses of the insert nuts produced from lead-free alloy could not be accessed, these substitution successes uses cannot be reflected in a restricted exemption scope.

Applicants need to provide evidence that the use of lead in a specific exemption is unavoidable. The examples of failed lead-free copper parts provided by ACEA et al. are in parts inconclusive and non-transparent. ACEA et al. claim that they selected the examples to what in their opinion were the most promising lead-free alloys and processing conditions and based on the weak points of the different lead-free candidate materials assessed with scientific support. ACEA et al. do not reveal, however, which considerations and scientific results led them to choose the materials that they selected for the failed parts. The same applies to the processing conditions. This situation of unsatisfying evidences was already criticized in the last review of this exemption by Gensch et al. (2016).

Given the various applications of leaded copper alloys in automotive parts, evidence that the use of lead is unavoidable may always remain anecdotal to a certain degree since not each and everything can be tested. It can, however, be expected that the presented evidence follows a more systematic approach and is transparent, complete and conclusive.

The consultants propose a less anecdotal, more systematic, transparent and substitution-oriented approach. This should imply to stop testing properties of lead-free copper alloys with the requirement that they either can substitute leaded copper alloys in all applications, or to otherwise disqualify the lead-free copper alloys (c.f. example on page 39 et sq.). ACEA et al. point out that lead-free alloys will be required for the various applications of leaded copper alloys. The examples of the successful lead substitutions show that a lead-free alloy which failed tests of ACEA et al. can be applied successfully in specific applications. Hence, the consultants suggest an application-specific approach. If not yet available, this would require, next to characterizing materials, to first of all characterize applications, for example setting up basic requirement profiles for copper alloy parts in each of the three main application groups[14], which can then be further specified for the various applications within each of these groups. Based on this, materials and their processing could be selected. The approach should include an iterative and systemic view. Components produced from copper alloys are parts of systems, which can, if needed, potentially be adapted within certain limits to accommodate the strengths and weaknesses of lead-free copper alloys. It should also be taken into account that processing of lead-free copper alloys may need different approaches as well. This experience was made already the substitution of lead in solders, which required different processing with modified soldering equipment.

The above-proposed approach does not imply that substitution of lead is already possible in each use of leaded copper alloys. It could rather be a step to allow systematic assessments, enable application-specific substitution and provide sound evidence where exemption 3 is still needed.

5.5 Recommendation

ACEA et al. reduced the use of leaded copper alloys in the past years thus complying with their legal obligation that accrues to them from Art. 4(2)(b)(II), i.e. to replace lead where its use is avoidable. ACEA et al. report to know of no case where lead-free could substitute leaded copper alloys and claim that the use of lead is still unavoidable. Substitution of lead in copper alloys could, however, be proved to be feasible in two specific applications while the evidence provided by ACEA et al. as to the unavoidability of lead use in copper alloys is anecdotal and in parts inconclusive due to lacking information and transparency. This situation had been criticized in previous reviews of ELV exemptions already.

Around 20 lead-free alloys are reported to be available meanwhile, including new ones just having entered the market. In the consultants' opinion, this should offer potential for further application/specific substitutions if application-specific and systematic tests are applied (c.f. section 5.4.4 above).

In the light of the above, appraising the fact that the use of lead in copper alloys has been reduced according to the information made accessible by ACEA et al., the consultants think that the continuation of exemption 3 might still be justifiable in line with Art. 4(2)(b)(II), despite the insufficient evidence provided. If the Commission shares this point of view, the consultants recommend continuing the exemption with the current wording. The available information and findings neither justify reducing the maximum lead content down from 4 %, nor excluding applications of leaded copper alloys from the exemption scope.

For the validity period, the consultants suggest three years. The Commission might consider four years to enable the review of this exemption in parallel to the corresponding RoHS exemption III-6(c). Eight years as requested by ACEA et al. in the consultants' view cannot be justified in line with Art. 5(2)(b)(2) taking into account the proven cases where lead could be avoided in copper alloys, and that in the consultant's opinion there is potential for

[14] ACEA et al. group copper alloy parts into sliding elements, mechanical connecting elements, and electric applications.

substitution in more applications. This should allow sufficient time for application-centred and specific assessments of substitution possibilities or, in case, impossibilities, so that in the next review, applicants can provide substantiated, sound and transparent evidence where the use of lead may still be unavoidable.

The consultants recommend the following wording for the exemption:

	Materials and components	*Scope and expiry date of the exemptio*	
	Copper alloys containing up to 4 % lead by weight	*This exemption shall be reviewed in 2024*	

5.6 References

ACEA et al. (2014): Contribution to the stakeholder consultation for the 2014 review of exemption 3. ACEA et al. Online verfügbar unter https://elv.exemptions.oeko.info/fileadmin/user_upload/Consultation_2014_1/Ex_3/E3__20___OEM2___JA-03__tire-valve.pdf.

ACEA et al. (2020): Answers to questionnaire 1 for exemption 3 of ELV Annex II (consultation questionnaire). Unter Mitarbeit von ACEA, CLEPA, JAMA, KAMA. Online verfügbar unter http://www.elv.biois.eu/ACEA_3.pdf.

ACEA et al. (2021a): Answers to questionnaire 2 for exemption 3 of ELV Annex II received via e-mail from Amélie Salau, ACEA, by Dr. Otmar Deubzer, UNITAR, on 28 January 2021. Unter Mitarbeit von ACEA, CLEPA, JAMA, KAMA. Online verfügbar unter http://www.elv.biois.eu/ACEA_3.pdf.

ACEA et al. (2021b): Answers to questionnaire 4 for exemption 3 of ELV Annex II received via e-mail from Amélie Salau, ACEA, by Dr. Otmar Deubzer, UNITAR, on 5 May 2021.

ACEA et al. (2021c): Answers to questionnaire 5 for exemption 3 of ELV Annex II received via e-mail from Amélie Salau, ACEA, by Dr. Otmar Deubzer, UNITAR, on 9 June 2021.

Gensch et al. (2016): 8th Adaptation to scientific and technical progress of exemptions 2(c), 3 and 5 of Annex II to Directive 2000/53/EC (ELV). Report for the European Commission DG Environment under Framework Contract No ENV.C.2/FRA/2011/0020. Final Report. Unter Mitarbeit von Carl-Otto Gensch, Yifaat Baron, Katja Moch, Öko-Institut (ELV 8). Online verfügbar unter https://circabc.europa.eu/.

MMC (2020): Answers to questionnaire 1 (consultation questionnaire) for exemption 3 of ELV Annex II. Unter Mitarbeit von Mitsubishi Materials Corporation. Online verfügbar unter http://www.elv.biois.eu/MITSUBISHI.pdf.

MMC (2021a): Answers to questionnaire 2 for exemption 3 of ELV Annex II, received via e-mail from Takashi Oka, Mitsubishi Materials Corporation, by Dr. Otmar Deubzer, UNITAR, on 22 January 2021. Unter Mitarbeit von Mitsubishi Materials Corporation.

MMC (2021b): Answers to questionnaire 3 for exemption 3 of ELV Annex II, received by Dr. Otmar Deubzer, UNITAR, from Takashi Oka, Mitsubishi Materials Corporation, via e-mail on 23 February 2021. Unter Mitarbeit von Mitsubishi Materials Corporation.

MMC (2021c): Answers to questionnaire 4 for exemption 3 of ELV Annex II, received via e-mail from Takashi Oka, Mitsubishi Materials Corporation, by Dr. Otmar Deubzer, UNITAR, via e-mail on 4 March 2021. Unter Mitarbeit von Mitsubishi Materials Corporation.

MMC (2021d): Answers to questionnaire 5 for exemption 3 of ELV Annex II, received via e-mail from Takashi Oka, Mitsubishi Materials Corporation, by Dr. Otmar Deubzer, UNITAR, via e-mail on 25 May 2021. Unter Mitarbeit von Mitsubishi Materials Corporation.

MMC (2021e): Answers to questionnaire 6 for exemption 3 of ELV Annex II, received via e-mail from Takashi Oka, Mitsubishi Materials Corporation, by Dr. Otmar Deubzer, UNITAR, via e-mail on 27 May 2021. Unter Mitarbeit von Mitsubishi Materials Corporation.

Zangl et al. (2010): Adaptation to scientific and technical progress of Annex II to Directive Adaptation Directive2000/53/EC (ELV) and of the Annex to Directive 2002/95/EC (RoHS). Final report - revised version. Final Report. Unter Mitarbeit von Stéphanie Zangl, Markus Blepp, Carl-Otto Gensch, Ran Liu, Katja Moch [Öko-Institut e.V.] und Otmar Deubzer, Deubzer, Otmar [Fraunhofer IZM]. Öko-Institut e. V. und Fraunhofer IZM. Freiburg (Adaptation to scientific and technical progress of Directive 2000/53/EC and 2002/96/EC; ELV and RoHS exemption review, RoHS IV, ELV II). Online verfügbar unter https://circabc.europa.eu/sd/d/a4bca0a9-b6de-401d-beff-6d15bf423915/Corr_Final%20report_ELV_RoHS_28_07_2010.pdf.

6 Exemption 5(b) of ELV Annex II: Lead and lead compounds in non-traction batteries

The exact wording of exemption 5(b) of Annex 2 is:

> *«Lead in batteries for battery applications not included in entry 5(a)»*

The exemption is due for review in 2021.

Declaration

In the sections preceding the “Critical review”, the phrasings and wordings of applicants’ and stakeholders’ explanations and arguments have been adopted from the documents they provided as far as required and reasonable in the context of the evaluation at hand. Formulations were only altered or completed in cases where it was necessary to maintain the readability and comprehensibility of the text.

Acronyms and definitions

AGM	absorptive glass mat
AUX	auxiliary
BEV	battery electric vehicle
BMS	battery management system
CCA	cold cranking amps
DCA	dynamic charge acceptance
DoD	depth of discharge
EFB	enhanced flooded batteries
ELV	end-of-life vehicles
EOL	end-of-life
HEV	hybrid electric vehicle
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
LAB	lead-acid battery
LFP	lithium iron phosphate
LIB	lithium-ion battery
NiMH	nickel metal hydride battery

NMC	nickel manganese cobalt
OEM	original equipment manufacturer
SEI	solid electrolyte interface
SLI	starting lighting ignition
SoC	state of charge

6.1 Background and Technical Information

Exemption 5(b) of ELV Annex II is due for review. A stakeholder consultation was conducted to which ACEA et al., EGARA and Bosch contributed by answering the questions of the consultation questionnaire.

6.1.1 Summary of the stakeholder contributions

ACEA et al.

According to (ACEA et al. 2020), lead acid batteries (LAB) are currently used in virtually all vehicles on the road from internal combustion engine vehicles (ICEV) all the way up to fully electric vehicles. These batteries are used either as a 12 V Starting Lighting Ignition (SLI) battery or as 12 V auxiliary (AUX) battery. According to (ACEA et al. 2020), through 2030, almost all light-duty vehicles are likely to feature a 12 V board net, and thus require either a 12 V SLI or AUX battery. There is a range of requirements for these applications that include cold cranking, high temperature durability, functional safety, cost, 12 V board net compatibility, manufacturing base, and ability to be highly recyclable. (ACEA et al. 2020) argue that lead batteries are the only known technology that currently meets all OEM requirements for 12 V applications.

12 V SLI batteries are used in vehicles that feature a combustion engine. Regarding SLI batteries, (ACEA et al. 2020) report that 12 V Li-Ion batteries (LIB) have made significant improvements in terms of cold-cranking and are now reported by their manufacturers to be comparable to lead batteries. However, it is further noted that OEMs remain concerned as there is still insufficient evidence that LIB can provide this cold cranking capability over the full lifetime of the battery. Additionally, further research is required into LIB in terms of high temperature durability, safety, and other challenges, in order to achieve mass market availability. It is stated that it remains a challenge for Li-Ion SLI batteries to meet the technical and safety requirements at temperatures that occur in the engine compartments of typical vehicles (>65°C).

12 V AUX batteries are used in vehicles without combustion engine, or in vehicles with combustion engine as supporting battery. Regarding AUX batteries, (ACEA et al. 2020) state that lead batteries are still the state of the art in vehicles, and the only chemistry used in this application. It is explained that there is no experience or knowledge of the suitability of other battery chemistries for this function.

According to (ACEA et al. 2020), from a market standpoint, 12 V LIB are still very much an emerging and high cost product. Although Li-Ion technologies have some performance advantages to lead-acid in 12 V SLI applications, they remain costly, are not commercially mature enough, and do not currently meet all critical OEM specific requirements. Some OEMs have deployed a very limited number of 12 V LIB (<<1% of current vehicles), most commonly in motor sport-oriented vehicles.

(ACEA et al. 2020) report that lead-acid batteries are almost completely recycled within the EU. It is stated that only 0.8 % of the total made-available end-of-life lead automotive batteries are exported outside the EU. In contrast, LIB recycling is in its infancy and 12 V LFP LIB do not contain economically valuable resources.

(ACEA et al. 2020) state that significant further research is needed to address safety and high temperature performance of Li-ion batteries. This requires development and testing on several levels, including development and testing at material, cell, battery pack, and vehicle level. Additionally, standardization work is needed for LIB to enable interchangeability. (ACEA et al. 2020) report that it is not possible to predict how long it will take to complete these tasks. Therefore, the use of lead in the application addressed under exemption 5(b) is still unavoidable. (ACEA et al. 2020) further request to keep the same wording for the entry and to avoid any further split into new subentries.

Bosch

According to (Bosch 2020), further research is needed on the following topics before LIB can substitute LAB in automotive 12 V applications in the mid-term:

- With current state-of-the art concepts, reliable functionality via LIB cannot be guaranteed in all operation points, e.g. post-crash or overvoltage situations.
- Dual battery systems with high safety requirements depend on diverse redundancy, therefore combined systems of LIB and LAB currently seem to be beneficial.

In terms of cold cranking performance, (Bosch 2020) state that parity of LIB versus LAB has been reached. In addition, (Bosch 2020) report that many electrified vehicles that feature higher voltage batteries use the higher voltage level rather than the 12 V battery to crank the engine. However, it is also stated that the power capabilities of LIB have an increased temperature dependency, which affects performances at extremely low or high temperatures.

(Bosch 2020) elaborate that the recycling rate for LAB in the EU is close to 99 %, with approximately 1 % of vehicles including their batteries exported to Africa, where the collection of the battery cannot be recorded. For LIB, (Bosch 2020) state that no actual recycling rate data or regulation is available. The LIB price is currently higher than comparable LAB mainly due to higher cell prices and additional safety electronics needed for the lithium-ion cells. However, a further reduction of LIB prices is expected.

(Bosch 2020) expect to see that LIB will replace LAB technology in the mid-term. However, for a broad market introduction of LIB, there is the need for further research on the above mentioned technical topics. (Bosch 2020) recommend continuing the exemption for lead acid batteries in vehicle applications until end of 2025 with a transition phase of 2-3 years until end of 2027/2028.

EGARA

With regards to LAB still being the default 12 V battery in vehicles, (EGARA 2020) state that the alternatives are expensive where lead is much more affordable. Li-ion requires a battery management system (BMS), making it an expensive technology. Li-ion batteries cannot function in cold temperatures, therefore heating systems are necessary, which are costly. LAB is a reliable technology, functioning under a range of conditions without any complex added technologies.

(EGARA 2020) further argue that lead does not affect the environment, as it will be collected at the end-of-life as a result of its high (economic) value. It is therefore stated to be a perfect example of a circular economy. The reason for the high recycling rate of lead is reported to be the high (economical) value of lead. Lead is easy and cheap to recycle, making lead-acid batteries recycling easy, as it does not require complex technology. LAB are as easy to store and to transport in the waste phase as in the pre-use phase. On the contrary, (EGARA 2020) state that lithium, and especially Li-ion applications, need special transport and storage safety measures, such as fire prevention and monitoring, as they can become unreliable and catch fire, especially in case of damage. (EGARA 2020) state that when lead is phased out, it will end up at undesired places.

Due to the above mentioned reasons, (EGARA 2020) argue that the exemption should be continued.

6.1.2 History of the Exemption

The legal text of the ELV Directive published in 2000 required in Article 4(2)(b) that the Commission shall evaluate the need for exempting the use of the ELV substances in a number of applications. This included evaluations for a number of specific applications including the use of lead in batteries. In light of this requirement, an evaluation was carried out, results of which recommended an exemption, subsequently added to Annex II.

Exemption 5 has been available for such applications as early as the first amendment of Annex II to the Directive. It was reviewed in 2009/2010, at which time it was recommended to extend the exemption, scheduling a review within five years. Based on evidence available at the time, the main rationale behind the recommendation was that substitution with the available lead-free alternatives would reduce the functionality and reliability of vehicles.

The Commission followed this recommendation so that the exemption was reviewed in 2015/2016 (Gensch et al. 2016). The conclusions are summarized with respect to three different cases, being SLI batteries, AUX batteries and propulsion batteries:

- With respect to SLI batteries, it was concluded that the use of lead in automotive batteries could not be avoided at the time, in cases where starter functionality is of relevance. The main rationale for this was that LIB still needed improvement with respect to their cold cranking performance at -30°C, in addition to safety aspects relating to the need to locate LIB away from crush zones and areas with high thermal stress, while SLI needed to be located in the engine compartment. Therefore, LIB could not be used as mass market starter battery at the time. Possible alternatives were not yet market mature at the time. Nonetheless, the current state of the various alternatives suggests that within a few years, the use of lead-acid batteries may become avoidable, at least in some vehicles, with other vehicles possibly requiring more time for implementation than others. The automotive industry could not commit to a certain timeframe for a possible phase-out of LAB without first surveying all models and without planning the various stages needed to complete and implement the redesign of vehicles. In the view of (Gensch et al. 2016), as the cold cranking performance of LIB was expected to reach parity with LAB within three to five years later, phase-out dates for LAB should be feasible to be set in the next review of the exemption.

- With respect to AUX batteries, where starter functionality is not required, (Gensch et al. 2016) followed the argument of the automotive industry that no field experience had been accumulated for lead-free batteries in this application. However, LIB were seen as a promising candidate to replace LAB as auxiliary battery.
- With respect to propulsion batteries, (Gensch et al. 2016) concluded that lead-acid batteries were not commonly used in this function, and were therefore technically avoidable. Consequently, propulsion batteries were recommended to be excluded from the scope of the exemption.

The Commission followed the recommendation to distinguish between propulsion and non-propulsion batteries with Commission Directive (EU) 2017/2096, which split Entry 5 into:

- 5 (a) “Lead in batteries in high voltage systems[15] that are used for propulsion in M1 and N1 vehicles”, and
- 5 (b) “Lead in batteries for battery applications not included in entry 5 (a)”.

An expiry date has been set for Exemption 5 (a) for vehicles type approved after 1st January 2019, for 5 (b) a review date for 2021 had been set.

6.1.3 Technical description of the exemption and use of restricted substance

Lead is used in lead-acid batteries (LAB) in most light-duty vehicles (LDV) for a range of different functions, either as 12 V starter battery (SLI) or as 12 V auxiliary battery (AUX). Several types of batteries are currently used in a diversifying market of light-duty vehicles that differ in their level of electrification. The following subchapters first describe automotive lead acid batteries in general, and then specify the different vehicle and powertrain types and automotive battery systems, and technical requirements imposed by each application.

Automotive lead-acid batteries

(Ricardo 2020) described that all lead-based batteries feature the same basic chemistry. The active material of the positive plate mainly comprises lead dioxide, and the active material of the negative plate comprises finely dispersed metallic lead. These plates react

[15] Systems that have a voltage of > 75 V DC as defined in Directive 2006/95/EC of the European Parliament and of the Council of 12 December 2006 on the harmonisation of the laws of Member States relating to electrical equipment designed for use within certain voltage limits (OJ L 374, 27.12.2006, p. 10).

with a sulphuric acid electrolyte to form lead sulphate during discharge; actions are reversed during recharging. The lead and lead dioxide accounts for approximately 60 % of the overall battery pack weight, the electrolyte typically accounts for 30 % of the weight. Other alloying components and polymers accounting for the remaining 10 % of the battery weight. (ACEA et al. 2020) stated that a standard lead SLI battery contains approximately 10.95 kg of lead and lead compounds.

(Ricardo 2020) explain that automotive 12 V lead-based batteries comprise six 2 V cells, connected in series. Conventional ICE-powered vehicles have typically used conventional flooded 12 V lead-based batteries for SLI applications and to power the 12 V board net. These flooded lead-based batteries use free-flowing electrolyte surrounding the electrode stack. Rapid adoption of Stop-Start technology has necessitated battery improvements. Absorbent glass mat (AGM) and enhanced flooded batteries (EFB) have been developed for micro-hybrid applications. These batteries have improved deep cycle resistance and charge recovery in comparison to traditional flooded SLI batteries. EFB and AGM batteries are necessary, not only to cope with frequent stops and starts of the engine, but also to provide enough power supply to the electrical system while the engine is in stop mode. In addition, micro-hybrids require improved dynamic charge acceptance (DCA) in order to facilitate regenerative braking.

Automotive vehicles and powertrains

Batteries of several technologies are employed in different automotive applications. A range of different light-duty vehicle types are currently available on the European market, featuring increasing degrees of electrification. The following definitions are adopted from (Gensch et al. 2016):

Table 6-1: Vehicle / powertrain types and their level of electrification

Vehicle / powertrain type	Description
Conventional internal combustion engine vehicles (ICEV)	No electrification. The battery is used only for starting the internal combustion engine, lighting and ignition.
Start-stop (S/S) vehicles	Low degree of electrification. The internal combustion engine is automatically shut down under braking and rest.
Micro-hybrid and mild-hybrid vehicles (MHEV)	Low to medium degree of electrification. Start-stop systems combined with regenerative braking, where stored energy is then used to boost the vehicle's acceleration.
Full-hybrid electric vehicles (HEV)	Medium degree of electrification. Equivalent characteristics to mild-hybrid vehicles, but the stored energy within the battery is also used for a certain range of electric driving
Plug-in hybrid electric vehicles (PHEV)	High degree of electrification. The battery is used as the main energy source for daily trips (i.e. 20-50 km), but if necessary PHEVs can also run in hybrid mode using a combustion

	engine. Batteries may be charged with off-board electric energy.
Battery electric vehicles (BEV)	Full electrification. The battery is used as the vehicle's only energy source, with no internal combustion engine. Batteries are charged with off-board electric energy.

Fuel-cell electric vehicles (FCEV) are another type of vehicle. FCEVs use a propulsion system similar to that of electric vehicles, where energy stored as hydrogen is converted to electricity by the fuel cell. The electricity can be stored in a high-voltage battery. FCEV are, however, not explicitly addressed in the stakeholder contributions.

Automotive battery systems

According to (ACEA et al. 2020), automotive batteries fall into the following three categories:

- 12 V Starting-lighting-ignition (SLI) batteries
- 12 V Auxiliary batteries
- Higher voltage traction batteries

(Gensch et al. 2016) clarified that the vehicle electrical system has developed over decades in parallel and together with the 12 V lead acid starter battery. Operating voltage of electrical and electronic components has been globally standardized at this level and installed batteries must be compatible with these 12 V systems. The vehicle electrical system is globally standardised for all vehicles – from ICEV up to BEV – to be compatible with 12 V lead-based batteries. 48 V and higher voltage traction batteries are a more recent development. According to (ACEA et al. 2020), vehicles with 48 V battery or higher voltage traction battery always also have a 12 V battery on board.

(ACEA et al. 2021a) provide descriptions for the different battery types, summarized in Table 6-2.

Table 6-2 : Battery types employed in automobiles today

Battery type	Common technology	Description of main functionality
12 V SLI batteries	LAB	SLI batteries are used in any vehicle that has an internal combustion engine (conventional, start-stop micro-hybrid, full and plug-in hybrid vehicles) to crank the engine and power a range of essential safety and electronic features as well as normal vehicle systems.
12 V AUX batteries	LAB	Auxiliary batteries are utilised in vehicles without combustion engine or in vehicles with combustion engine as supporting battery and are considered safety batteries. For instance in BEV, in the case of the high voltage traction battery failing, the auxiliary battery can power safety features (brakes, power steering) to allow the car to pull over safely and to sustain control systems. These batteries can also power the Battery Management System (BMS) to ensure that the high voltage battery operates safely.

48 V batteries	LIB	48 V batteries are used in mild hybrid vehicles. The battery mainly recovers braking energy and is discharged into an electric traction motor to provide power assist. 48 V batteries can also supply air conditioning, pumps and fans, depending on the vehicle architecture. A 12 V SLI battery is required in addition to start the combustion engine, ensure a stable voltage on the 12 V system during driving, support the key off loads during parking, and to supply power to all the car's electronic control units, including the high voltage battery.
High voltage traction batteries	LIB	These batteries provide propulsion to vehicles and have a much higher voltage (400 V or higher) than the batteries described above. Note: This battery type is not included in the scope of exemption 5(b) and is only listed for the sake of completeness.

(ACEA et al. 2020) provide descriptions of the functions provided by the different battery types as listed in the following.

12 V SLI batteries provide the following main functions:

- Starting, lighting, ignition
- Start-stop and micro-hybrid functions
- Power supply in sleep mode and in vehicle wake-up
- Emergency illumination and hazard warning lights
- Electronic locks
- ABS (anti-lock braking system) control units
- ESP (Electronic Stability Program) control units
- Independent heating systems
- Emergency call support after a crash
- Defrosting systems
- Displays for car information
- Power steering
- Electric windows levers
- Infotainment

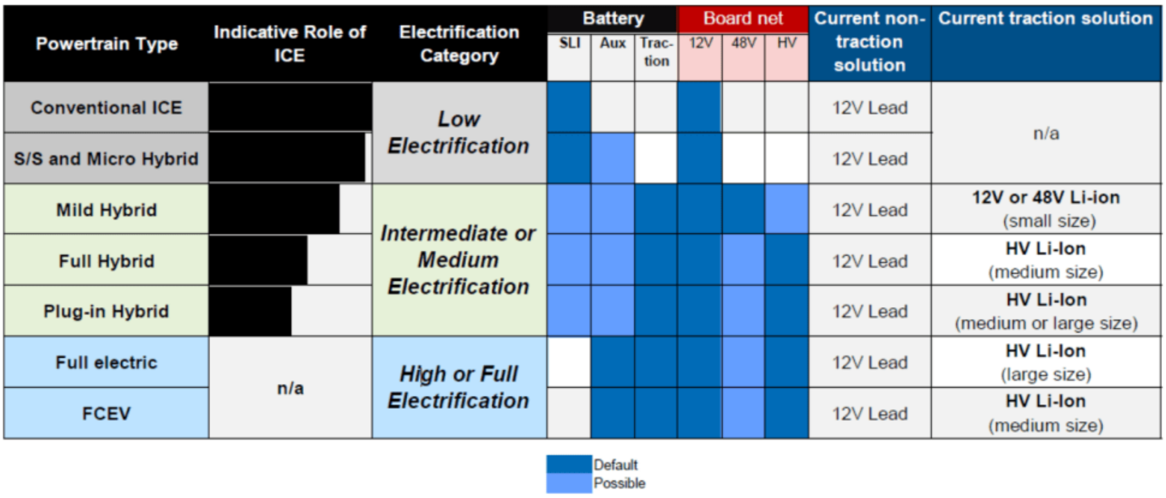
In addition to functions listed above (except start-stop and micro-hybrid functionality), 12 V AUX batteries for hybrid and electric vehicles also provide the following functions:

- Powering the battery management system of traction battery
- SLI for range extender ICE

48 V batteries are used in mild hybrid vehicles. The battery mainly recovers braking energy and is discharged into an electric traction motor to provide power assist. This means the engine can be downsized resulting in reduced CO_2 emissions. These vehicles can also use the 48 V battery to supply components that are normally powered by the engine such as air conditioning, pumps and fans depending on the vehicle architecture. A 12 V battery will still be required to start the engine (ACEA et al. 2021a).

The battery types (Table 6-2) are employed in different combinations in the different types of light duty vehicles (Table 6-1), where different requirements are placed on the batteries. Figure 6-1 provides an overview of the main vehicle / powertrain types, the battery types, board net, and current traction and non-traction battery solution employed. According to (Ricardo 2020), all vehicle types currently employ 12 V lead-based batteries for non-traction battery-powered functions. It is expected that through 2030, almost all light-duty vehicles are likely to feature a 12 V board net, and thus require either a 12 V SLI or AUX battery.

Figure 6-1 : Categories of main existing and possible light-duty vehicle powertrain solutions



Source: (Ricardo 2020)

Battery types and technical requirements

(ACEA et al. 2020) summarised technical requirements that need to be met by batteries in different applications (SLI and AUX) in different vehicle types (Figure 6-2).

Figure 6-2: Summary of technical requirements imposed on different vehicle batteries in different vehicle types

	ICE	S/S Micro-hybrid		Mild-hybrid		
	12 V SLI	12 VSLI	12 V Aux*	12 V SLI	48 V	12 V Aux
CCA (°C)/ cold temp performance (°C)	-30	-30	-30	-30	-30	-30
Cycling or Start-Stop	No	High	No	No	High	No
High Temp (°C)	> 75	>75	> 75	> 75	> 75	> 75
Board net	12 V compatible	12 V	12 V	12 V	12 V	12 V
Calendar life (years)	5 to 7	5 to 7	5 to 7	5 to 7	5 to 7	5 to 7
Safety	High	High	High	High	High	High
Functional Safety	High	High	High	High	High	High
Cost	Low	Low	Low	Low	Low	Low
Manufacturing base	EU extensive	EU extensive	EU extensive	EU extensive	EU extensive	EU extensive
Recycling	High	High	High	High	High	High

	Full-hybrid			PHEV/EV	
	12 V SLI	12 V Aux	HV Traction* *	12 V Aux	HV Traction**
CCA (°C)/ cold temp performance (°C)	-30	-30	N/A	-30	N/A
Cycling or Start-Stop	No	No	High	No	High
High Temp (°C)	> 75	> 75	N/A	> 75	N/A
Board net	12 V	12 V	N/A	12 V	N/A
Calendar life (years)	5 to 7	5 to 7	N/A	5 to 7	N/A
Safety	High	High	N/A	High	N/A
Functional Safety	High	High	N/A	High	N/A
Cost	Low	Low	N/A	Low	N/A
Manufacturing base	EU extensive	EU extensive	N/A	EU extensive	N/A
Recycling	High	High	N/A	High	N/A

* only small number of models
** only batteries with voltages less than 75 V under scope of this exemption

Source: (ACEA et al. 2020)

(Ricardo 2020) reported another summary of requirements imposed on batteries by different vehicle electrification categories (Figure 6-3).

Figure 6-3 : Summary of current and future vehicle requirements

Summary of High-Level Vehicle Requirements			
	Low Electrification Vehicles	**Medium Electrification Vehicles**	**High Electrification Vehicles**
Vehicle Types	* Conventional ICE vehicles * Start/Stop micro-hybrid vehicles	* Mild hybrid vehicles (MHEVs) * Full hybrid vehicles (HEVs) * Plug-in hybrid vehicles (PHEVs)	* Battery electric vehicles (BEVs) * Fuel-cell electric vehicles (FCEVs)
12 V Battery Present?	* Yes	* Yes	* Yes
Battery Responsibilities	* Starting the engine * Power 12 V board net when engine off during Stop operation * Power 12 V board net during driving	* Power 12 V board net when engine turned off during Stop/Start operation * Power 12 V board net hotel loads, i.e. central locking & alarms * For some vehicles, starting engine	* Enable starting of HV system * Power 12 V board net when HV system turned off * Power 12 V board net hotel loads, i.e. central locking & alarms
Current Vehicle Requirements: 12 V Battery	* Cold cranking performance * Sufficient to power board net during ICE shut-down * Sufficient to power safety devices when engine-off * Compatibility with 12 V board net	* Sufficient capacity to power board net during engine shut-down * Sufficient capacity to power safety devices when engine-off * Compatibility with 12 V board net	* Sufficient capacity to power safety devices when HV system is turned off/disconnected * Compatibility with 12 V board net
Future Requirements: 12 V Battery	* Capacity increase for connectivity (e.g. V2V V2X), over the air updates; Car will always need to be 'on'; increase in quiescent loads * Autonomy – may need for an additional 12 V battery for back-up redundancy purposes	* More vehicles cranking engine with 48 V battery; 12 V battery may be needed for cold cranking situations (i.e. more battery combinations) * Car will always need to be 'on'; increase in quiescent loads * Autonomy – may need an additional 12 V battery for back-up redundancy purposes	* Car will always need to be 'on'; increase in quiescent loads * Autonomy – may need for an additional 12 V battery for back-up redundancy purposes

Source: (Ricardo 2020)

(ACEA et al. 2020) argue that lead batteries are the only known technology that currently meets all OEM requirements for 12 V applications. This is described in more detail in chapter 6.2.

6.1.4 Amount of lead used under the exemption

According to (ACEA et al. 2020), approximately 18 million vehicles (M1, N1) were newly registered in the EU-28 in the year 2019. As every new vehicle contains a lead acid battery, 18 million units were placed on the market by OEMs in a newly registered vehicle. A standard lead SLI battery contains approximately 10.95 kg of lead and lead compounds. Therefore, it can be estimated that in 2019, new passenger cars placed on the market contained approx. 198,000 metric tonnes of lead.

(ACEA et al. 2020) further estimate that in 2019, the EU represented approximately 20 % of new vehicle (M1 and N1) registrations on the global market. It can therefore be estimated that approximately 90 million new M1 and N1 were registered globally, containing approximately 985,000 metric tonnes of lead in their batteries.

As of 2018, (Ricardo 2020) estimated that the European market annually required over 20 million OEM 12 V SLI batteries and over 40 million aftermarket 12 V SLI batteries. Light-duty vehicles require, and will continue to require for at least a decade, tens of millions for 12 V batteries to perform critical functions. It can therefore be estimated that approximately

438,000 metric tonnes of lead were placed on the market through aftermarket 12 V SLI batteries.

Combining the data for 12 V LAB placed on the EU market in newly registered vehicles in 2019 and as aftermarket batteries in 2018, approximately 58 million batteries were placed on the market, containing approximately 636,000 metric tons of lead.

Table 6-3: Estimation of amount of lead used in automotive 12 V batteries per anno

Relevant products placed on the EU market	Approximate number	Approx. amount of contained lead [tonnes/p.a.]
LAB in newly registered vehicles in the EU in 2019	18,000,000	198,000
Aftermarket LAB placed on the EU market in 2018	40,000,000	438,000
Sum	58,000,000	636,000

Ferg et al. 2019 estimated approximately 97 million LAB SLI batteries were placed onto the global market in new passenger and commercial vehicles in the year 2017, in addition to about 165 million replacement batteries in the same year, with projected increase of 3-5% per year. This data is in line with the data approximated above.

6.2 Justification for the requested exemption

6.2.1 Substitution of lead

No information regarding the substitution of lead in lead acid batteries with another material has been made available to or could be identified by the consultants. The direct substitution of lead in lead acid batteries does not appear to be a viable concept at the current time.

6.2.2 Elimination of lead

(ACEA et al. 2020) argue that lead batteries are the only known technology that currently meets all OEM requirements for 12 V applications. Lithium iron phosphate (LFP) batteries are most commonly discussed as a potential alternative to lead-acid batteries in this application, but are not mature enough for large market applicability (ACEA et al. 2020). Supercapacitors were extensively covered as a potential alternative in the previous review of this exemption carried out by (Gensch et al. 2016), but were not a major theme in the current stakeholder contributions.

(ACEA et al. 2020) elaborate that for a battery to be selected by an OEM for automotive use, it has to meet the following requirements:

- Cold cranking at -30°C
- Robust performance in start-stop and micro-hybrid functions

- High temperature performance at 75°C (or OEM specific temperatures)
- Specific safety standards on battery and vehicle level
- Calendar life of 5-7 years
- Compliance with applicable international standards and specific OEM requirements for performance, durability, and safety

In addition, the technology should be:

- Low cost
- Standardised
- Compatible with the 12 V board net
- Fully recyclable at end of life
- Easy to handle in service procedures

(ACEA et al. 2020) report that significant technical progress has been made with LFP batteries. Parity in cold cranking capability is reported by LIB manufactures, which is a key requirement for automotive use. However, (ACEA et al. 2020) further state that lithium batteries still do not meet all the OEM requirements listed above, and need to make further progress with regard to:

- High temperature durability
- Wide range of temperature spread
- Safety
- Failure in Time (FIT)-Rates: Availability for safe energy supply
- Cost (initial cost and lifetime cost)
- Interchangeability
- Recycling
- Availability of parts for the replacement market

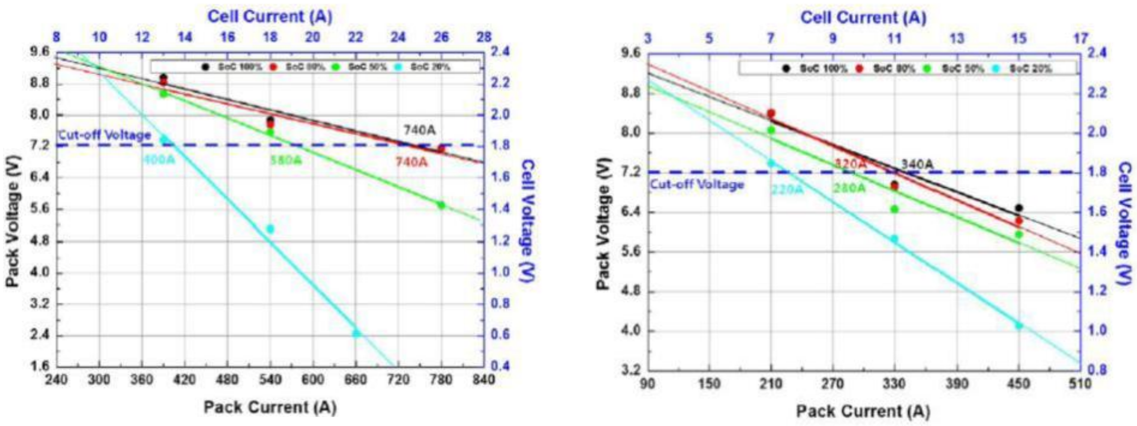
The detailed information provided by (ACEA et al. 2020) on some of the above points has been summarized under subheadings below.

Cold cranking performance

(ACEA et al. 2020) state that the cold cranking performance of Li-Ion SLI batteries has improved significantly in the past few years and that LIB manufacturers now report parity with 12 V LAB in terms of cold cranking performance. Reportedly, they have achieved this by optimising the electrolyte, using materials with lower freezing points in addition to making use of electrolyte additives. (ACEA et al. 2020) state that while new electrode materials are used to ensure lithium batteries can meet cold cranking requirements, this has resulted in a trade-off in high-temperature performance and safety. (ACEA et al. 2021b) added that in order to improve the low temperature performance of LIB, new thinner electrodes were employed, which also compromised the high-temperature performance and safety of those batteries.

(ACEA et al. 2020) state that although cold cranking parity has reportedly been reached, OEMs remain concerned as there is still insufficient evidence that LFP batteries can provide this cold cranking capability over the full lifetime of the battery. When requested to provide empirical data on the performance of LIB and LAB from the field or laboratory testing, (ACEA et al. 2021b) provided the figures and data tables described in the following paragraphs.

Figure 6-4: CCA current provided by lithium-ion batteries at -18°C (left) and -30 °C (right)



Source: (ACEA et al. 2021b)

According to (ACEA et al. 2021b), OEMs report that on current architectures, the minimum voltage level is fixed to a minimum of 6.5-7.0 V for robust starting procedures. Below that value, electronic control units fail to operate properly or go into reset mode. A voltage drop below 6.5 to 7.0 V during cold starting operation is not acceptable. This is seen as a challenge for LIB. The data presented in Figure 6-4 was collected from vehicles equipped with 12 V LFP batteries, showing their cold cranking performance at -18°C and -30°C, respectively. In both diagrams, the coloured lines represent the current provided by a battery and a cell at different states-of-charge (SoC). The dotted line across both graphs represents the cut off voltage. The cut off voltage is the lowest limit at which the battery can provide sufficient current to start the engine. In general, if the voltage is below the lowest limit, the power would be shut off for safety (ACEA et al. 2021b).

Table 6-4: Maximum current provided by lithium-ion batteries at different states-of-charge (SOC)

BATTERY TEMP.	SOC	MAX CURRENT (A)	COMMENTS
-18°C	100%	740A	-
	80%	740A	-
	50%	580A	-
	20%	400A	-
-30°C	100%	340A	46% compared to - 18 °C
	80%	320A	43% compared to - 18 °C
	50%	280A	48% compared to - 18 °C
	20%	220A	55% compared to - 18 °C

Source: (ACEA et al. 2021b)

Table 6-4 summarizes the data presented in Figure 6-4. According to (ACEA et al. 2021b), a current of more than 580 A is typically required to start the engine. The data shows that the LIB meets this requirement at 100 % and 80 % state of charge at -18°C. However, it does not deliver the required current below 80 % state of charge at -18°C. At -30°C, the problem is worse – the data shows that insufficient current is provided by the lithium-ion battery at all states-of-charge. According to (ACEA et al. 2021b), this highlights that although LIB have made progress with cold cranking, they still do not meet the OEM requirements at -30°C.

Table 6-5: Cold cranking tests of 12 V Li-ion batteries for gasoline and diesel vehicles

Aging by Cycling LFP

Overview Cold Cranking Tests (green: passed, red: failed)

Cycles	Otto Engine		Diesel Engine	
0	003	004	003	004
	006	008	006	008
100	003	004	003	004
	006	008	006	008
250	003	004	003	004
	006	008	006	008
500	003	004	003	004
	006	008	006	008
750	003	004	003	004
	006	008	006	008
1000	003	004	003	004
	006	008	006	008
1250	003	004	003	004
	006	008	006	008
1500	003	004	003	004
	006	008	006	008

Cycles	Otto Engine		Diesel Engine	
1750	003	004	003	004
	006	008	006	008
2000	003	004	003	004
	006	008	006	008
2250	003	004	003	004
	006	008	006	008
2500	003	004	003	004
	006	008	006	008
2750	003	004	003	004
	006	008	006	008
3000	003	004	003	004
	006	008	006	008
3250	003	004	003	004
	006	008	006	008
3500	003	004	003	004
	006	008	006	008

Source: (ACEA et al. 2021b)

According to (ACEA et al. 2021b), Table 6-5 contains data based on cycling tests on a 12 V Li-ion starter battery. Cycling was carried out using cell samples designed to deliver approximately 60 Ah. Ambient temperatures during cycling were 45°C, while the cold cranking ability was tested at -25°C after cooling overnight. The cold cranking ability was considered a failure in case the voltage of specimen (cell) falls below 1.75 V (or 7.0 V on battery pack level) (ACEA et al. 2021c). In one test, the battery was cycled between 0 % and 100 % state-of-charge and the battery performed satisfactorily for cold cranking for 250 cycles for gasoline engine vehicles but only 100 cycles for diesel engine vehicles. In a second test, the battery was cycled between 60 % and 80 % state-of-charge and the cranking performance was satisfactory for gasoline engine vehicles for 500 cycles but only for 100 cycles for diesel engine vehicles. The duty cycle for cold cranking with a diesel engine is more severe than for a gasoline engine and these tests further show the current limitations of Li-ion batteries for mass market application as 12 V engine starting batteries (ACEA et al. 2021b).

(ACEA et al. 2021b) stated that there has been a very small number of vehicles on the road that have been fitted with 12 V LIB, primarily for weight saving in motorsport-oriented vehicles, in addition to testing the new technology over the vehicle lifetime. These vehicles represent a very small fraction of the European market and most OEMs do not offer vehicles with 12 V LIB. Further, these vehicles were all gasoline vehicles, as 12 V LIB have not been shown to meet the cold cranking requirements in diesel vehicles (ACEA et al. 2021b).

For auxiliary batteries, cold cranking performance is not relevant, as they are not used to start the engine. (ACEA et al. 2020) state that for AUX batteries, lead batteries are still the state of the art in vehicles, and the only chemistry used in this application. It is stated that there is no experience or knowledge of the suitability of other battery chemistries for this function. (ACEA et al. 2021b) slightly corrected this statement by reporting that there is an extremely small number of vehicles on the European market using 12 V lithium AUX batteries, adding that these vehicles have typically been on the road less than 1 year - insufficient time to assess whether the 12 V lithium-ion batteries meet OEM requirements (ACEA et al. 2021b).

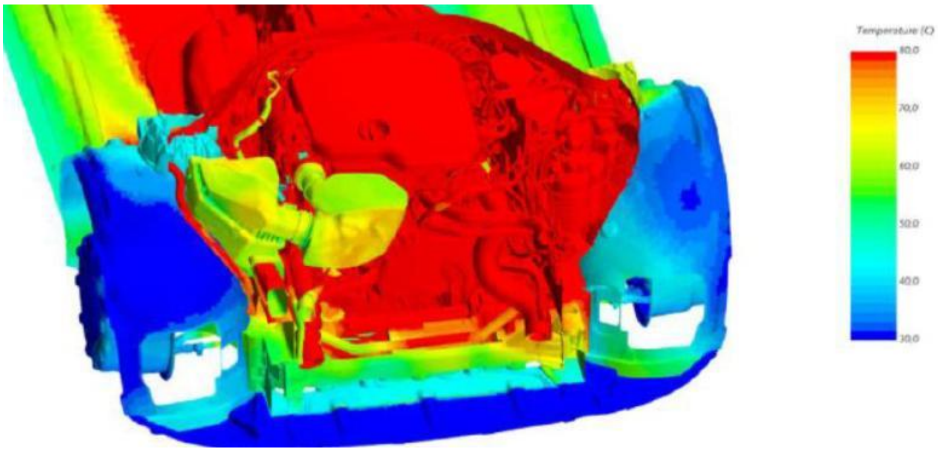
High temperature durability

(ACEA et al. 2020) state that in order to meet cold cranking requirements, the preferred battery location is as close as possible to the engine. Locating the battery away from the engine compartment requires long lengths of heavy-duty cables and a higher battery performance may be needed to compensate for any voltage drops. This means that 12 V batteries must be able to operate at the temperatures that can exist in the engine compartment.

(ACEA et al. 2020) state, citing an unnamed OEM, that lead-based batteries can operate at an internal temperature of up to 75°C to 80°C and will survive short excursions to 100°C, thereby covering all scenarios relevant for light duty vehicles. (Bosch 2020) state the typical temperature range for the operation of LAB to be -30°C to 85°C, although the latter only temporarily up to 3 hours. Laboratory test conditions are up to 75°C and the safety limit is up to 105°C.

To illustrate the high temperature requirement, (ACEA et al. 2020) provide thermal imaging of an engine compartment under harsh driving conditions in summer (mountaineous territory, with a caravan or trailer load). In most areas, temperatures exceed 60°C and are generally at 80°C.

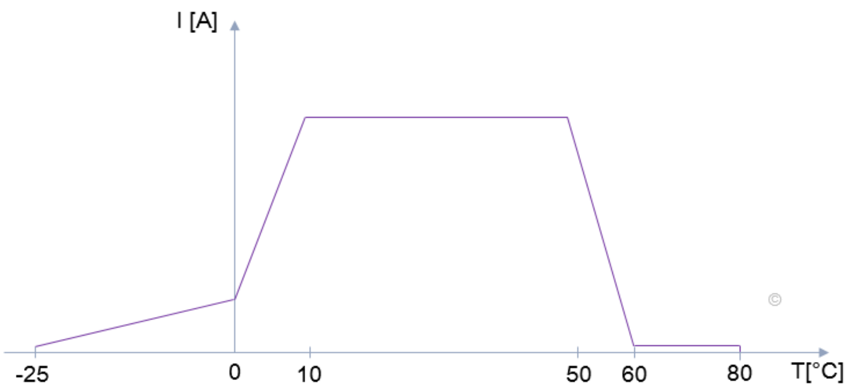
Figure 6-5: Thermal environment in the engine compartment of an ICEV under harsh conditions in summer (Temperature fields >80°C coloured red)



Source: (ACEA et al. 2020)

In comparison, the upper process windows for the operating temperature range for a Li-ion battery is 55-65°C, although this will depend upon battery chemistry (ACEA et al. 2020). To illustrate, (ACEA et al. 2021b) provide the schematic in Figure 6-6. The diagram shows a temperature operating profile for LFP cells with current as function of temperature. This is stated to highlight the issues for LIB above 60°C. When the temperature exceeds safety limits, LIB will switch to open circuit, thereby disconnecting from the vehicle electrical system.

Figure 6-6: Temperature operating window for LFP batteries



Source: (ACEA et al. 2021b)

(ACEA et al. 2020) explain the technical difference with respect to high temperature durability as follows: LAB have a very high thermal mass with a high volume of aqueous electrolyte and weight of active materials and therefore take a lot of time to heat up. In contrast, LIB have a much lower thermal mass, meaning that passive heating can quickly become a problem and the battery will heat up quickly. At elevated temperatures, the off-gassing processes in LIB will exponentially increase with increasing temperature, which leads to increasing damage to the cell, an increase in internal resistance, a decline in capacity and therefore a decrease in the lifetime of the battery. The electrolyte may be formulated to have better high temperature stability, but this inevitably leads to a reduction in low temperature performance. (ACEA et al. 2020) state that additionally, heat from the vehicle in operation can transfer quickly to a Li-ion battery. Furthermore, if LIB are used for energy recuperation, this will result in an increase in internal heating due to the higher energy throughput at high power ratings.

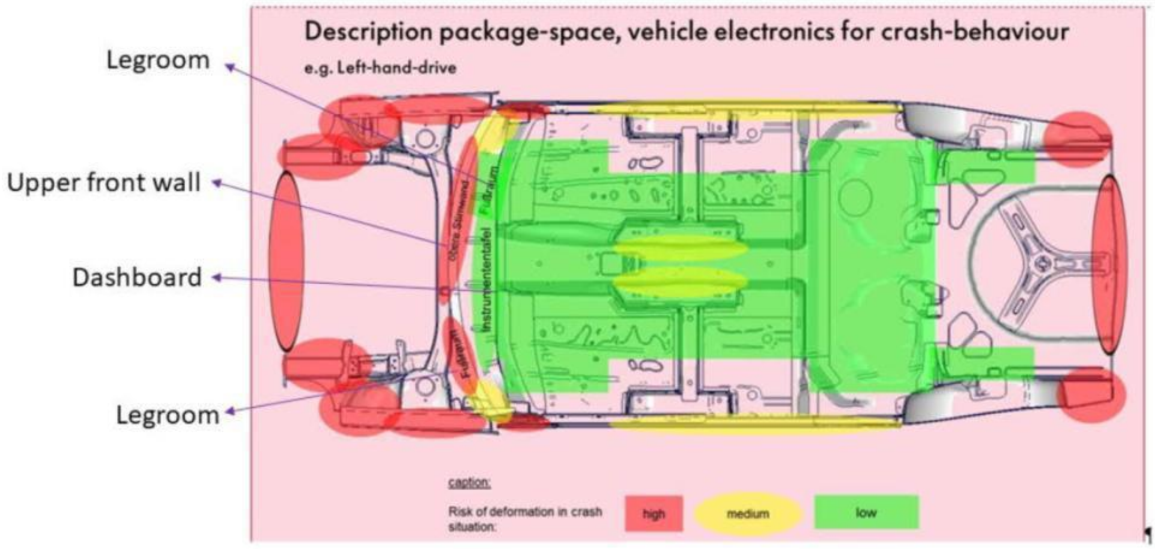
(ACEA et al. 2020) state that unlike SLI batteries, which are installed as close as possible to the engine, auxiliary batteries can be installed in other locations. When asked whether this means that 12 V AUX batteries can be located away from the engine compartment to avoid elevated temperatures, thereby relativizing the high temperature requirements set out above, (ACEA et al. 2021a) answered that there may be more flexibility for the location of a battery in completely new vehicle architectures. However, in existing architectures, there are a lot of constraints in packaging due to heat exposure or potential crash risks (ACEA et al. 2021a). Further, it is likely that the vehicle designer would locate the AUX battery close to the Engine Control Unit (ECU) as this is the most critical unit in terms of continuity of power, and it is generally located close to the engine. As a result, temperature tolerance is required which means that LIB are not preferred for auxiliary applications in hybrid vehicles. For pure BEVs, the traction motors and power conversion equipment will get hot but the AUX battery does not need to be located adjacent to them. (ACEA et al. 2021a) emphasize that LIB would need to be located outside crash-affected zones, as it may vent, catch fire or undergo thermal runaway if crushed in an accident, further restricting the space available.

Safety

According to (ACEA et al. 2020), lead batteries do not pose a major risk of catching fire and have been shown to be inherently safe, with thermal events being extremely rare. (ACEA et al. 2020) state that vehicle crash tests, with battery case deformation of around 40 %, have shown that a deformed lead battery is still able to provide energy for supplying emergency functions. In contrast, it is estimated that a current LFP battery, under the same conditions, will start venting and shutdown, in the best case.

Due to the inherently higher fire risk of LIB, the car industry would have to locate Li-Ion starter batteries in a crash-protected area or embedded in a crash safe structure. This is demonstrated in Figure 6-7 which highlights the risks of deformation of different areas for vehicle electronics considering crash behaviour (ACEA et al. 2020). This shows the importance of having the LIB in the green section to prevent its impact/deformation in the event of a collision.

Figure 6-7: Package space for vehicle electronics considering crash behaviour, demonstrating risk of deformation for different areas of a vehicle



Source: (ACEA et al. 2020)

According to (ACEA et al. 2020), even if a full vehicle redesign was possible, not every position of the battery makes sense. Putting the battery in the centre of the vehicle will result in a long main power wiring harness, which results in loss of voltage and efficiency. Further, (ACEA et al. 2020) state that reinforcing the car body area to establish a crash safe cage for a component needs to be implemented in the total crash behaviour design of a vehicle. Locating the LIB in the same place as the LAB (under the bonnet) would result in even more complicated technical issues (thermal and crash). This is a key concern of all OEMs, and no vehicle can be offered for sale until crash safety has been correctly established (ACEA et al. 2020). It is further stated that a lithium-ion starter battery can also not be integrated in the passenger compartment due to off-gassing from the battery in case of venting.

(ACEA et al. 2020) describe one major difference between LAB and LIB: For safety reasons, some LIB have a switch for disconnecting it from the vehicle in case of operating conditions that the battery cannot withstand. Such a switch, if present, is integrated into the battery management system. However, it is argued that in ICEV the battery can never be disconnected as it is required for functional safety, unless the vehicle is equipped with an auxiliary battery in addition. Conditions under which a LIB would disconnect itself include detected battery defects, charging at high temperatures, high recharge voltages at low temperatures, deep discharge, and other conditions. A disconnect may result in electronics systems failing (e.g. the electronic stability program, power steering or braking), resulting in a situation in which the vehicle operation becomes dangerous. In contrast to this, LAB do not need and do not have such switches or sophisticated electronic management systems. They remain safely connected to the vehicle electrical system and do not present the same hazard challenges as LIB (ACEA et al. 2020).

(ACEA et al. 2020) further explain the difference between 12 V LIB and high voltage traction batteries, with respect to safety, with the higher power density of 12 V batteries. In high voltage vehicles, safely protecting the high voltage battery is essential. This means it will have significant crash protection. Adding further crash protection for a 12 V lithium battery would be very difficult and costly to add. It would also add weight to the vehicle (ACEA et al. 2020).

(ACEA et al. 2020) further discuss storage as a safety concern for LIB. LIB require the implementation of a temperature-controlled storage facility with fire suppression systems and from a legal perspective are subject to special transportation requirements. It is further stated that LIB are classified as Class 9 Dangerous Goods and as such, must adhere to stringent shipping requirements. Special transport requirements need to be adhered to when transporting the goods on roads, including completion of a dangerous goods note, and carrying a suitable fire extinguisher in the mode of transport that is being used.

Citing (Ricardo 2020), (ACEA et al. 2020) report that when transported, LIB should be individually packed in approved packaging, which has to be labelled and marked as defined by the ADR (The European Agreement concerning the International Carriage of Dangerous Goods by Road), IATA (International Air Transport Association), and IMDG International Maritime Dangerous Goods Code) regulations. Spent or damaged batteries have to be placed in an inner packaging surrounded by non-combustible and electrically non-conductive insulation material. In addition, for granting transport authorization, LIB must be tested to the UN Manual of tests and criteria, section 38.3, and to exceed safety tests and manufactured under an appropriate quality assurance standard. Required tests include testing the battery at altitude (can be simulated in a low-pressure chamber), in thermal scenarios, vibration and shock testing, and passing an impact test. Li-Ion cells and batteries are forbidden for transport as cargo on passenger aircrafts but can only be transported in cargo aircraft. It must also be noted that, recalled, damaged or non-conforming Lithium cells or batteries cannot be transported by air freight due to the safety concerns surrounding ignition of the Li-Ion battery whilst in the aircraft (ACEA et al. 2020).

With respect to LAB, (ACEA et al. 2020) state they are classified as class 8 dangerous goods and are subject to ADR as well. However, due to the intrinsic safety of lead batteries a special provision is defined that removes the carrier from ADR obligations for the transport of new and spent LAB.

(Ricardo 2020) concluded that autonomous driving will necessitate the use of at least two battery chemistries per vehicle. These batteries will support safety critical back-up power sources required for emergency stopping (steering to standstill and braking to standstill), to power emergency lighting, and to power the telematics communication. It would be a key consideration that OEMs do not use the same battery chemistry for all batteries in a vehicle to avoid common failure modes which could result in the back-up power source failing when it is required. Some OEMs believe that lead is most suitable for back-up power sources, because the battery will not 'shut-off' in the way a lithium battery will under certain conditions and may be a lower risk option compared to a Li-ion back-up battery (Ricardo 2020).

Cost

Citing (Ricardo 2020), (ACEA et al. 2020) state that cost is a major drawback of Li-ion 12 V batteries and that LIB are approximately four times more expensive than lead-based equivalent batteries. (ACEA et al. 2021b) further argue that this does not yet take into account the cost of the additional safety and technical components and software that need to be implemented into a vehicle to incorporate a 12 V lithium-ion battery. Additional costs are stated to be associated with recycling end-of-life 12V LFP batteries. To that end, (ACEA et al. 2021b) point out that LFP batteries contain few commercially relevant materials that can be recovered. Therefore, the cost of storing, transporting and recycling of 12 V LFP batteries will need to be accounted for.

Interchangeability and parts availability

According to (ACEA et al. 2020), 12 V lead batteries for automotive service are widely available as replacement parts across the EU from a wide variety of sources. These include the service networks of car suppliers, independent garages, specialist battery suppliers, retail outlets for spares and motor factors. Lead batteries are interchangeable between suppliers given that the container size, terminal arrangements and electrical performance meet the vehicle requirements. The same considerations need to apply for 12 V Li-ion batteries in order to provide user convenience and competitive supply. Many other parts such as tyres and brake pads are supplied from a wide range of outlets and competition law prevents the major car manufacturers from controlling the market for service and spares. It would be a retrogressive step to mandate the use of 12 V Li-ion batteries until widespread availability was established (ACEA et al. 2020).

Additionally, (ACEA et al. 2020) state that as there is no known LFP cell manufacturer currently operating in Europe, the raw materials and cells need to be imported to EU which will also add additional transportation costs. Lead batteries have no resourcing availability issues and are manufactured within Europe with a high content of secondary raw materials originating from European waste (ACEA et al. 2020).

Standardization

(ACEA et al. 2021a) state that for volume production, standardisation of the specifications for widely used components is essential to the automotive industry.

(Ricardo 2020) state that for lead-based automotive SLI batteries, a specific European Standard defines the characteristics and test procedures; EN 50342 details the basic functions required from all lead-based starter batteries. This standard outlines requirements for lead-based batteries in micro-cycle applications, such as micro-hybrid Stop/Start vehicles. The micro-hybrid test covers battery preparation, micro-cycles, and checking status after cycling. (ACEA et al. 2020) add that the main standards for 12 V SLI batteries to be for lead batteries: EN 50342 (7 parts) and IEC 60095 (7 parts). Both standards have been established decades ago and are periodically updated.

In contrast, according to (ACEA et al. 2020), the development of standards for 12 V Li-ion batteries for automotive applications is at a very early stage and only addresses a limited range of the parameters necessary for broad application. The standards committee responsible considers that battery performance should be defined to cover a wider range of service conditions with particular emphasis on the temperature range required for the electric power supply of safety relevant car systems and durability and to ensure cold cranking performance in all regions.

According to (ACEA et al. 2021b), IEC 63118 in IEC TC21 Working Group 2 is currently working on a standard titled “12 V Lithium-ion Secondary Battery for Automotive SLI Applications and Auxiliary purposes: Part 1 - General requirements and methods of test”. (ACEA et al. 2021b) explain that the current status is that a second draft of this standard (CD2) remains in the discussion/commenting phase. The remaining steps are CDV (committe draft for voting), FDIS (final draft international standard) and publishing. The discussion (commenting phase) of this CD2 has taken 2 years. The next step is the CDV (Committee Draft for Voting), which is expected in 2022. It could then be anticipated to take 2 further years more until the result of FDIS. It then typically takes a further year until publication (including translations) (ACEA et al. 2021b).

Compatibility with 12 V board net

(ACEA et al. 2020) stated that with respect to electrical architectures, both lead and lithium 12 V batteries are generally compatible with 12 V board nets. However, depending on the vehicle and its board net wiring specifications from the OEM, some vehicles may not be suitable for the higher short-term current draw from lithium batteries. Specifically, with highly efficient board nets, under peak loads the voltage requirements can rapidly reach 14 V or more for limited periods of time. This could result in lithium batteries overheating due to their higher charge acceptance allowing a greater current at the same voltage. However, if the board net wiring is designed to accept higher currents, there should be no compatibility issues.

With respect to aftermarket “drop-in” LIB marketed to substitute LAB, (ACEA et al. 2020) state that it cannot be assumed that a drop-in 12 V lithium battery would be suitable for a board net that was designed for a lead-based battery. Because Li-ion 12 V batteries remain niche products, it should not be assumed that all vehicles have either a suitable board net, or a safe component position, for both lead and lithium 12 V batteries.

Transition to 48 V board net

When asked about a possible transition away from 12 V to 48 V vehicle electrical systems, (ACEA et al. 2021a) stated that it is an untested architecture and would require significant testing and development before it was available for the mass market. Safety is a key issue here and it is not known what additional safety features would be required and whether they could be applied across the automotive industry. (ACEA et al. 2021a) further argue that 48 V systems also introduce additional cost as although heavy consumers can use lighter cabling, additional insulation will be required. For light consumers lighter cabling is not realistic in view of the large number of circuits that would need to be redesigned and tested. There are safety considerations with arcing at higher voltages and all connectors will need to be respecified and tested. Many of the 12 V systems are in moving parts such as doors, seats and the trunk which would need to be respecified for safety for arcing in the event of disconnection. Arcing from damaged connectors or cables is a fire risk and can cause a breakdown in the insulation leading potential short circuits. Finally, the use of a common ground connection needs to be validated with a dual voltage system. There are important challenges for higher voltage systems in respect of electromagnetic compatibility which has safety related issues. All components would need to be re-tested and many may need to be redesigned or protected in some way (ACEA et al. 2021a).

(ACEA et al. 2021a) emphasize that all known vehicles with 48 V applications on the road also utilise a 12 V lead battery. 48 V separate board net clusters in parallel to 12 V board net is becoming more important but will not replace the 12 V systems.

(ACEA et al. 2020) cite that (Ricardo 2020) see a strong demand within low-voltage (<75 V) batteries for 48 V batteries and assume the needs of this application will be wholly fulfilled by Li-ion technology, although 48 V lead batteries have been developed. Therefore, it can be assumed that the exemption for lead may not be technically required for this particular application.

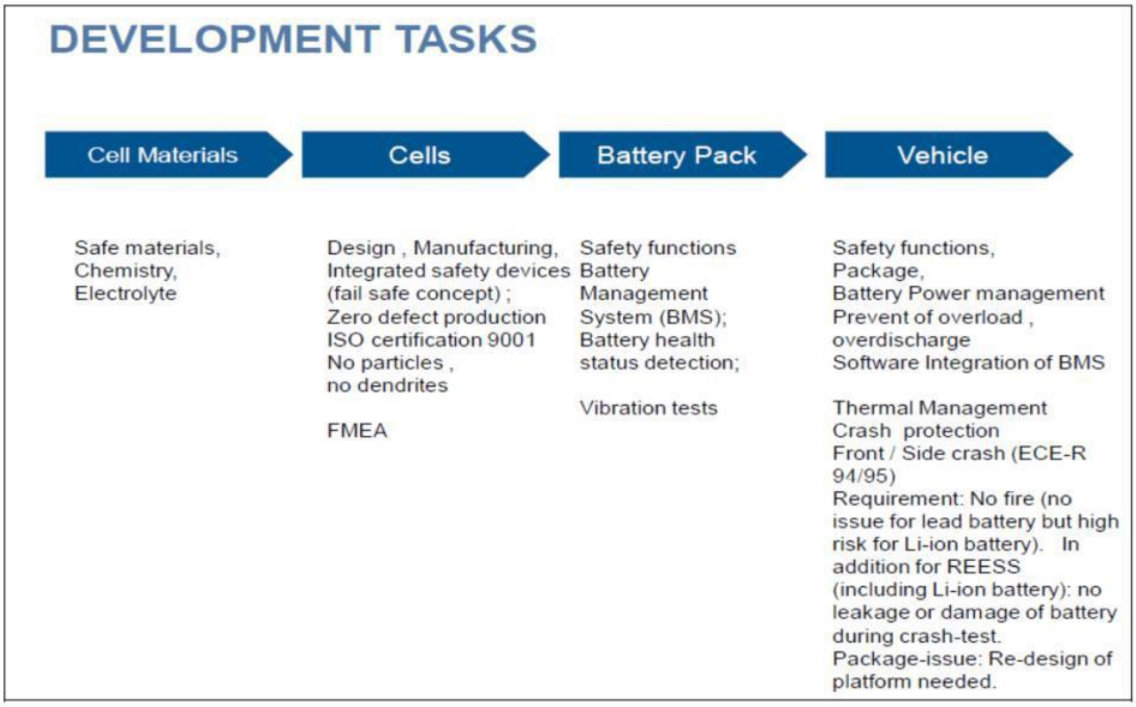
6.2.3 Roadmap towards substitution or elimination of lead

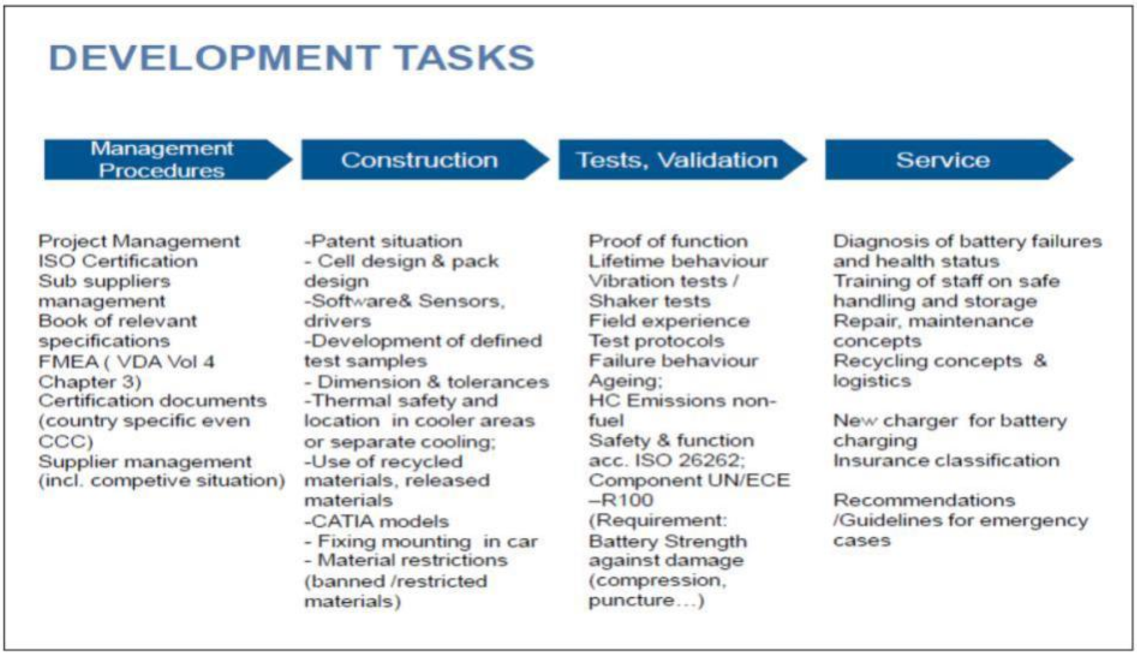
According to (ACEA et al. 2020), significant further research is needed to address safety and high temperature performance of Li-Ion batteries. As with any research, it is not possible to put precise timings on how long it will take to overcome these issues. (ACEA et al. 2020) provide a list of ongoing R&D programmes for energy storage devices in vehicles and strongly recommend allowing these projects to proceed to completion to allow the preferred solutions an opportunity to find their way into European vehicle production after a full evaluation.

(ACEA et al. 2020) further state when an alternative technology is developed, the necessary process involves many stages, starting with tests at cell level, component tests under a range of different conditions followed by the development of prototype vehicles. If these are successful, summer and winter tests need to be carried out and then pilot applications will be undertaken to ensure correct and reliable operation.

(ACEA et al. 2020) provide an overview of different development tasks at component and vehicle level. This is an iterative process at each stage.

Figure 6-8: Vehicle development tasks

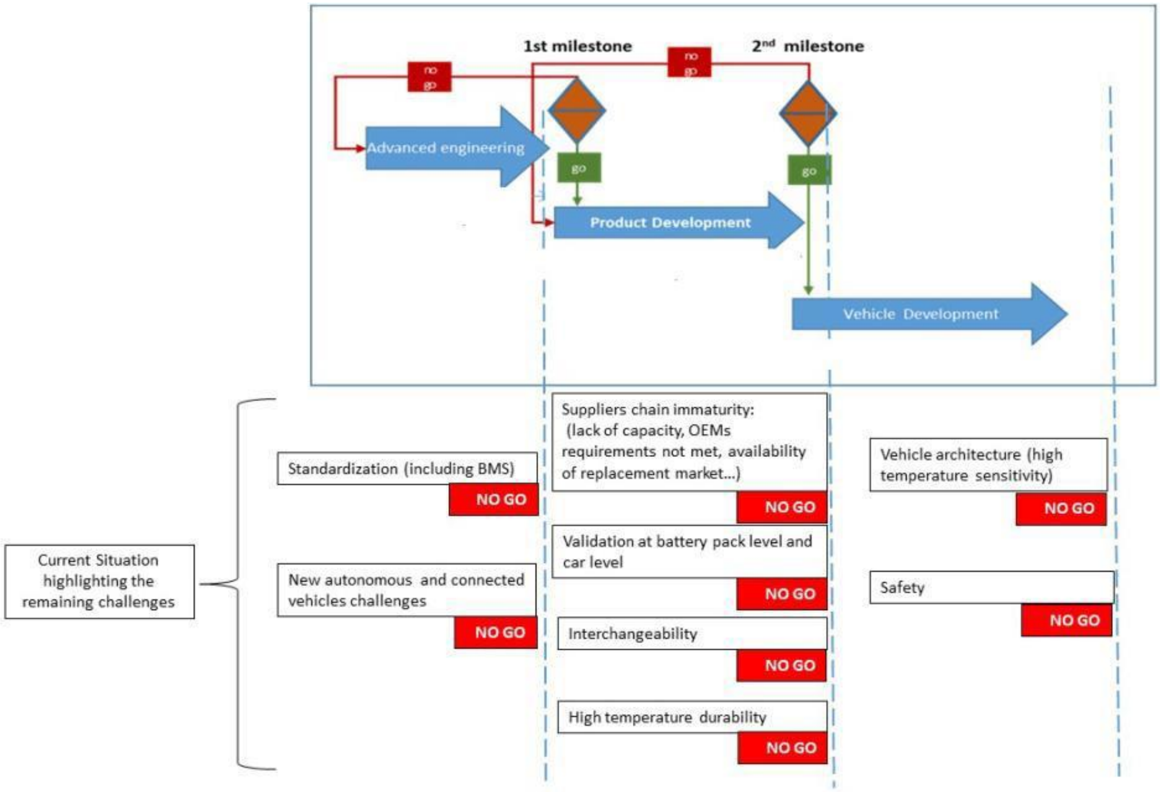




Source: (ACEA et al. 2020)

(ACEA et al. 2020) stated that technology development and integration for automotive products typically occurs in 3 phases: advanced engineering, and vehicle development (product and platform level). A simplified project plan for the research, development and the required test-phases for a new battery system is presented in Figure 6-9. This highlights the situation since the last stakeholder consultation described in (Gensch et al. 2016), showing many areas where issues have yet to be overcome and that significantly more work and research is required (ACEA et al. 2020).

Figure 6-9 : Project plan for a first volume application of LIB



Source: (ACEA et al. 2020)

(ACEA et al. 2020) describe that car manufacturers have to follow strictly defined development processes in order to get to robust and safe vehicle implementations. This is particularly true for Li-Ion SLI batteries, considering the impact of Li-Ion technology on vehicle safety with regard to both component safety (hazards caused by the battery as well as the impact of abuse or accident to the battery) and vehicle safety in general (e.g. functional safety of electrified chassis or driver assistance systems affected by power supply failure).

Further, (ACEA et al. 2020) reiterate that those cars that are presently equipped with Li-ion starter batteries have run through modified pilot processes which are not applicable for mass volume production. Hence applications are restricted for example to moderate climate markets because of the limitations of Li-Ion technology already described. The current field trials feature over dimensioned Li-Ion batteries with a very high cost impact and very high integration efforts, linked with functional limitations and are only feasible in order to obtain first long-term field experience. Furthermore, volumes are kept very low, with the customer vehicles being closely monitored by OEMs. An additional reason for these very low volumes is the present limitations in service and recycling capabilities. These early adopter applications have to be considered as early field trials rather than as regular series applications.

In contrast, (Bosch 2020) expect to see that LIB will replace the LAB technology in the mid-term, however, for a broad market introduction of LIB, there is the need for further research on certain technical topics. (Bosch 2020) therefore recommend continuing the exemption for lead-acid batteries in vehicle applications until end of 2025 with a transition-phase of 2-

3 years until end of 2027/2028. In this context, (ACEA et al. 2021c) note that Bosch do not manufacture vehicles or 12 V Li-ion batteries for M1 and N1 vehicles and therefore may have limited knowledge of the technical challenges that still exist for replacing 12 V lead batteries with LFP alternatives on a vehicle level. In contrast, (ACEA et al. 2021c) state to have provided detailed technical information supporting their arguments that have been developed through a collaboration with experts representing most of the automaker's manufacturing M1 and N1 vehicles in the European parc.

(ACEA et al. 2021c) reiterate their request that the current exemption is maintained and that the next review of Annex II exemption 5(b) for lead batteries is timed to be after the publication of the ongoing review of the ELV Directive - ideally no earlier than 5 years after the conclusion of this assessment of technical and scientific progress. This will also enable consideration of the results of on-going EU R&D projects studying new cell chemistries with enhanced technical and environmental performance.

6.2.4 Environmental arguments and socioeconomic impacts

Recycling

(ACEA et al. 2020) state that automotive lead batteries are the "gold standard" for a closed loop product operating in a circular economy. Accordingly, the efficiency of lead battery recycling processes is very high with >95 % of the available lead being recycled. On average, approximately 80 % of a new automotive lead battery is manufactured from raw materials recovered from recycled batteries collected in the EU.

(IHS Markit 2020) report a collection rate of lead automotive batteries from passenger cars, and light, medium and heavy commercial vehicles of 97.3 %, calculated as the amount of collected batteries reported by Member States relative to the estimated amount of waste batteries that should be available for recycling, both from in-use vehicles (battery replacement) and EOL vehicles.

(ACEA et al. 2020) state that recycling efficiencies are somewhat dependent upon the smelter type used to recover the lead and whether the battery casing is recycled or used for fuel, but typically range from 75 % to 90 % with most processes recovering >95 % of the available lead. As close to 100 % of the lead in a recycled battery can be used to make new batteries.

With respect to 12 V LFP Li-ion batteries, (ACEA et al. 2020) state that recycling is somewhat in its infancy as 12 V Li-ion automotive batteries are present in relatively few vehicles on the road there is no formal collection infrastructure currently available in the EU. Cost of collection, storage, and transportation of used Li-ion 12 V batteries will be comparatively high given the inherent safety and dangerous goods rules pertaining to this chemistry (ACEA et al. 2020). In contrast to LAB, there is little economic incentive in collecting and recycling spent 12 V LFP batteries as they contain no economically valuable metals. Any materials recovered are currently subject to downcycling and are not used to manufacture new LFP cells (ACEA et al. 2020).

(ACEA et al. 2020) further state that typically only copper is recovered from waste LFP batteries in the form of a high value product, and it can therefore be estimated that a theoretical recycling efficiency for a 12 V LFP battery is in the order of 30 % to 35 %. It is therefore likely that to meet the existing 50% recycling efficiency target specified in the EU Battery Directive, LFP cells would need to be mixed with other battery chemistries with before processing (ACEA et al. 2020).

(ACEA et al. 2020) claim that automotive lead batteries are one of the few consumer products that can be considered to be operating in a closed loop circular economy in the EU. Removal of the Annex II exemption could in effect break the loop and eventually convert saleable products into waste that would have no market. (ACEA et al. 2020) further state that removal of this exemption could in effect break the recycling loop, suggesting that over a million tonnes of lead batteries per year would be taken out of the EU circular economy and would either require disposal or would be recycled only for the resulting products to be exported to other regions where lead battery manufacturing still exists

Environmental impacts

ACEA et al. commissioned an LCA study to compare the cradle-to-grave environmental impacts associated with LIB and LAB. (ACEA et al. 2020) state that this study concluded that the environmental impact (GWP) of LFP battery manufacturing is currently around a factor six times higher than the impact of manufacturing equivalent lead batteries. This conclusion is based on a scenario of a 12 kg LFP battery with a lifetime of 8 years that is considered by OEM's to best represent 60 Ah LFP 12 V SLI batteries currently on the market. (ACEA et al. 2020) further state that the main advantage of lead batteries is that >75 % of the raw material present in the battery is recycled lead compared to the use of virgin raw materials in LFP manufacture. This benefit is maintained during the full life cycle for conventional internal combustion vehicles. For both the start-stop and the micro-hybrid applications, the baseline scenario shows only small environmental life cycle differences between battery chemistries due to the benefits of the use phase fuel savings achieved by using these technologies (ACEA et al. 2020).

Table 6-6: Global Warming Potential [kg CO2 eq.] for ICE, Start-stop and Micro-hybrid vehicles

	Conventional ICE		Start-Stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB-LFP	PbB	LiB-LFP	PbB	LiB-LFP
Manufacturing stage	45	254	35	254	47,8	254
Use stage	44	0	-970	-1030	-1990	-2060
EoL	-6	-12	-4	-12	-2	-12
Total Life Cycle	**83**	**243**	**-938**	**-788**	**-1944**	**-1818**

Source: (Sphera 2020)

Supply chain

(ACEA et al. 2020) state that lead-acid 12 V batteries benefit from a mature supply chain and manufacturing base and a track record of consistent performance. In Europe alone, the battery industry produces in excess of 60 million lead batteries for both OEM and aftermarket applications. In contrast, the supply chain for lithium-based 12 V batteries is relatively immature, and the volume capability does not currently exist. One leading producer estimates it could in the future produce and assemble around 600,000 lithium 12 V battery units per year, but this is only equivalent to 1 % of the total European market for 12 V batteries.

According to (ACEA et al. 2020), there is a lack of Li-ion SLI battery suppliers at present, claiming that this is in conflict with the EU's legislative and regulatory framework guaranteeing a fair competition between suppliers. Currently there are no European LIB suppliers that can provide and promote a cross-border and integrated European approach to battery manufacturing. These have to be developed (ACEA et al. 2020).

Socio-economics

(ACEA et al. 2020) claim that a regulatory mandate to substitute 12 V LAB with LFP batteries would significantly increase the cost of purchase and replacement of the vehicle battery for the consumer. Citing several sources, (ACEA et al. 2020) state that in 2020 the cost of purchase of a replacement 12 V lead battery is between 110 € and 150 €, whereas according an equivalent LFP alternative is expected to be 4x this (i.e. up to 600 €). This would undoubtably increase the purchase price of new vehicles but importantly, as it is estimated that approximately 50 million replacement 12 V batteries were sold in 2019, it would represent significant additional costs for the consumer for after-sales replacements.

6.3 Critical review

6.3.1 Substitution of lead

No information regarding the substitution of lead in lead acid batteries with another material is available to the consultant. Instead, the use of lead could potentially be eliminated (in LAB) by using an alternative battery technology, which is subject of section 6.3.2.

6.3.2 Elimination of lead

Li-ion LFP (lithium iron phosphate) batteries have been handled as the most promising candidate to eliminate lead-acid batteries in the applications relevant to this exemption. The focus of this review has been on the technical capability of LFP to substitute LAB. Additionally, the question whether traditional 12 V batteries are still technically necessary is addressed. Further, supercapacitors were discussed extensively in the previous review and are briefly discussed further below.

Lithium-ion 12 V batteries

ACEA et al. provided an extensive contribution that focused on reasons why LIB are not yet capable of fulfilling requirements in 12 V SLI or AUX applications in mass market vehicles today. Additionally, ACEA et al. provided three studies that had been commissioned to independent consultants, assessing automotive technology trends (Ricardo 2020), lead-acid battery recycling (IHS Markit 2020), and environmental impacts of LIB and LAB (Sphera 2020). To complement this information situation, the consultants carried out a non-exhaustive research survey of published scientific literature, grey literature (reports, presentations), press releases from OEMs, and other sources. This section summarizes findings from this survey, in addition to highlighting statements from the three above mentioned studies, which tend to shine a different light on the capabilities of LIB in 12 V applications, thereby complementing the argumentative basis provided by ACEA et al.

(Ricardo 2020) report that within the automotive industry, Li-ion has already become the technology-of-choice for all traction-focused batteries, 48 V and above. Consequently, Li-ion is the technology selected for the HV batteries used for traction purposes in HEVs and BEVs. Li-ion batteries are also selected for 48 V mild-hybrid systems due to their weight advantage over other materials, despite the higher cost for lithium batteries in comparison to lead-based batteries (Ricardo 2020). Among the reasons for lead acid batteries not being used in these applications is their much lower volumetric and gravimetric energy density compared to Li-ion (Tarascon and Armand 2001), which would make traction batteries considerably heavier and physically larger than their Li-ion counterparts.

One notable difference with 12 V batteries is that 48 V and HV traction LIB commonly feature nickel manganese cobalt (NMC) or nickel cobalt aluminium (NCA) cathodes, while 12 V LIB are typically based on lithium iron phosphate (LFP). This is, among other reasons, due to its straightforward compatibility with the 12 V board net (a series of four 3,3 V LFP cells result in a 13,2 V pack). Tesla has started using LFP in traction batteries of their Model 3 manufactured in China, besides several Chinese OEMs also utilizing LFP-based traction batteries. Further advantages of LFP cells over NCM or NCA are that they contain neither nickel nor cobalt, a critical raw material associated with high cost and supply chain issues. LFPs are considered inherently safer (Saldaña et al. 2019).

Pointing out technological advantages of Li-ion technology, (Ricardo 2020) conclude that lithium chemistries can deliver higher power densities and therefore smaller cell sizes with lower weights compared to lead-based batteries. LIB have a number of other technical advantages over LAB, in particular their charge acceptance during recuperation, and therefore potential to reduce CO_2 tailpipe emissions. This characteristic makes LIB particularly attractive for stop-start applications. The low weight and small physical (size) footprint of LIB is attractive to OEMs looking for lightweighting or space-saving opportunities (Ricardo 2020).

With regards to barriers for LIB adoption in 12 V applications, (Ricardo 2020) summarize that across all stakeholder interviews they carried out, it was agreed that the main barrier facing lithium-ion starter batteries is cost; as lithium-ion starter batteries typically cost between 3 and 5 times more than lead-based starter batteries. For non-luxury automotive OEMs, this cost could be significant both for their businesses and their customers. The cost-competitiveness of Li-ion batteries and the recycling infrastructure and processes are expected to continue to improve to 2025 as the industry becomes more established and there is an increased demand for lithium battery recycling, mainly from vehicles with spent lithium-ion traction batteries (Ricardo 2020).

(Ricardo 2020) further compare key 12 V SLI battery capabilities shown in Figure 6-10, pointing out equal cold cranking capability, and a differentiated picture with respect to the superior technology (LIB or LAB) for several key criteria. Lead-acid is seen in the lead for high temperature resistance, weight of additional structures (e.g. for crash protection), and unit cost, while LIB is seen in the lead for recuperation, weight (without crash protection), and lifetime (8-10 years LIB vs. 5-7 years LAB).

Figure 6-10: Comparison of key 12 V SLI battery capabilities

	Performance	Attribute (unit)		Ref.	Battery Technology				Superior Technology?
					EFB	AGM	LFP	LTO	
A. Technology Capability	What are the maximum capabilities for each battery chemistry? (important factors in **bold**)	Battery voltage	*(V)*	1,2,3	12	12	13.2	13	n.a.
		Nominal capacity	*(Ah)*	1,2,3	70	70	60	-	n.a.
		Cold Cranking Amps (CCA) at -29°C	*(% of 700A)*	5	75	75	75	-	Equal
		CCA at -18°C	*(A)*	5	760	760	900	-	Equal
		Max Battery Temperature possible (NOTE Typical max = 60°C; some standards specify 75°C)	*(°C use)*	1,2,3	70	70	60	-	Lead
			(°C storage)	1,2,3	70	70	60	-	
		DCA(dynamic charge acceptance) Recuperation (max)	*(A)*	5	140	140	200	-	Li-ion
		DCA Recuperation (min)	*(A)*	5	90	90	200	-	
		Energy throughput / Micro-hybrid shallow cycling	*(capacity turns)*	5,6	800	1200	1200	1200	Equal
		Weight (without crash protection)	*(kg min)*	1,2,3	18	19	10	-	Li-ion
			(kg max)	1,2,3	20	21	11	-	
		Weight of additional structures (e.g. crash protection)	*(kg)*	5	0	0	3	3	Lead
		Unit cost	*(€)*	5	100	150	500	-	Lead
		Lifetime	*(years min)*	5,6	5	5	8	-	Li-ion
			(years max)	5,6	7	7	10	-	

Source: (Ricardo 2020)

(Ferg et al. 2019) analysed the feasibility and challenges of Li-ion SLI batteries from cradle to grave and concluded that

- “Replacement of Pb-acid SLI battery with Li-ion type is feasible
- Li-ion batteries are lighter, last longer but considerably more expensive
- Initial SLI « drop-in » battery would be limited to LFP cathode material
- Global recycling of Li-ion batteries is increasing due to increased use of BEV”

According to (Ferg et al. 2019), the main advantages of Li-ion SLI battery design, compared to LAB, is weight reduction and expected longer life cycle (10 years or more compared to 5-7 years of LAB). Besides, the phase out of lead and the ability to monitor and manage the battery carefully via its integrated battery management system are mentioned as secondary advantages of LIB in SLI applications. (Ferg et al. 2019) specified the main disadvantages to be the limit of prolonged high current discharge at low temperatures of −30 °C, a lack of competitive pricing to the consumer, safety concerns in terms of fires due to cell damage, and the effective recycling of materials.

(Kim et al. 2019) presented a quantitative analysis of the characteristics and performance of internal combustion engine vehicles with different types of starter batteries. This was done by simulating the power-net system of a vehicle, including charging control, through a test bench based on actual vehicle data and an automotive power-net hardware-in-the-loop simulation (HILS). Comparing LIB and LAB, (Kim et al. 2019) reported that the replacement of an AGM battery with a Li-ion battery in an ICEV could improve the fuel efficiency (+ 1.7%) and power-net stability (+ 8.7%), while maintaining the charging and discharging balance. In this comparison, the only advantages of LAB over LIB are development feasibility and economics, both of which are expected to improve for LIB through continued research and an expanding market.

(Vergossen 2018) concluded their PhD thesis, carried out for Audi AG, by answering the core question of the work – whether 12 V Li-ion SLI battery may be used to substitute 12 V lead-acid battery – with a yes. In comparative testing, the LFP battery performed better compared to LAB in cold cranking according to DIN EN 50342. LFP was also more capable of stabilizing the board net voltage in a test of lane changing. In recuperation testing, the

LFP battery performed 24 % better compared to LAB in a standard NEDC (New European Driving Cycle), leading to improved fuel economy and reduction of CO_2 emissions.

(Moseley et al. 2017) presented data compiled from several sources to compare an LFP and an AGM 12 V battery, in which the LFP battery fares better in cold cranking at -25°C and battery life in years, lifetime, and weight.

Table 6-7: Comparison of a 12-V Li-ion (Graphite/LFP) and an AGM battery

	Graphite/LFP 60 Ah	AGM 90 Ah
Capacity at 25°C, 0.1C (Ah)	61	90
Capacity at 25°C, 1.0C (Ah)	60	65
Nominal voltage (V)	13.2	12.6
CCA at 100% SoC, 18°C (A)	880	-
CCA at 100% SoC, -25°C (A)	820	~700
Life (Years)	>10	3-5
Weight (kg)	10	24

Source: (Moseley et al. 2017)

(Ventura 2014) provided a comparison of technical characteristics of lead-acid AGM and Li-ion (LFP) in their work carried out for Opel AG. (Ventura 2014) highlight the high current acceptance of LFP as a major advantage over LAB. The comparatively low internal resistance allows a higher current peak that is not affected by the state of charge, which means it is possible to quickly recharge it with a high current, even when the battery is almost at its full charge capacity. Another major advantage of LIB is stated to be that is normally not affected by deep discharge events, permitting the battery to support loads more often without harm, while LAB suffer from sulfation and permanent damage, unable to return to their full capacity. Regarding disadvantages of LIB, (Ventura 2014) mention their inferior performance at low temperatures (-30°C).

(BMW 2014) listed the advantages of using LIB instead of LAB in their M3 and M4 models as follows:

- Reduction of the starter battery by 12.5 kg, from 26.5 kg for a conventional AGM 90 Ah battery down to 14 kg for the LIB
- CO_2 saving through improved automatic engine start/stop function availability, as the LIB can absorb considerably higher currents in a shorter time for charging compared to LAB
- Increased life cycle: The number of available full cycles for LIB is around 14 times higher compared to LAB; the battery life of LIB is about twice as high compared to LAB
- Very high intrinsic safety: LFP generally have an even lower hazard potential than other lithium-based chemistries.

In summary, the results of the research survey are optimistic regarding the substitutability of LAB with LIB in 12 V applications in large parts. Nevertheless, the consultants acknowledge that ACEA et al. are in a position to have the most expertise with respect to the requirements batteries need to fulfil in current and future automotive 12 V applications. Therefore, the above information is considered to complement and naturally not to negate information provided by ACEA et al.

Vehicles with 12 V LIB

(ACEA et al. 2021b) stated that a very small number of niche and high-performance vehicles have been fitted with 12 V Li-ion SLI batteries, that are not representative of the mass market. This section lists examples of vehicles on the market that employ 12 V LIB, either as SLI or AUX battery, which could be identified by the consultants. The list is not exhaustive and can likely be extended with further examples.

Porsche was reportedly the first car maker to offer a Li-ion starter battery in January 2010 for several vehicle models (911 GT3, 911 GT 3 RS, Boxster Spyder), delivered together with the car as an alternative to the conventional lead-acid starter battery. However, Porsche delivered the vehicles with both a LIB and a LAB at the time, denoting the reduced starting capacity of LIB at temperatures below 0°C (Porsche 11/23/2009). Today, Porsche utilises 12 V Li-ion batteries in its current Taycan BEV.

In their stakeholder contribution to the previous review of this exemption (A123 et al. 2015) listed the following examples of series production vehicles with a single LIB supporting micro-hybrid systems:

- Several Mercedes / Mercedes-AMG vehicle models (S-Class, SLS AMG Coupe, SLS S63 AMG, S65 AMG Coupe) with a Li-Ion LPF battery manufactured by A123 Systems (approx. 12.000 units in service at the time)
- BMW M3 with a Li-ion LFP battery manufactured by GS Yuasa (approx. 1.000 units in service at the time)
- Porsche 911 models (GAIA)
- McLaren MP4-12C (A123 Systems)
- Ferrari LaFerrari (A123 Systems.)

BMW used 12 V LIB in their M3 F80 and M4 F82 vehicles that were produced between 2014 and 2020. Global sales numbers on the BMW M3 and M4 fitted with 12 V LIB were reported to be more than 111.000 units in total[16].

(Atiyeh 2017) reported that the 2017 Hyundai Ioniq hybrid was the first modern production car without a traditional 12 V battery. Instead, a lithium-ion starter battery was installed together with the main traction battery. While the 240 V and 12 V circuits are functionally separate, Hyundai reportedly wired permanent jumper cables from the main traction battery to the 50 Ah starter battery. Should it discharge and fail to start the car's engine, the driver

[16] https://www.carscoops.com/2021/03/flagship-2021-bmw-m3-and-m4-variants-to-account-for-most-sales/ [Accessed on : 24.05.2021]

presses a 12 V battery reset button. The main hybrid battery then feeds a couple seconds worth of current to the starter battery, enabling the engine to be cranked. Four years later, (Green Car Reports 2021) reported that all 2020 Hyundai hybrid vehicles feature a 12 V Li-ion AUX battery instead of a LAB.

(ACEA et al. 2021a) reported Lamborghini Urus and Porsche 911 (Turbo and Turbo S) utilize 12 V SLI Li-ion batteries, stating that LIB are used in these vehicles due to weight optimization, packing considerations and the fact that they have better recuperation efficiency.

With respect to Li-ion AUX batteries, (ACEA et al. 2020) made the statement that lead batteries are still the state of the art, and the only chemistry used in this application. It is stated that there is no experience or knowledge of the suitability of other battery chemistries for this function. However, in their response to the third questionnaire, this statement was revised, as (ACEA et al. 2021b) stated that “there are an extremely small number of vehicles on the European market using 12 V lithium AUX batteries” and that “these vehicles have typically been on the road for less than a year – insufficient time to assess whether the 12 V lithium-ion batteries meet OEM requirements”. Further, (ACEA et al. 2021b) stated that “the 12 V auxiliary lithium batteries must be located away from heat sources such as within the engine compartment”.

The consultants identified that BMW used 12 V Li-ion AUX batteries in some configurations of the X5 and X7 models, located under the hood of the vehicle. BMW stated in personal communication that these were lithium titanate oxide (LTO) cells (rather than LFP) that were only used for a limited time and only in the United States (Arizona). In these vehicles, the 12 V lead battery is located in the trunk area of the vehicle, reportedly to add weight for a better mass balance of the vehicle. No additional information could be provided by BMW on this example.

According to Tesla, 12 V LIB will be used as auxiliary batteries in the upcoming refreshed Tesla Model S and Model X which are expected to be placed on the market from 2021 on, substituting LABs in these vehicles (Kane 2021). This has been confirmed for the 2021 Tesla Model S, where Tesla specifies a 15.5 V with 6.9 A low voltage Li-ion battery (Tesla 2021).

(A123 Systems 2016) reported that the Suzuki Wagon R uses low voltage LIB, packaged under the seat, with >1 million units in service. However, these were used for energy recuperation, with an additional 12 V LAB on board for SLI functionality.

(Ricardo 2020) stated that it is primarily premium vehicles that currently use Li-ion SLI batteries, where cost is less of a concern, and where vehicles tend to be kept in garages, thereby potentially providing continuous trickle charge and avoiding extreme cold temperatures – a contrast to mass market vehicles, which may be parked outside without immediate access to charging ports more often.

(Ceraolo et al. 2011) reported of Li-ion « drop-in » replacements for 12 V LAB put on the market by companies such as A123 Systems, Valence, K2 Battery, or M2 Power. 12 V LIB are available on the market today, marketed as « drop-in » solutions to LAB by their manufacturers. For instance, CS-Batteries includes the following in their product description for such a battery:

- 1 :1 substitute for conventional lead-, gel- or AGM battery[17]
- Replaces a 160 Ah lead-, gel- or AGM battery[18]
- Operation on conventional and intelligent alternator[19]

These products do exist, but no information on market relevance could be obtained. ACEA et al. stated that such aftermarket batteries are not endorsed by OEMs, indicating that use is not recommended.

In conclusion, there is a range of vehicle models that have been on the market featuring 12 V Li-ion batteries in the EU, both as SLI or AUX battery. There are examples where the 12 V LIB is located in the trunk area of the vehicle, under the hood and under the seat. Ultimately, it does not seem that LIB are installed on a broad scale at the current time. Indeed, they tend to be utilized more often in higher-end or motorsport-oriented vehicles. However, in the consultants view, the use of LIB is also not strictly limited to extremely few pilot applications.

Cold cranking performance

Typically, cold cranking amps (CCA) denote the maximum amperage that a battery can deliver at a temperature of -18°C for 30 seconds before the battery voltage falls below a certain level. Relevant norms, such as DIN 43539 and IEC 60095, differ in their definition and requirements to cold cranking. ACEA et al. stated that at least 580 A are required to start a gasoline engine, and considerably more for a diesel engine (factor ~1.4x).

The last review of this exemption concluded that LIB still required technological improvement to fulfil the requirement for cold cranking performance at -30°C (Gensch et al. 2016). During the current review of exemption 5(b), (ACEA et al. 2020) stated that manufacturers of LIB have reported parity between LIB and LAB with respect to cold cranking performance. (Bosch 2020) also reported that parity has been reached between LIB and LAB with respect to cold cranking performance.

Despite this, (ACEA et al. 2020) state that OEMs are still concerned about the ability of LIB to provide the same performance over their entire lifetime. When asked for empirical data from the field or laboratory, comparing the performance of LIB and LAB to underpin these concerns, (ACEA et al. 2021b) stated that such component-specific test results under accelerated ageing are sensitive business information and such data cannot be shared by OEMs publicly. Despite this, (ACEA et al. 2021b) provided data to show that LIB are not capable of delivering sufficient cold cranking amperage (≥580 A) at -30°C and only delivering sufficient amperage at -18°C when the state of charge of the LIB is equal or above 80 % (Table 6-4 on p.87). This data, however, lacks contextual information required for its interpretation. For instance, (ACEA et al. 2021b) did not provide specifications on the battery under test. The amperage a battery can provide is dependent on various factors, one of which being the battery capacity. For the data on long-term performance of LIB

[17] Original text in German: “1&1 austauschbar gegen herkömmlich Blei,- Gel- oder AGM-Batterien“

[18] Original text in German: “Ersetzt eine 160Ah Blei,- Gel- oder AGM-Batterien”

[19] Original text in German: “Betrieb an gängigen und intelligenten Lichtmaschinen"

(Table 6-5 on p.87), (ACEA et al. 2021c) state “the battery capacity is designed to deliver approximately 60 Ah”, but it is not clear whether this also applies to the data in Table 6-4. Further, the cell configuration used in the test is highly unusual, connecting 4 cells in series and 30 cells in parallel, i.e. 120 cells make up one pack. 4s2p or 4s3p configurations are much more common in 12 V batteries according to (Bosch 2021).

When requested to provide comparable data for LAB, (ACEA et al. 2021c) stated that each type (LIB and LAB) has important differences and a side-by-side comparison does not make sense, as this would not consider the different properties of the battery chemistries, and that any comparison must be carried out in the overall system, not at the battery level. Further, (ACEA et al. 2021c) argue that there are no corresponding international standards for testing the performance of 12 V Li-ion batteries, as these are in still under development. It would not be appropriate or scientifically justified to use test standards developed for 12 V lead batteries to compare the performance of Li-ion (ACEA et al. 2021c).

In the consultants view, the cold cranking performance of LIB versus LAB can only be demonstrated reliably when comparative data is presented in a transparent and accountable manner. Not providing such data leads to remaining doubts. Therefore, other sources were consulted to obtain comparative data on LIB and LAB.

On the contrary, (A123 Systems 2017) reported that their latest generation 12 V LIB was superior to AGM LAB in terms of cold cranking performance both at -18°C and -30°C (A123 Systems 2017). The data also show that LAB are not capable of providing 580 A at -30°C.

(Bosch 2021) state that their Li-ion 40 Ah (550 CCA) and 60 Ah (850 CCA) samples fulfil EN 50342 cranking requirements. Bosch 60 Ah sample Li-ion has in real vehicle tests outperformed 105 Ah AGM 950 A CC (EN) when cranking a 4.0l V8 engine at -25°C and 30 % to 100 % SoC conditions.

(Vergossen 2018) performed comparative cold cranking tests in accordance with DIN EN 50342 (at -18°C) using LIB and LAB of equivalent nominal capacity, denoting that the LIB delivered four times more current compared to the LAB, which would be an advantage for LIB in longer cranking events under low temperature conditions. In conclusion, (Vergossen 2018) state that using LIB for engine cranking at low temperatures provides a higher assurance for success compared to using LAB of the same capacity. Additionally, the electrical energy consumption is lower when using LIB, resulting in positive effects on battery lifetime as well as on the energy and therefore CO_2 footprint.

(ACEA et al. 2021b) further provided a table presenting data on the long-term performance of LIB, where a battery is cycled with a depths of discharge of 100 % (cycle between 0 % and 100 % SoC) and 20 % (cycle between 60 % and 80 % SoC), to show that the LIB can only fulfil requirements for cranking of a gasoline engine for max. 500 cycles and diesel engine only for 100 cycles (Table 6-5 on p.87). Again, comparative data for LAB was not provided despite being requested. The data provides no indication on the question for how many cycles LAB can provide sufficient cold cranking amps under the same conditions. Therefore, the interpretation of the data cannot lead to the conclusion that LIB fail where LAB work well.

When asked to provide battery specifications and test parameters for the presented data, (ACEA et al. 2021c) provided some information, including the approximate capacity of the tested battery, ambient temperature profile for testing and pass/fail criteria. It is also stated that only cells were tested rather than batteries and that no BMS was linked to the cell test, therefore no cut-off protection from the BMS for the cells or other measures affected the test. This can be seen in contradiction to some degree to the previous statement by (ACEA et al. 2021c), that a comparison of battery performance of LIB and LAB must be carried out in the overall system context, not at the battery level.

(Bosch 2021) state that In order to compare cycle life of starter batteries, definitions according to EN 50342 are applicable and widely used. Cycle life levels (Mx) are defined with respect to degree of discharge (DoD) per cycle: 50% DoD / 17,5% DoD.

- M1 (typ. premium SLI): > 150/9 cycles
- M2 (typ. EFB): >240/15 cycles
- M3 (typ. AGM): > 360/18 cycles
- 12V Li-ion is in our experience able to provide >750/20 cycles.

(Bosch 2021) conclude that their data doesn't indicate aging issues of 12V Li-ion, but they rather expect that 12 V Li-ion will exceed LAB life in typical applications.

(Ricardo 2020) state that the power capabilities of LIB have an increased temperature dependency. Specifically, the danger of lithium plating is mentioned at extremely low temperatures of -30°C, difficulty charging LIB at extreme temperatures, low performance of LIB at extremely low temperatures under -20°C, and risk of degassing at very high temperatures.

According to (Ricardo 2020) lead batteries are generally resistant to cold conditions and are outside negatively affected outside standardisation and specification temperature ranges. For instance, the plastic battery case can become brittle below -30°C, and exposure to extreme cold can impact a battery's ability to charge (Ricardo 2020).

(ACEA et al. 2021b) stated that the very small number of vehicles that have been fitted with a 12 V LIB were all gasoline vehicles, as LIB has not been shown to meet CCA required by diesel vehicles. 12 V LIB can be found on the market that are claimed to be compatible with diesel engines (e.g. from CS-Batterien[20]), however, no additional information on the compatibility could be collected.

(Bosch 2020) report that many electrified vehicles (HV and 48V) use the higher voltage level to crank the vehicle. In those cases, the 12 V battery provides power during parking and in case of malfunctioning of the main power source (failure of DC/DC). In such cases, cold cranking performance is not a relevant factor for or against a specific 12 V battery technology.

(Ricardo 2020) also state that their analysis indicates that "both lead- and Li-ion batteries are capable of meeting high-level OEM vehicle requirements (cranking and shallow cycling)"

[20] https://cs-batteries.de/Lithium-LiFePo4-Auto-Starter-Batterie-12V-60Ah-BMS-1200AEN-Peak-Euro6

As stated, in the consultants view, the provision of empirical data, collected with transparent methods, would support claims that LIB cannot compete with the cold cranking performance of LAB. Even if comparative data from the field over a longer time was not available, accelerated ageing tests under various conditions can be carried out in laboratory environments. Determining the cycle life and calendar life of batteries using varying parameters, such as ambient temperature, charge and discharge currents, vibration, etc., can generally be carried out by independent laboratory service providers. Certainly, this requires the existence of standards that prescribe appropriate testing methods, but the exact reasons for why those are not applicable have not been specified by ACEA et al. Studies cited above did carry out such comparative tests. A standard specific for testing 12 V LIB (IEC 63118) is expected to be published within the next few years.

Reviewing the available information, the consultants understand that LIB have made progress with respect to cold cranking performance since the last review of this exemption. Different stakeholders report conflicting information on the cold cranking performance of LIB and LAB. The information provided by ACEA et al. suggests LIB do not deliver sufficient current or voltage in most cases at -18°C and -30°C. Information provided by several other stakeholders or identified by the consultants suggests that LIB outperform LAB in cold cranking. Doubt remains regarding the long-term cold cranking performance.

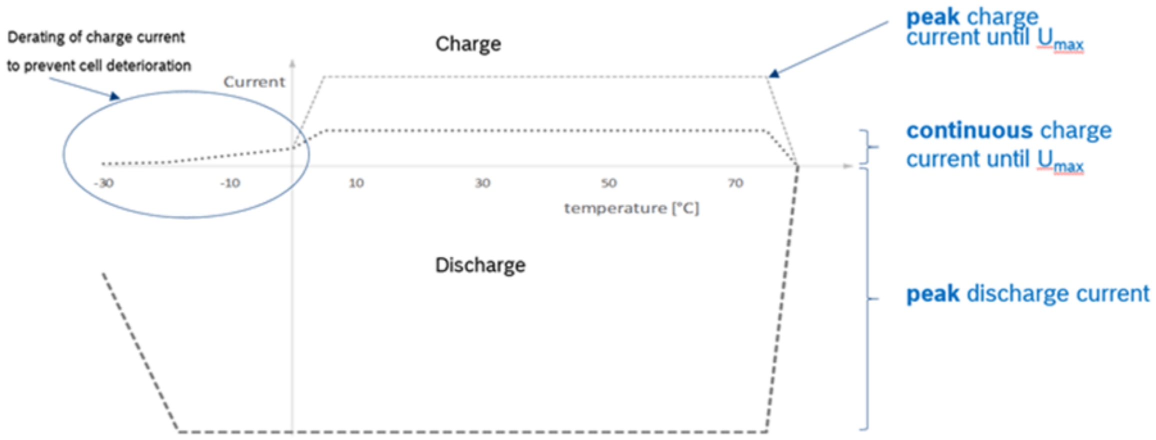
High Temperature Durability

(ACEA et al. 2020) stated that the temperature range of LAB is much larger compared to LIB, and that LIB have an upper operational temperature of 65°C while LAB can even operate at 80°C or higher. This prevents OEMs from safely utilizing 12 V LIB in the engine compartment, where temperatures of 80°C and higher can be reached. (ACEA et al. 2021b) provided a schematic, illustrating the approximate temperature window in which LIB operate (Figure 6-6 on p.89). The diagram indicates the current the LIB is able to provide at different temperatures, but does not provide actual numbers on its axis. The diagram suggests that LIB provide almost zero current at -25 °C, contradicting data provided by (ACEA et al. 2021b) that showed that LIB are able to provide 340 A at -30°C (Table 6-4 on p.87). Further, when requested to provide comparable data for LAB, (ACEA et al. 2021c) stated that the OEM who provided this data couldn’t share more information due to confidentiality issues. Therefore, the consultants cannot conclude that LAB have a higher temperature tolerance from this diagram alone.

(Ricardo 2020) explain that both lithium and lead-based starter batteries are negatively affected by operating at high temperatures; the difference at high temperatures is the increased safety risk associated with Li-ion batteries. If lithium batteries are exposed to temperatures greater than 85°C, the risk of a thermal runaway event occurring increases substantially. Further, (Ricardo 2020) stated that the internal temperature of any lead-based battery should not exceed 60°C for an extended period. In order to minimise vaporisation of fluids, lead-based batteries are best operated between +10°C and +30°C. High temperature operation of lead-based batteries can lead to premature ageing and early failure modes including corrosion (Ricardo 2020).

(Bosch 2021) provided a similar schematic of typical LFP battery characteristics, stated to be based on real measurements. According to Bosch, the diagram shows a constant discharge performance over a wide temperature window. While Li-ion has in general an excellent charge acceptance, charge control at low temperatures (to prevent cell deterioration) needs to be considered in the vehicle system design (Bosch 2021).

Figure 6-11: Typical temperature charge and discharge characteristics for LFP batteries



Source: (Bosch 2021)

(ACEA et al. 2020) further stated that in order to meet cold cranking requirements, the preferred battery location is as close as possible to the engine. Locating the battery away from the engine compartment requires long lengths of heavy-duty cable and a higher battery performance may be needed to compensate for any voltage drops. This means that 12 V batteries must be able to operate at the temperatures that can exist in the engine compartment. While the consultants can follow the argument that longer length heavy-duty cables may be required when the SLI battery is located away from the engine, it is technically feasible to implement, as has been shown by e.g. the BMW M4 F82 vehicle that was put on the market in 2014 (until 2020) and had a 12 V Li-ion SLI battery installed in the trunk area. BMW X5 and X7 models also have their 12 V lead batteries located in the trunk area. Indeed, (Varta 2019) claims that nowadays, only 58% of batteries are in the engine compartment, while 40% are in the trunk and 2% are installed in the passenger compartment. (Ricardo 2020) concluded that many manufacturers are starting to move the starter batteries into the rear of the vehicle, away from the engine as this also improves the performance and cycle life of lead-based batteries. Due care is needed to avoid positioning a lithium-ion battery within the vehicle’s rear crash zone. Furthermore, it could take 5-10 years for all the main OEMs to move the starter battery away from the engine compartment due to design cycles of existing models and costs associated with making these changes (Ricardo 2020). However, given that a potential revocation of exemption 5(b) would only apply to new vehicle types (type approvals), the consultants do not believe this argument needs to be taken into consideration.

(A123 Systems 2017) presented a case study of LIB utilized under the hood of a minivan. The data appears to show that the 65°C cell temperature limit of A123 System LIB is reached and exceeded on a small number of days in a milder climate (scenario: US city Detroit) and exceeded on a considerable number of days in hotter climate (scenario: US city Phoenix). According to (A123 Systems 2017), the maximum cell temperature in the Detroit setting is approx. 65°C and the max. cell temperature in the Phoenix setting is above

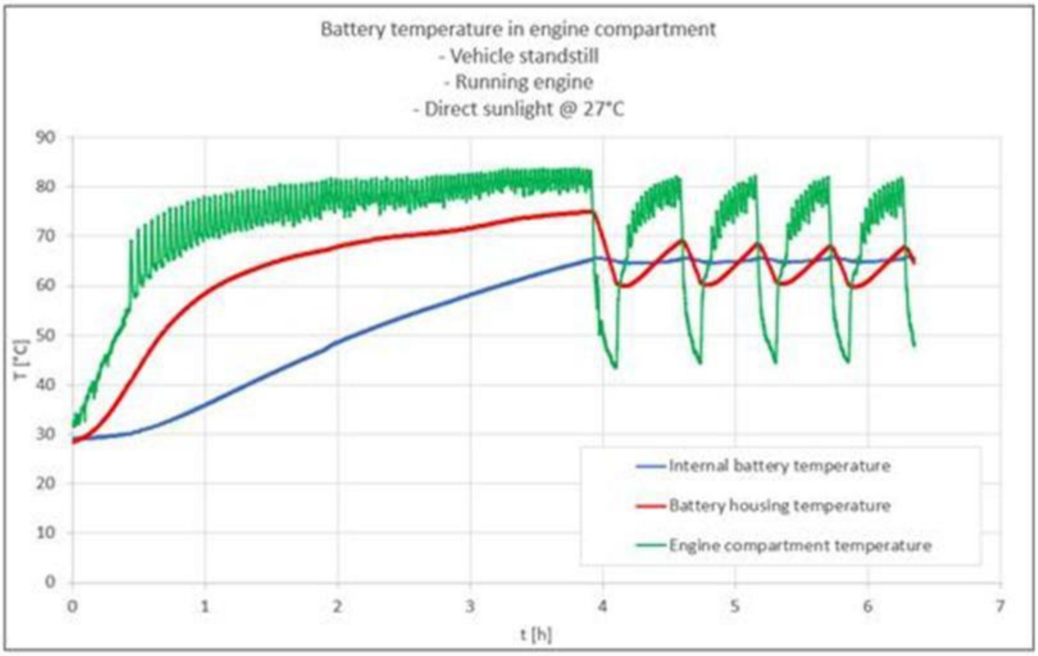
80°C. It should be noted that it is not immediately clear how the exceeding temperature events are mitigated, e.g. whether the battery shut itself off on these occasions or continued operating.

Despite exceeding the cell temperature limit repeatedly in the Phoenix setting, the battery lifetime was predicted to be very good, with only 40 % capacity fade after 10 years in use (A123 Systems 2017).

(Bosch 2021) state that Bosch specification for LAB temperature range is 60°C and 55°C for long-term for flooded (conventional) LAB and AGM, respectively, and 80°C (up to 3 hours over the life time) in the short term. According to (Bosch 2021), state-of-the-art 12 V Li-ion batteries are able to handle the same requirements.

(Bosch 2021) further elaborate that in situations with extremely high ambient temperatures, the temperature inside the LIB is not changing/increasing rapidly, so that there is time to alert vehicle (through Li-ion communication interface, e. g. LIN, CAN) and driver before an actual switch-off is happening. Figure 6-12 shows the results of a real vehicle measurement where the 12V Li-ion battery was mounted under the hood. The vehicle was exposed to sun, engine was running but the vehicle was not moving which is a harsh condition with respect to under the hood temperature development. According to (Bosch 2021), the measurement shows that the battery cells are very much protected against temporary high ambient temperatures. Due to the thermal resistance of the battery housing, it takes hours to heat the battery up from the outside.

Figure 6-12: Measured temperature development in engine compartment, battery housing, and internal battery temperature



Source: (Bosch 2021)

With respect to AUX batteries, (ACEA et al. 2020) initially stated that unlike SLI batteries, which are installed as close as possible to the engine, auxiliary batteries can be installed in other locations. (ACEA et al. 2021a) later specified that there may be more flexibility for the location of the AUX battery in completely new vehicle architectures, however, that there are a lot of constraints in due to heat exposure and potential crash risks in existing architectures. It is likely that the vehicle designer would locate the AUX battery close to the Engine Control Unit (ECU) as this is the most critical unit in terms of continuity of power and this is generally located close to the engine. As a result, temperature tolerance is required which means that Li-ion batteries are not preferred for auxiliary applications in hybrid vehicles. For pure BEVs the traction motors and power conversion equipment will get hot but the AUX battery does not need to be located adjacent to them (ACEA et al. 2020).

(Bosch 2021) agree that under-the-hood applications, in particular mounting positions close to hot parts of the engine, are not recommended for 12V Li-ion. However, the same is true for lead-acid batteries, in particular AGM. Typical mounting positions for AGM are under the front passenger seat or in the trunk, which virtually eliminates the exposure of the battery to steady ambient temperatures above 60°C according to (Bosch 2021). The suitability of 12V Li-ion with respect to high ambient temperatures is not depending on powertrain type or application but rather on the mounting position. When considered in the vehicle system design, 12V Li-ion is suitable for all applications mentioned (Bosch 2021).

While the consultants can follow the logic of the argumentation, examples for vehicle designs with the AUX battery in the trunk area can be found online. One example is the Mercedes CL Type 216 Coupé, sold on the market between 2006 – 2014 (Mercedes-Benz 2021). Another example is the VW Touareg, which features a single or dual battery setup, depending on configuration. In none of those setups is any of the batteries located under the hood (Volkswagen n.d.).

Assessing the available information, the consultants can follow that LIB are more sensitive to high temperatures than LAB. Therefore, installing a 12 V LIB under the hood near the ICE, where currently LAB are typically installed, may not be a sensible solution. In new vehicle designs, it is possible to install the starter battery, as well as the AUX battery, if present, in a different area of the vehicle. This has been demonstrated by major OEMs in a few of their vehicles, where both LIB and LAB can be found in the trunk area. For vehicles without ICE, such as BEV, heat from the engine is less of an issue.

The consultants conclude that SLI and AUX batteries can be installed away from the engine bay in vehicles with ICE. For vehicles without ICE, the high temperature issue is less severe and may not be a barrier for the employment of LIB.

Safety

(ACEA et al. 2020) point out two main concerns with LIB as SLI with regards to safety:

- In contrast to LAB, LIB cannot be located in the crumple zone of the vehicle, as in event of a collision/crash, it may degas, shut down, or even catch fire. This is less of an issue with LAB that are more robust than LAB (e.g. LAB do not contain flammable electrolyte)
- In contrast to LAB, LIB cannot be located in the engine bonnet, as very high temperatures may be reached that may result in accelerated degradation, shutdown, or even a thermal event in case of overheating. Again, this is less of an issue with LAB, as they are more resilient to high temperatures. This is the same argument that has been discussed above (high temperature durability).

(ACEA et al. 2021a) stated that LIB must be located away from crash-affected zones as it may vent, catch fire or undergo thermal runaway if crushed in an accident. This is not the case for lead batteries which have aqueous electrolytes that are intrinsically non-flammable and electrodes that are stable if exposed to air. The consultants can follow this argument that LIB would need to be located away from crash-affected zones in vehicles.

(ACEA et al. 2020) stated: "Locating the Li-Ion battery as the same place as the Lead battery (under the bonnet) would result in even more complicated technical issues (thermal and crash). This is a key concern of all OEMs, and no vehicle can be offered for sale until crash safety has been correctly established." The consultants previously pointed out that a range of vehicles has been available on market utilizing Li-ion SLI batteries. When asked how OEMs solved the safety and thermal issues in those vehicles, (ACEA et al. 2021b) stated the LIB had been located further away from the engine compartment to avoid safety and performance issues. However, (ACEA et al. 2021b) further explain that this raises a range of further issues, such as the need to install a battery with a higher capacity and long, heavy-duty cables, among others.

(ACEA et al. 2020) stated that in high voltage vehicles (e.g. BEV), safely protecting the high voltage (traction) battery is essential. This means it will have significant crash protection. However, (ACEA et al. 2020) further state that adding crash protection to a 12 V LIB would be very difficult and costly, and would also add weight to the vehicle. Again, it should be noted that several OEMs appear to have solved these issues, as vehicles with 12 V LIB have been and are available on the market. When asked to further specify the safety measures that would need to be added to 12 V LIB, (ACEA et al. 2021b) only provided general comments on thermal propagation and stated that it requires very careful development on component and vehicle level and needs to be done repeatedly in case of changes in design or cell chemistries.

(ACEA et al. 2020) stated that one issue of 12 V LFP batteries is that their power density is higher compared to traction batteries and are therefore inherently less safe. This is in contrast to various publications comparing different Li-ion types, concluding that the power density of LFP is approximately equal to NMC, the currently most commonly used Li-ion type for traction batteries (cp. section "Lithium-ion 12 V batteries" on p.100ff). Additionally, Tesla has started using LFP batteries for their Model 3 vehicles manufactured in Shanghai, indicating that the technology is considered sufficiently safe even for large traction batteries. This casts some doubt on the initial statement made by (ACEA et al. 2020).

Further, ACEA et al. stated that Li-ion batteries cannot be placed under the front seats due to safety reasons. However, it was found that this had already implemented in practice, for instance in case of the Mazda CX-30 mild hybrid vehicle (Mazda 2019). The consultants therefore consider that the safety concerns have been solved, otherwise Mazda would not sell this mass market vehicle to a large number of consumers.

(Ricardo 2020) concluded that lead-based batteries are extremely robust and offer OEMs significant advantages in terms of post-crash behaviour. If a lithium-ion battery is damaged during a crash, the battery will shut-down and stop the energy supply to the 12 V board net, which is likely to include warning lighting and door locks. For most cars, door locks are electronically controlled and after a crash there still needs to be power provided to the 12 V board net, if not, an OEM is likely to have a reduced NCAP scoring if the power supply is broken during a crash. Of note is the eCall system, mandatory in the EU for all new cars from April 2018. In the event of a crash, the car automatically calls the nearest emergency centre. On the contrary, OEMs require a 'shut-down' feature to be present to ensure that the lithium-ion battery will not overheat or overcharge and lead to a thermal runaway event (Ricardo 2020).

According to (Ricardo 2020), for 12 V auxiliary applications, LIB offer OEMs a lower weight solution. However, given the critical nature of these batteries' functions, (Ricardo 2020) believe that lead-based batteries offer OEMs some important functional-safety advantages. For instance, one of the main advantages of lead batteries is the availability of energy supply after a crash and under extreme conditions.

(A123 Systems 2017) provided insights into a crash test case study with a LIB, where the car is propelled sideways against a pole at 32 km/h, the bench level test proxy being a 150 kN pole crush test. This pole crush test resulted in no permanent battery cell deformation. (A123 Systems 2016) further reported the same test at an increased simulated speed, equivalent to 250 kN, where the battery did not take permanent damage, either.

In conclusion, the consultants can follow the argument that LIB appear to have some disadvantages in terms of safety compared to LAB. Firstly, LAB are more resilient against mechanical damage, and may continue to power essential vehicle safety features post-crash. LIB are more sensitive to mechanical damage and may shut down to prevent thermal runaway, or in the worst case, a thermal runaway may occur.

However, the consultants also understand that it is technically feasible to design vehicles in a way that LIB are well protected within the vehicle structure. This has been proven by the many vehicles featuring 48 V and high voltage traction batteries on Li-ion basis. These batteries are commonly based on NMC cathodes, which are considered less safe compared to LFP, and they are still employed in millions of vehicles around the world. If the safety of the 12 V SLI or AUX battery is taken into account in a new vehicle design, it may be just as safe as the HV batteries. Further, as stated above, a number of vehicles from different OEMs have featured 12 V LIB in the past. The consultants do not believe that OEMs would sell those to consumers in considerable numbers if safety had not been sufficiently safeguarded. Nevertheless, in case a 12 V LIB does sustain damage, unintended consequences appear to be more drastic in comparison with lead batteries, and functional safety provided by 12 V batteries may be more dependable when LAB are used.

Cost

(Ricardo 2020) stated that current commercial 12 V battery technology relies heavily on lead-based chemistries, and while Li-ion chemistries such as lithium iron phosphate (LFP) or lithium titanate (LTO) have emerged in low-voltage applications recently, mainstream applications have been limited by cost. (Ricardo 2020) summarize that across all stakeholder interviews they carried out, it was agreed that the main barrier facing lithium-ion starter batteries is cost; as lithium-ion starter batteries typically cost between 3 and 5 times more than lead-based starter batteries.

This assessment is confirmed by various other publications. For instance, (Moseley et al. 2017) presented a cost prediction of lithium-ion and lead-acid batteries (courtesy of the Advanced Lead-Acid Battery Consortium). Whereas there is much debate about future prices, (Moseley et al. 2017) stated it seems likely that lead-acid will retain a significant cost advantage for some time to come. While it appears certain that the initial investment into

LIB is considerably higher compared to LAB on a per-unit basis, total cost of ownership should also be considered when taking into account the cost borne by the consumer. Thereby, the longer lifetime of LIB and increased fuel economy in start/stop and microhybrid applications are expected to relativize the higher initial purchase costs over the lifetime of a vehicle.

(Ricardo 2020) stated that the lifetime of LAB is 5-7 years while LIB can be used for 8-10 years, leading to a more frequent need to replace LAB with a new unit compared to LIB over a vehicle lifetime. The total cost of ownership was reported by A123 to be advantageous for one of their Li-ion solutions compared to AGM (Green Car Congress 2012). However, it should be noted that the consultants merely reproduce the reported data for informational purpose without having checked the appropriateness of assumptions behind the comparison.

The consultants understand that cost is a major concern in a highly competitive globalized industry. However, cost is not the main focus of this assessment, which instead focusses on scientific and technical progress. Therefore, the topic of cost is not investigated in more depth.

Interchangeability and parts availability

ACEA et al. state that while 12 V LAB are widely available from a range of suppliers, this is not the case for 12 V LIB. Further, production capacity in Europe cannot fulfil the demand for 12 V batteries at the current time or in the near future.

In the consultants view, the situation is, at least to some extent, a chicken and egg problem, in which little incentives for OEMs to utilize LIB instead of LAB lead to low demand, which in turn leads to a lack of incentives for investment in large production capacity for LIB. (Ricardo 2020) report that both A123 Systems and GS Yuasa have setup LIB assembly plants in Europe to support anticipated European volumes, although the production capacity falls well behind the total numbers of required SLI and AUX batteries (initial annual capacity at Yuasa plant: 500.000 units; A123 Systems plant: 600,000 units).

Therefore, increasing demand can be expected to incentivize market entry by new players and increasing production capacity, including in Europe. As this is not considered a core technical issue in this assessment, a more in-depth analysis of the market potential was not conducted by the consultants.

Roadmap towards elimination of lead

Reviewing the available information, it is the consultants' impression that the description of a roadmap provided by ACEA et al. does not differ significantly from the roadmap provided in the last review of this exemption.

According to (ACEA et al. 2020), it is not possible to put precise timings on how long it will take to overcome the issues stated to prevent the mass market adoption of 12 V LIB. Nevertheless, (ACEA et al. 2020) indicate the following steps, partially providing assumptions on the required time:

- Allowing listed research projects to complete. The latest date for the listed projects to conclude is by **mid-2025**. This argument was also brought forward by ACEA et al. in the last review of this exemption conducted by (Gensch et al. 2016). A renewed list of ongoing research projects into different aspects of battery technology was provided by ACEA et al. High voltage traction LIB have been used in hybrid and fully electric vehicles for over a decade, while research projects continuously attempt to improve their performance. Considering that the listed projects do not specifically focus on 12 V batteries, the consultants do not consider the conclusion of the projects a necessary prerequisite to adopt LIB in 12 V SLI and AUX applications. However, it is understandable that OEMs would prefer to wait for improved, future Li-ion technology, that no longer requires flammable, liquid electrolytes, and other improvements expected within this decade.

- ACEA et al. stated that the cell technology available today would not allow an engine bay package which also has crash zone package issues. For these applications, suppliers have still to do fundamental material and cell research and development work for which **3 years** duration is a very optimistic assumption. While the consultants acknowledge that more time may lead to a further improvement of LIB technology, surveyed information shows that placing batteries in locations other than the engine bay is technically feasible.
- Given the high technological risk, fast adaptation for mainstream volumes would require standardisation of requirements, avoiding the need for multiple OEM specific parallel tests and reducing the engineering risk. **Four years** is an optimistic timing assumption for this process that will include life tests validation in several iterations.

(Bosch 2020) stated to expect that LIB will replace the LAB technology in the mid-term, however, for a broad market introduction of LIB, there is the need for further research on certain technical topics. (Bosch 2020) therefore recommend continuing the exemption for lead-acid batteries in vehicle applications until end of **2025** with a transition-phase of 2-3 years until end of **2027/2028**.

(ACEA et al. 2021c) reiterate their request that the current exemption is maintained and that the next Annex II 5(b) exemption for lead batteries is timed to be after the publication of the ongoing review of the ELV Directive; ideally **no earlier than 5 years** after the conclusion of this assessment of technical and scientific progress.

Supercapacitors

The last review of this exemption covered supercapacitors extensively, particularly the Olife battery, the prototype battery combining Li-ion with supercapacitor (a result of the European project LEFAPO[21]). (Gensch et al. 2016) reported that it was expected that the Olife battery would be a commercial product within 3-5 years following the time of writing. This, however, does not seem to have materialized.

When asked about the major barriers, (Olife 2021) stated that the lack of clarity on the future of SLI batteries in the EU, which brings uncertainty to investors, resulting in difficulties to find strategic investors. With regards to cold cranking performance, Olife provided the following data on their 30 Ah battery: 400 A @-18°C and 200 A @-30°C, while other currents

[21] EU Horizon 2020 project « Lead free automotive SLI power (LEFAPO) », Grant agreement ID: 697234

were not tested. Olife stated to have tested their battery in commercial vehicles from two major manufacturers for several months without any performance issues (Olife 2021).

(Olife 2021) further provided information on high temperature performance, stating that their battery had passed UN 38.3 methodology test at 75°C, however, adding that such high temperatures are detrimental to the battery. Therefore, the current version of Olife battery is recommended to be placed in the trunk area. Another disadvantage of the technology is currently the cost, as the prototype has been stated to cost 1000 Euros. However, it is expected that semi-mass production scale will drive significant production cost reduction.

One vehicle model that uses a combination of Li-ion and supercapacitor technology as default SLI battery is the Mercedes S 63 AMG that entered the EU market in 2013 (Brandl 2013). The battery is stated to have been manufactured by A123 Systems. The supercapacitor substitutes the start-stop systems commonly realised via AGM lead-acid batteries.

Trend towards 48 V

(Ricardo 2020) see a strong demand within low-voltage (<75 V) batteries for 48 V batteries. and assume the needs of this application will be wholly fulfilled by Li-ion technology, although 48 V lead batteries have been developed. Therefore, it can be assumed that the exemption for lead may not be technically required for this particular application.

(Ricardo 2020) lead interviews with vehicle OEMs, in which it was indicated that engine cranking with the 48 V battery is possible, stating that for mild-hybrid vehicles, the future of 12 V batteries will depend on the electrical architecture; the engine may be cranked from the 48 V battery or the 12 V battery. If the 48 V battery cranks the engine, the 12 V battery can be significantly downsized (Ricardo 2020).

(ACEA et al. 2020) stated not to be aware of any OEM developing a board net without a 12 V battery. Removing the 12 V battery will automatically lead to massive requirements at the corresponding DC/DC converter (highly transient loads, functional safety). The standard vehicle architecture relies on a 12 V board net for most vehicle systems which is powered by a 12 V battery. If a 48 V battery is used on the vehicle, it is primarily used specifically for kinetic energy recuperation and power assist as it is optimised for this function.

The consultants can follow the argumentation that the industry is not shifting from 12 V to 48 V systems, but rather integrates 48 V systems (and batteries) into vehicles with existing 12 V systems (and batteries). It appears that the 12 V battery can be downsized if additional functionality are taken over by the 48 V battery, such as cranking the engine. This may reduce the overall amount of lead used in this application.

6.3.3 Environmental arguments and socioeconomic impacts

Recycling

While (IHS Markit 2020) reported the collection rate for LAB to be 97.3 % in the period 2015 to 2017, the study does not investigate LIB recycling. The consultants have no indication that collection rates for LIB should be considerably lower, especially if the same networks can be used (e.g. workshops, vehicle dismantling companies).

(IHS Markit 2020) report that in the period 2015-2017 around 2.7 million second-hand passenger cars were exported outside of the 14 EU countries considered in the study (representing about 92% of the parc of in-use vehicles in the EU in 2017) annually. (IHS Markit 2020) further reports that the tonnage of batteries exported as part of second-hand cars (and not available for collection within the EU) represents about 45,000 tonnes of lead batteries per year of the 14 countries surveyed in the study. The study does not reflect further upon the destination of these batteries and the circumstances under which they are treated at EOL. Considering the hazards posed by both the sulfuric acid and highly toxic lead (compounds) contained in LAB, the consultants consider this amount of lead non-negligible.

The recycling efficiency, defined as the percentage of useful recycled materials relative to the input fractions, of individual EU member states was reported by (eurostat 2020) for the years 2012 and 2018. (eurostat 2020) reported that for the year 2018, recycling efficiencies of lead-acid batteries were reported higher than 65 % for 21 Member States; the 5 Member States that had not yet reported data for year 2018 had reached this target in 2017. However, the recycling efficiencies did not display a clear trend across the countries during the period 2012-2018. In 2018, 15 Member States reported recycling efficiencies above 80 % (Hungary: close to 100 %).

Due to the low-cost materials employed in LFP batteries, traditional material recycling of those batteries is indeed economically less viable compared to LAB or other LIB types, such as NMC. This situation may be mitigated in the future via the steady progression of recycling technologies and legislative minimum targets for the recycling efficiency overall as well as for individual materials. (Halleux 2021) report that the new proposed Battery Regulation increased targets for the recycling efficiencies for lead-acid batteries, i.e. recycling of 75 % by average weight of LABs by 2025, rising to 80 % by 2030. It also stipulates new targets for lithium-based batteries, i.e. 65 % by 2025 and 70 % by 2030. The proposed Regulation also envisages specific material recovery targets, namely 90 % for cobalt, copper, lead and nickel, and 35 % for lithium, to be achieved by the end of 2025. By 2030, the recovery levels should reach 95 % for cobalt, copper, lead and nickel, and 70 % for lithium (Halleux 2021). Nevertheless, the collection and recycling efficiency of LAB set a very high standard, which LIB, and LFP batteries in particular, are not likely to reach in the near future.

(Oeko-Institut e.V. 2016) describe the manifold issues with recycling of lead from LAB in African countries, where processes are not as controlled and awareness for risks for human health and the environment is not on the same level as in the EU. It is pointed out that most of the approximately 800.000 tonnes of recycled lead from Africa is exported to refineries in Asia and Europe. As 85 % of all lead globally is used for the manufacturing of batteries, it is likely that secondary lead from Africa is again used for the production of new lead-acid batteries (Oeko-Institut e.V. 2016).

(ACEA et al. 2020) claim that automotive lead batteries are one of the few consumer products that can be considered to be operating in a closed loop circular economy in the EU. A revocation of exemption 5(b) could thereafter break the loop and eventually convert saleable products into waste that would have no market. Without looking deeper into this topic, the consultants would like to remark that following this argument would freeze the status quo. It should also be noted that lead batteries are also used in other sectors, such as stationary energy storage market relevant to the increasing use of renewable energy.

However, the consultants cannot judge to which degree this market would be capable of absorb lead from EOL 12 V batteries.

In conclusion, the consultants can follow the argument that the recycling of LAB is a highly established industry, achieving much higher collection and recycling rates compared with other similar industries (e.g. portable batteries). Lead recycling is technically less complex than LIB recycling. The consultants also see the issues surrounding future recycling of EOL automotive Li-ion batteries. However, it can be expected that the Li-ion recycling industry will inevitably have to vastly increase its capacity to deal with the enormous amounts of traction Li-ion batteries expected to become due for recycling in the coming years. Indeed, traction batteries currently contain more economically valuable materials, particularly cobalt, that are not contained in LFP technology, likely leading to initially lower recycling efficiency. However, as LFP is considered cheap and safe compared to NMC or NCA used in traction batteries today, it is expected that the market share of LFP will increase also in traction batteries. Recycling technologies will have to follow suit in order to achieve the targets foreseen in the new Battery Directive.

Environmental impacts

(Sphera 2020) reported that for traditional ICEV, the lifecycle GWP impact of LAB is considerably lower compared to LIB, as the higher manufacturing impact of LIB cannot be balanced out by fuel savings during the use phase due to the comparatively lower mass of LIB. However, according to (Sphera 2020), the lifecycle GWP impact of LIB and LAB does not differ extensively when start-stop or micro-hybrid vehicles are assessed (cp. Table 6-6 on p.99). According to a market forecast by (Ricardo 2020), regular ICEV will no longer be part of the powertrain production in the year 2025 and beyond – rather, all ICEV will feature start-/stop systems or higher degrees of electrification. Therefore, judging from the data provided by (Sphera 2020), the consultants conclude that the implementation of LIB will not lead to a substantial increase in GWP compared to the continued use of lead.

Additionally, while (Sphera 2020) account for fuel savings during the use phase afforded by the lower mass of LIB compared to LAB, it is not clear whether the increased recuperation performance of LIB has been accounted for that is made possible via the higher dynamic charge acceptance attributed to LIB. For instance, (Moseley et al. 2017) noted that “to maximize benefits in terms of fuel economy and CO_2 emission, the 12-V micro-hybrid battery should consistently absorb high-rate charge pulses of regenerative braking during micro-cycling operation within a partial state-of-charge (PSoC) window. This charge ability is measured as dynamic charge-acceptance (DCA). Many present EFBs and AGM VRLA batteries, however, are not always able to accept the full recuperation power of about 3 kW when it is available from the alternator.” In the same argumentative line, (Vergossen 2018) reported that the recuperation performance of LIB was 24 % higher compared to LAB in testing the different battery technologies in an NEDC (New European Driving Cycle). In case this was not taken into account, the presented results may underestimate the improved fuel economy afforded when using LIB in micro-hybrid vehicles.

(Sphera 2020) do not report data on toxicity, citing limitations in the precision of characterization factors for human health and freshwater ecotoxicity. (Sphera 2020) acknowledge that toxicity, among other impact categories, is recommended by ILCD but in need of some improvements or to be applied with caution. (Sphera 2020) further state that although these impacts are relevant environmental concerns, it is the position of the metal industry that the characterization of these impacts from the inventory data does not adequately support decision-making. The consultants understand there is indeed a known elevated uncertainty in the method to estimate toxicity in life cycle assessment studies. Nevertheless, it needs to be pointed out that a study assessing the environmental impacts of a product containing approximately 60 % lead by weight, a heavy metal with known toxic properties, can be expected to provide results for impact categories indicating the associated effects for human health and the environment. This applies even more taking into account that the objective of the study is to obtain an exemption for the continued use of lead whose use has been restricted for its known toxicity. From a methodological point of view it is perfectly sound and understandable to not include impact categories associated with higher uncertainty than more established and robust impact categories, such as GWP, but GWP will only tell part of the story for products with expected high toxicity potential. Of course, the results would also highly depend on assumptions made regarding the production and recycling operations in EU and non-EU facilities, the later related to the massive exports of second-hand passengers also to developing countries, where the LAB treatment is one of the dirtiest industries.

Assessing environmental impacts of the manufacturing of several battery technologies, (Wang et al. 2018) base their life cycle inventories on primary data from a Chinese factory, assuming the use of primary rather than secondary materials. The results indicate lower impacts for LFP compared to LAB across 17 out of 18 impact categories assessed (exception: agricultural land occupation), following the ReCiPe midpoint model for life cycle impact assessment. According to (Wang et al. 2018), among all the 18 environmental impact categories, the lithium iron phosphate production process has the least environmental impact. In contrast, except ionizing radiation, agricultural land occupation and water consumption, the LAB production process has the greatest impact on the rest of the environmental impact categories. The GWP for LAB was calculated as 103 kg CO2-equivalent (Sphera 2020: 45 kg) and for LFP as 16 kg (Sphera 2020: 254 kg). The consultants recognize a significant difference in the results of both studies, which cannot be explained without further investigating the methods and data of both studies. This is beyond the scope of this review. The difference for LAB may be explained, at least in part, with the fact that (Wang et al. 2018) assume all materials used for manufacturing to be primary rather than secondary materials. Therefore, this reference is only considered to provide complementary information without being immediately applicable to the reality of the European context with respect to LAB manufacturing.

6.3.4 Conclusions

While acknowledging progress made by LIB technology, ACEA et al. describe lead-acid batteries as a mature, reliable and robust technology in contrast to Li-ion as a comparatively immature and inherently less safe technology. Information exchange with other parties, including Bosch and A123 Systems, as well as a survey of available literature on the topic, shines a different light on some of the key aspects. The following paragraphs condense all collected information into brief, and therefore inevitably simplified, conclusions drawn by the consultants.

(Ricardo 2020) summarize that battery and vehicle manufacturers consider cost as the main barrier for the use of lithium-ion starter batteries, their price being between 3 and 5 times higher compared to lead-based starter batteries. All stakeholder contributions and surveyed literature also highlight the high cost of LIB over LAB to some extent. Overall, in the consultants' view, the accessed information suggests that major factors preventing the implementation of 12 V LIB on a mass market scale, including investments to solve remaining challenges, are of economic nature. There appears to be no economic incentive for OEMs to switch to LIB, preventing a broader adoption in the mass market.

Besides cost, the consultants understand that 12 V LAB are a tried and tested technology that has been well established over decades of automotive development and real-world usage. In contrast, there is comparatively little experience with LIB in 12 V applications, as only few OEMs have implemented them in practice.

While ACEA et al. argue that vehicles that have been fitted with 12 V Li-ion SLI batteries are niche, pilot or performance vehicles for which weight savings matter more than cost, these vehicles demonstrate the real-world usability of LIB in those applications. The consultants can follow the argument that there are technical barriers to implementing 12 V LIB into existing vehicle designs that were designed with 12 V LAB in mind. However, in new vehicle designs, the consultants consider the existing examples evidence that 12 V LIB can be safely operated, i.e. located away from heat sources and crash-affected zones, and mechanically protected within the structure of the vehicle. Since ACEA et al. frequently highlight that OEMs are responsible for the safety of their vehicles, it can be concluded that they would not sell such vehicles to a considerable number of consumers if it had not been deemed to be sufficiently safe. While ACEA et al. state that those vehicles fitted with 12 V LIB are pilot vehicles to test the performance of LIB in the field, it is also stated that those are niche vehicles not comparable to the mass market.

If ACEA et al. were interested in investigating the performance of 12 V LIB for the mass market, it would have been logical to install 12 V Li-ion SLI and AUX batteries in smaller numbers in actual mass market vehicles, as is commonly done before the introduction of new technologies. It seems that there have not been any such tests in the past years featuring 12 V LIB in AUX applications.

Recent technological improvements have further increased the feasibility of utilizing 12 V LIB. Nevertheless, the consultants understand that besides cost, 12 V LIB still face technical challenges that do not affect 12 V LAB to the same extent. ACEA et al. brought forward an amalgam of technical, economic and environmental reasons to argue for the exemption to be continued. The technical challenges are in essence related to concerns regarding cold cranking performance, high temperature performance, safety, and standardization of 12 V LIB.

Cold cranking performance

The fact that ACEA et al. did not provide comparative data on the performance of 12 V LIB versus 12 V LAB to underpin the claimed inferior cold cranking performance of LIB under low ambient temperature, despite requested by the consultants, was justified with two arguments: Firstly, such data are sensitive business information and cannot be shared publicly by OEMs, and secondly, the different technical properties of 12 V LIB and 12 V LAB forbid comparative assessments. Both these arguments cannot be followed fully by the consultants. In the consultants view, it is essential to provide comparative data to accountably and transparently substantiate claims on the disparity of two competing technologies for the same application with credible and replicable data. Even if OEMs cannot share available comparative data, ACEA et al. could commission, as a minimum, comparative assessments carried out by independent laboratories to provide credible data to back up their arguments for the continuation of the exemption. Instead, ACEA et al. provided data only on the performance of 12 V LIB. The consultants therefore do not have any reference data for 12 V LAB and are expected to rely on the fact that 12 V LAB have been used for the last many decades in automotive applications successfully. However, their use in vehicles over decades does not automatically mean that 12 V LAB would fare equal or better in the tests 12 V LIB were subjected to. While it is acknowledged that test procedures defined in standards such as EN 50342 are specific for 12 V LAB and cannot always be applied to 12 V LIB, certain comparative testing has been demonstrated in literature.

Comparative test results have been published by academia and manufacturers of 12 V LIB, suggesting that LIB exhibit superior cold cranking performance to LAB at ambient temperatures of both -18°C and -30°C. The consultants could, however, not identify comparative data on the long-term CCA performance, leaving some room for remaining doubt with respect to concerns expressed by ACEA et al. However, it should be noted that it is the duty of ACEA et al. to provide comprehensive evidence that lead is still not unavoidable in the applications in scope of this exemption, not the role of the consultants or other stakeholders to do the opposite.

Naturally, cold cranking is only a requirement for batteries that are used for starter functionality in vehicles that feature an internal combustion engine. In vehicles without an ICE, such as BEV and FCEV, cold cranking capability is not a requirement. Surveyed information, including data provided by ACEA et al., suggests that 12 V LIB continue to function at ambient temperatures of both -18°C and -30°C, however, delivering smaller currents compared to room temperature, not unlike any other battery technology including 12 V LAB. While cold cranking requires high currents, other vehicle loads powered by 12 V batteries require comparatively smaller currents. Concerns regarding cold cranking performance of 12 V LIB therefore do not apply to AUX batteries, or to a lesser extend. In fact, the discussion of low temperature performance is almost exclusively focused on cold cranking ability, leading the consultants to believe that low temperature performance of AUX batteries is not a specific issue associated with 12 V LIB. Nevertheless, the consultants acknowledge concerns regarding the use of 12 V LIB in sub-zero temperatures, such as issues with charging and energy recuperation.

High temperature durability

High temperature durability is the second major technical argument brought forward by ACEA et al. Indeed, evidence suggests that 12 V LAB perform better at extremely high temperatures, in which 12 V LIB disconnect (shut off) to avoid sustaining damage. However, data published by A123 Systems suggests a level of inertia that delays the temperature increase of the battery cells to a degree that allows them to continue functioning even in out-of-spec ambient temperature ranges. These tests were carried out with the 12 V LIB located in the engine bay (under the hood). Further, the question that suggests itself is whether it is technically unavoidable to install the battery in the engine bay, where such high ambient temperatures are more frequently expected, or whether batteries can be installed in generally cooler areas of the vehicle. Inquiries from the consultants to ACEA et al. in this respect were answered with several of reasons arguing that it is technically difficult to implement. While the arguments provided are understandable, they are relativized, again, by the examples of vehicles that already implement 12 V batteries, both lead and Li-ion, in the trunk area or under the passenger seats. While it is clear that such a change can hardly be implemented in existing vehicle designs, in the consultants view, it is possible when taken into consideration in new vehicle models in the design stage. As above, AUX batteries are affected to a lesser degree, as has also been stated by ACEA et al., as AUX batteries can be placed in other locations in the vehicle, as proximity to the engine is not necessary.

Safety

Another technical theme is a lack of safety that prevents the broad implementation of LIB in 12 V applications according to ACEA et al.. Again, analogous to the thermal issue, evidence suggests that lead batteries are indeed more robust than LIB when damaged or operated in other out-of-spec situations. LIB are known to have issues with thermal runaway in extreme situations. Among LIB chemistries used in the automotive context, LFP is frequently reported to be inherently safer than chemistries used in high voltage batteries (e.g. NCM, NCA). Nevertheless, lead batteries require less technical and mechanical protection to be considered safe. From the consultants point of view, the fact that a range of hybrid and fully electric vehicles have been on the market for more than a decade, with progressively increasing numbers, are sufficient evidence that it is possible to safely utilize LIB in automotives. The consultants believe that it is technically feasible to safely install 12 V LIB, weighing 10-15 kg, when it has been possible to safely install and use large, 400 kg traction Li-ion batteries. While high voltage traction batteries and 12 V batteries are very different in many aspects, ACEA et al. did not unambiguously demonstrate that 12 V LIB cannot be safely used in vehicles when much larger HV LIB can – commonly using cathode materials (NMC, NCA) considered less safe than the material (LFP) used in 12 V applications. Further, this has also been demonstrated by the multiple examples of vehicles from several OEMs that were fitted with 12 V LIB as early as in 2010. However, the consultants understand safety concerns remain, and additional experience may be required before mass market implementation of LIB can follow.

The functional safety provided by the battery is another concern raised by ACEA et al. They argued that secondary safety risks may result from 12 V LIB switching off power for self-protection. When damaged or being operated in out-of-spec situations (e.g. very high temperature), 12 V LIB may disconnect from the vehicle electrical system, and therefore no longer power several safety functions, including EPS and energy call support. Further, in hybrid and fully electric vehicles, 12 V batteries have been stated to power the BMS of high voltage batteries, controlling their (dis-)connection with the high voltage electrical vehicle system, which is an essential safety feature. Further, ACEA et al. argue that safety of such vehicles is increased when using two different battery types for high voltage and low voltage batteries, as it may prevent the same failure mechanism occurring to both batteries at the same time. It is not clear to the consultants to which degree the implementation of different Li-ion types for traction (e.g. NMC, NCA) and 12 V battery (e.g. LFP, LTO) would provide the same level of safety in this regard, but it is clear that LAB do generally not disconnect from the vehicle grid system for self-protection. The consultants therefore follow the argument that concerns exist regarding functional safety when relying solely on 12 V LIB.

Standardization

Lastly, standardization is addressed as an issue for 12 V LIB that makes the continued use of 12 V LAB unavoidable. In this regard, ACEA et al. explained that the specific standard for 12 V LAB, EN 50342, is not directly applicable to 12 V LIB. However, the development of IEC 63118 is in the last stages and is expected to be published as final standard in 2025. The consultants can follow that components require a certain level of standardization before mass market implementation can take place.

General remark

In the consultants view, the situation is, at least to some extent, a chicken and egg problem, in which higher cost for OEMs to utilize LIB instead of LAB lead to low implementation rates, preventing OEMs from gaining additional experience, therefore leaving doubts with respect to real-world and long-term performance, in turn emphasizing low implementation rates. Legislative certainty would likely stimulate additional investment in R&D and European production capacity, thereby accelerating progress. The same applies to the cost gap between LIB and LAB – 12 V LIB are only manufactured in comparatively low quantities and are therefore more expensive, preventing broader implementation - which would be a pre-condition to economies of scale taking effect in case of mass production. Although 12 V LIB are not likely to match the affordability of 12 V LAB anytime soon, or ever for that matter, their price is expected to drop in the mid-term if demand from OEMs increases. Without legislative incentives, the adoption of 12 V LIB is likely to commence much slower, with companies like Tesla and Hyundai spearheading the industry.

Conclusions by battery application

With respect to the individual battery applications in scope of exemption 5(b), the consultants arrive at the following conclusions:

- Mild hybrid vehicles feature 48 V systems and batteries for energy recuperation, in parallel with the 12 V board net and 12 V batteries. The market share of mild hybrid vehicles is expected to further increase as part of the effort to meet climate targets set by the European Commission. It is expected that 48 V batteries will increasingly also take over SLI functionality in the future. ACEA et al. confirmed that while lead batteries for 48 V batteries have been under development, 48 V systems are commonly implemented without the use of lead batteries. The consultants therefore conclude that lead is avoidable in 48 V, as well as the currently less prevalent 24 V batteries, in mild hybrid vehicles.
- 12 V SLI batteries that serve, among other functions, to crank the engine, need to provide sufficient amperage and voltage even at very low temperatures. ACEA et al. did not provide comprehensive evidence that unambiguously show that LIB cannot fulfil the requirements which LAB can fulfil, as no comparative data was presented. Other sources have shown that LIB can fulfil requirements, although there is remaining doubt expressed by ACEA et al. regarding their long-term performance. The consultants therefore do not believe that cold cranking in 12 V Li-ion is a major barrier for their implementation. However, the consultants can follow the argument that there is remaining doubt regarding the functional safety provided by 12 V Li-ion SLI batteries, as LIB may disconnect from the vehicle electrical system when out-of-spec situations occur, which 12 V lead-acid SLI batteries do not.

- Regarding 12 V AUX batteries, ACEA et al. stated that lead batteries are still the state of the art in vehicles, and the only chemistry used in this application, and that there is no (or very little) experience or knowledge of the suitability of other battery chemistries for this function. The consultants cannot follow this, considering that the requirements AUX batteries need to fulfil appear less harsh compared to SLI (no cold cranking, more freedom in placement of battery away from heat source). Progress with testing and prototype/pilot applications should have been possible since the last review of this exemption, but was not reported. In the consultants' view, ACEA et al. have not presented substantiated evidence that LIB cannot fulfil the requirements that LAB can fulfil in 12 V AUX applications. However, the consultants can follow the argument that there is remaining doubt regarding the functional safety provided by 12 V batteries when LIB are utilized in this function, as LIB may disconnect from the vehicle electrical system when out-of-spec situations occur, which 12 V lead-acid AUX batteries do not.

6.4 Recommendation

Article 4(2)(b)(II) provides that an exemption can be justified if the use of a restricted substance is unavoidable.

ACEA et al. request that the current exemption is maintained and that the next review is timed to be after the publication of the ongoing review of the ELV Directive and ideally no earlier than 5 years after the conclusion of this assessment of technical and scientific progress.

In order to adapt the exemption to the current scientific and technical progress, and considering the conclusions derived in section 6.3.4, the consultants make the following recommendations.

Automotive 48 V and 24 V batteries used in mild hybrid vehicles are a growing market segment. In this application, battery types other than LAB are commonly used. Therefore, lead-based batteries are avoidable in this application and can be removed from the scope of this exemption.

The following phrasing is recommended for exemption 5(b) to reflect this:

Exemption phrasing variant A

	Materials and components	Scope of the exemption	Review date
5(b)(i)	*Lead in batteries for battery applications not included in entry 5(a) and entry 5(b)(ii)*	*Vehicles type approved before 1 January 2024 and spare parts for these vehicles*	*n/a*
5(b)(ii)	*Lead in batteries used in 12 V applications*	*Vehicles and spare parts for these vehicles*	*This exemption shall be reviewed in 2025*

Explanatory remarks:

- 5(b)(i) includes batteries that are not included 5(a) ("Lead in batteries in high voltage systems that are used only for propulsion in M1 and N1 vehicles") and are not included in 5(b)(ii) ("Lead in batteries used in 12 V applications"). Although the consultants did not encounter any vehicles on the market that feature such a battery (e.g. 24 V LAB) during the evaluation period, the possibility cannot be fully excluded without remaining doubt. Therefore, a transition period until the end of 2023 is granted, after which newly type approved vehicles may no longer be fitted with such a battery.
- 5(b)(ii) includes lead in batteries used in 12 V applications. This entry includes both 12 V SLI and 12 V AUX batteries. These are the only remaining applications in which lead may still be used in batteries in vehicles type approved from 1 January 2024.
- A review in 2025 is recommended to allow the industry to complete the currently ongoing standardisation efforts for 12 V LIB and to gather more experience and data on 12 V LIB in SLI and AUX applications.

As it is not clear whether a transition period is indeed required for batteries included in the above entry 5(b)(ii), as no vehicles are currently known to required it, a simpler version of the exemption phrasing would be as follows:

Exemption phrasing variant B

	Materials and components	Scope of the exemption	Review date
5(b)	*Lead in batteries used in 12 V applications*	*Vehicles and spare parts for these vehicles*	*This exemption shall be reviewed in 2025*

For the next review, the consultants recommend the following:

- The publication of the standard IEC 63118 is expected for the year 2025. Therefore, standardization should no longer be considered an issue preventing the mass market implementation of LIB in 12 V applications.
- It shall be expected that, when claims are made regarding the inferior performance and durability of alternatives to LAB, especially with respect to low and high temperature performance, including in the long-term, that comparative test results are presented. If vehicle manufacturers cannot provide results of such tests, these should be carried out by independent service providers. They should be produced using appropriate methods according to available standards. Deviations from available standards require the provision of rationale and need to be transparently communicated. Ideally, the test setup is agreed upon with representatives of OEMs and battery suppliers manufacturing all tested battery technologies.
- It is expected that experience with alternatives to LAB in 12 V AUX applications is gained before the next review of this exemption and remaining doubts, if any, are substantiated with data.

- The consultants recommend other stakeholders outside ACEA et al. to participate in future reviews of this exemption to enable balanced and multi-perspective discussions as to the unavoidability of the use of lead. Exemptions can then better reflect the actual state of science and technology and better progress may be possible towards the elimination of lead in automotive batteries.

6.5 References

A123 et al. (2015): Review of ELV Exemption 5. From the view of lithium-ion battery makers and experts. With assistance of Fraunhofer ICT, LG Chem Ltd., Samsung SDI Co. Ltd, checked on 5/4/2021.

A123 Systems (2016): Lithium-ion 12V Starter Battery 60 Ah Product Brochure. Available online at http://www.a123systems.com/wp-content/uploads/12V-Starter-Battery-Flier_2016_Gen-3.pdf, checked on 5/4/2021.

A123 Systems (2017): 12V Li-Ion Batteries –Ready for Mainstream Adoption (Advanced Automotive Battery Conference). Available online at http://cii-resource.com/cet/AABE-03-17/Presentations/BATO/Fehrenbacher_Christoph.pdf, updated on 2/1/2017, checked on 4/6/2021.

ACEA et al. (2020): Submission of ACEA, CLEPA, JAMA, KAMA et al. representing the affected automotive industry including the supply chain to the stakeholder consultation published by Biosis on 15.Sept. 2020 on the review of three entries in EU ELV Directive Annex II. 08. December 2020. With assistance of CLEPA, JAMA, KAMA. Available online at https://elv.biois.eu/ACEA_5(b).pdf, checked on 3/21/2021.

ACEA et al. (2021a): Response to Questionnaire 2 Exemption 5 of ELV Annex II. Lead in batteries for battery applications not included in entry 5(a), checked on 3/31/2021.

ACEA et al. (2021b): Response to Questionnaire 3 Exemption 5 of ELV Annex II. Lead in batteries for battery applications not included in entry 5(a), checked on 5/24/2021.

ACEA et al. (2021c): Response to Questionnaire 4 Exemption 5 of ELV Annex II. Lead in batteries for battery applications not included in entry 5(a). ACEA et al., checked on 11/6/2021.

ADAC e.V. (2021): Pannenstatistik 2021: Der Streik der Starterbatterien. ADAC e.V. Available online at https://www.adac.de/rund-ums-fahrzeug/unfall-schaden-panne/adac-pannenstatistik/, updated on 6/17/2021, checked on 6/17/2021.

Atiyeh, Clifford (2017): How the Hyundai Ioniq Ditched Its Traditional 12V Lead-Acid Starter Battery. In *Car and Driver*, 5/19/2017. Available online at https://www.caranddriver.com/news/a15341302/how-the-hyundai-ioniq-ditched-its-traditional-12v-lead-acid-starter-battery/, checked on 5/17/2021.

BMW (2014): Technical Training. Product Information. F80/F82 Complete Vehicle. BMW, checked on 5/19/2021.

Bosch (2020): Stakeholder contribution to the cosultation questionnaire on exemption 5(b) of ELV Annex II. Available online at https://elv.biois.eu/Bosch.pdf, updated on 2020, checked on 3/29/2021.

Bosch (2021): Response to Questionnaire 2 Exemption 5 of ELV Annex II. Bosch.

Brandl, Maria (2013): Mercedes S 63 AMG - mehr als nur „S“. Neben 585 PS und 900 Nm bringt er auch Innovationen wie eine Lithium-Starterbatterie. In *motor.at*, 10/1/2013. Available online at https://motor.at/news/mercedes-s-63-amg-mehr-als-nur-s/29.124.158, checked on 5/16/2021.

Ceraolo, Massimo; Huria, Tarun; Pede, Giovanni; Vellucci, Francesco (2011): Lithium-ion starting-lighting-ignition batteries: Examining the feasibility. In : 2011 IEEE vehicle power and propulsion conference (VPPC 2011). Chicago, Illinois, USA 6-9 September 2011. 2011 IEEE Vehicle Power and Propulsion Conference (VPPC). Chicago, IL, USA, 9/6/2011 - 9/9/2011. Piscataway NJ: IEEE, pp. 1–6.

EGARA (2020): EGARA answers consultation lead in batteries. Available online at https://elv.biois.eu/EGARA.pdf, checked on 3/29/2021.

eurostat (2020): Waste statistics - recycling of batteries and accumulators. Recycling efficiency for lead-acid batteries. eurostat. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_recycling_of_batteries_and_accumulators#Recycling_efficiency_for_lead-acid_batteries, updated on 6/16/2021, checked on 6/16/2021.

Ferg, E. E.; Schuldt, F.; Schmidt, J. (2019): The challenges of a Li-ion starter lighting and ignition battery: A review from cradle to grave. In *Journal of Power Sources* 423, pp. 380–403. DOI: 10.1016/j.jpowsour.2019.03.063.

Gensch et al. (2016): 8th Adaptation to scientific and technical progress of exemptions 2(c), 3 and 5 of Annex II to Directive 2000/53/EC (ELV). Final Report for the European Commission DG Environment under Framework Contract No ENV.C.2/FRA/2011/0020. ELV III.5. With assistance of Carl-Otto Gensch, Yifaat Baron, Katja Moch, Oeko-Institut. Available online at https://elv.exemptions.oeko.info/fileadmin/user_upload/Consultation_2014_1/20160216_ELV_Final_Gen_Ex_2c__Ex_3_Ex_5.pdf.

Green Car Congress (2012): A123 Systems introduces new Nanophosphate EXT Li-ion battery technology with optimized performance in extreme temperatures; OEM micro-hybrid program due next year. Available online at https://www.greencarcongress.com/2012/06/ext-20120612.html, updated on 6/15/2021, checked on 6/15/2021.

Green Car Reports (2021): All 2020 Hyundai hybrids have a clever 12-volt lithium-ion accessory battery. Available online at https://www.greencarreports.com/news/1127972_all-2020-hyundai-hybrids-have-a-clever-12-volt-lithium-ion-accessory-battery, updated on 5/17/2021, checked on 5/17/2021.

Halleux (2021): New EU regulatory framework for batteries. Setting sustainability requirements. Briefing: EU Legislation in Progress. With assistance of Vivienne Halleux. European Parliament. Available online at https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf, checked on 9/6/2021.

IHS Markit (2020): 2019 Recycling flow study. With assistance of Martin Seban, Oliver Nowak. IHS Markit, checked on 9/6/2021.

Kane, Mark (2021): Elon Musk: Refreshed Tesla Model S/X Will Have Li-Ion 12V Battery. In *InsideEVs*, 2/3/2021. Available online at https://insideevs.com/news/485543/refreshed-tesla-model-sx-liion-12v-battery/, checked on 5/17/2021.

Kim, Tae-Hoon; Jeong, Jin-Beom; Song, Hyun-Sik; Shin, Seung-Min; Shin, Dong-Hyun; Lee, Byoung Kuk (2019): Study on Performance of Vehicle with Different Types of 12 V Starter Batteries Using HILS. In *J. Electr. Eng. Technol.* 14 (5), pp. 1973–1982. DOI: 10.1007/s42835-019-00210-0.

Mazda (2019): Mazda CX-30_DM_2019_GER. Mazda. Available online at https://at.cdn.mazda.media/c7e5e5a068f44d66ab844296ab77d1a7/116dc1374bef48c294cfd2651584ad5e.pdf?rnd=49c171, checked on 6/17/2021.

Mercedes-Benz (2021): Rettungskarte PKW, Version 04/2021, CL Typ 216 Coupé, 2006-2014. Available online at https://rk.mb-qr.com/de/216/, updated on 6/7/2021, checked on 6/7/2021.

Moseley, P. T.; Rand, D.A.J.; Garche, J. (2017): Lead–acid batteries for future automobiles. In Jürgen Garche, Eckhard Karden, Patrick T. Moseley, D. A. J. Rand (Eds.): Lead-acid batteries for future automobiles. Amsterdam: Elsevier, pp. 601–618, checked on 5/18/2021.

Oeko-Institut e.V. (2016): The Deadly Business - Lead Recycling in Africa. Oeko-Institut e.V. Available online at https://www.oeko.de/oekodoc/2549/2016-076-de.pdf, checked on 3/6/2021.

Olife (2021): Response to Questionnaire 2 Exemption 5 of ELV Annex II, checked on 6/16/2021.

Porsche (11/23/2009): World Debut: Starter Battery in Lithium-Ion Technology. New Lightweight Battery Option for the Porsche 911 GT3, 911 GT3 RS, and Boxster Spyder. Available online at https://www.porsche.com/usa/aboutporsche/pressreleases/pag/?pool=international-de&id=2009-11-23-02, checked on 5/7/2021.

Ricardo (2020): Lead Battery Automotive Technology Trends Review - Final Report. With assistance of Charlie Allen, Carl Telford, Phil Barker, Gael Chouchelamane. Ricardo Strategic Consulting. Available on request from the European Commission, checked on 3/22/2021.

Saldaña, Gaizka; San Martín, José Ignacio; Zamora, Inmaculada; Asensio, Francisco Javier; Oñederra, Oier (2019): Analysis of the Current Electric Battery Models for Electric Vehicle Simulation. In *Energies* 12 (14), p. 2750. DOI: 10.3390/en12142750.

Sphera (2020): Comparative LCA of Lead and LFP Batteries for Automotive Applications. On behalf of ACEA, JAMA, KAMA, EUROBAT and ILA, checked on 9/6/2021.

Tarascon, J. M.; Armand, M. (2001): Issues and challenges facing rechargeable lithium batteries. In *Nature* 414 (6861), pp. 359–367. DOI: 10.1038/35104644.

Tesla (2021): MODEL S Owner's Manual. Software version: 2021.12.4.2 North America. Tesla. Available online at https://www.tesla.com/sites/default/files/model_s_owners_manual_north_america_en_us.pdf, checked on 6/14/2021.

Varta (2019): How do I change an EFB or AGM battery? Available online at https://batteryworld.varta-automotive.com/en-gb/how-do-i-change-an-efb-or-agm-battery, updated on 6/16/2021, checked on 6/16/2021.

Ventura, Lucas (2014): Developing controls for a 12V lithium-ion starter battery. Report Submitted to Federal University of Santa Catarina, as requirement to approval in subject: DAS 5511: End of Course Project. End of course project. Universidade Federal de Santa Catarina, Brazil. Available online at https://repositorio.ufsc.br/xmlui/bitstream/handle/123456789/170512/PFC-20141-LucasVentura.pdf?sequence=1&isAllowed=y, checked on 5/4/2021.

Vergossen, David (2018): Entwicklung, Aufbau, Charakterisierung und Validierung einer 12 Volt Lithium-Ionen Starterbatterie. RWTH Aachen. Available online at http://publications.rwth-aachen.de/record/729983/files/729983.pdf, checked on 12/6/2021.

Volkswagen (n.d.): The Touareg Electrical System. Design and Function. Self-Study Programme 298. Volkswagen, checked on 6/16/2021.

Wang, Qingsong; Liu, Wei; Yuan, Xueliang; Tang, Hongrui; Tang, Yuzhou; Wang, Mansen et al. (2018): Environmental impact analysis and process optimization of batteries based on life cycle assessment. In *Journal of Cleaner Production* 174, pp. 1262–1273. DOI: 10.1016/j.jclepro.2017.11.059.