Technical Report

Development of a European Utility Factor Curve for OVC-HEVs for WLTP

A. Eder[1], N. Schütze[2], A. Rijnders[3], I. Riemersma[4], H. Steven[5]

November 2014

1. Introduction

In contrast to vehicles with combustion engines or NOVC-HEVs (not off vehicle chargeable hybrid electric vehicles), an OVC-HEV **(**off vehicle chargeable hybrid electric vehicle**)** can be operated in two distinct driving modes:

1.) Charge Depleting mode (electric energy is dissipated from the storage)**;** and

2.) Charge Sustaining mode (electric storage is on a minimum level and only able to support the driving with regenerated energy; the energy for driving is provided by the combustion engine, see Figure 1)

The extent to which a vehicle will be driven in either of these modes depends on a combination of the following factors:

- The capacity of the electric energy storage system;
- The electric energy consumption of the vehicle while driving in charge depleting mode;
- The distance that the vehicle is able to drive in charge depleting mode (resulting from the first two factors);
- The length and frequency distribution of trips made with the vehicle; and
- The (off-vehicle) charging frequency for the electrical energy storage system.

The share between driving in 'charge depleting' and 'charge sustaining' mode can be calculated from these factors, and is expressed as the 'Utility Factor' (UF). The UF is defined as the ratio between the distance driven in 'charge depleting' mode divided by the total driven distance, and can therefore range from 0 (e.g. *for a conventional vehicle or for an HEV*) to 1 (for a pure electric vehicle or OVC-HEV that is driven in charge depleting mode only). Since the fuel and energy consumption, as well as the emissions, are very different between the two driving modes, Utility Factors are needed in order to calculate weighted emissions, electric energy consumption, fuel consumption and CO_2 values. UFs are based on driving statistics and the ranges driven in 'charge-depleting' and 'charge-sustaining' mode for OVC-HEVs in practical use. From these data, a Utility Factor (UF) curve can be generated which facilitates a weighting between the measured (emission/electric consumption/CO_2/fuel consumption) values in the two driving modes ('charge-depleting' and 'charge-sustaining') in dependence of the measured range that was driven in charge depleting test on the WLTC.

[1] Dr. Andreas Eder, BMW Group, Germany, Email: andreas.ea.eder@bmw.de
[2] Nico Schütze, BMW Group, Email: nico.schuetze@bmw.de
[3] Andre Rijnders, RDW, Netherlands, Email: ARijnders@rdw.nl
[4] Iddo Riemersma, Sidekick Projects, Netherlands, Email: iddo@sidekickprojects.nl
[5] Heinz Steven, Data Analysis and Consultancy, Germany, Heinz.Steven@t-online.de

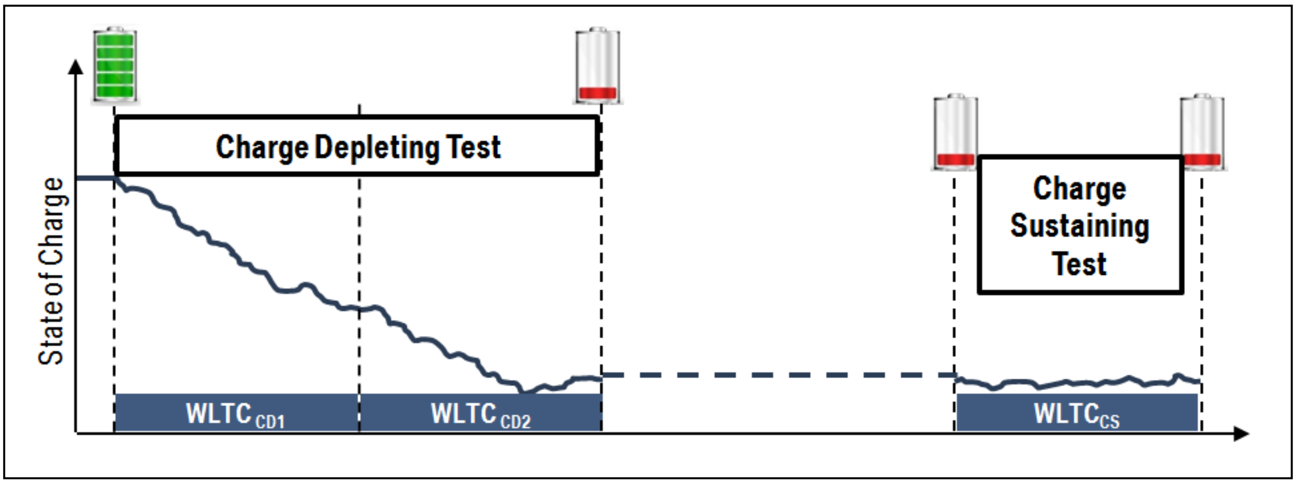

Figure 1: Procedure with charge depleting and sustaining test

The current version of the WLTP Global Technical Regulation (GTR) does not contain a uniform UF curve; each contracting party may develop its own UF curve based on the regional driving statistics. For the purpose of further harmonization between regions, a methodology for the UF calculation and how to analyse available driving data needs to be defined, which should then be used for the determination of the regional Utility Factor. This Technical Report describes the methodology that was applied to determine the UF curve for the European Union, and is intended to also provide a template for UF determination in other regions.

2. Methodology for UF determination

In order to develop a methodology for the UF in such a way that the test result will be as representative as possible for real-life driving situations of an average OVC-HEV fleet, it is in general important to follow the procedure as described as follows (Riemersma [9]):

1. Search for all available databases with vehicle trips that can be used as input;
2. Exclude the data that is erroneous or outside the scope (in this case, that might include taking out data from vehicles that have an extreme high or low daily average distance);
3. Verify the balance in UF relevant characteristics, such as road types (city, rural, highway), vehicle types, share between EU member states, etc.;
4. Where necessary and appropriate, apply weighting to correct any imbalance in these characteristics;
5. Develop a UF curve for the individual (weighted) databases, and explain differences through analysis; and
6. Based on the analysis, decide which weight should be applied to each database in order to reach the most representative UF curve.

In SAE J2841 [1] several methodologies for UF determination are described, which are defined for different purposes. Two of them in principal are suitable for the above described purpose using travel survey data:

- Fleet UF (FUF) – Parameters for the UF curve are determined at fleet level, assuming the distribution within the database is representative for the target fleet (in this case: EU region); and
- Individual UF (IUF) – Parameters for the UF curve are first determined at individual vehicle level, and are weighted to reflect the distribution within the target fleet.

The Fleet UF is only an adequate method for the calculation of UF if a representative database of OVC-HEVs is available. For the FUF, the ratio of the total electric ranges and the total daily kilometres travelled for <u>all</u> vehicles in the database are taken into consideration.

This therefore leads to vehicles with high daily travelled distances receiving a higher weight in the UF calculation than those with lower daily travelled distances. As a result this method is liable to produce inaccurate results if the database is not a valid statistical sample, for example if it contains an unrepresentative share of vehicles travelling longer or shorter distances than that travelled by average OVC-HEV drivers.

In order to avoid this effect, SAE J2841 provides the method for calculating an Individual UF. For this method, a distance weighted individual UF for each vehicle is determined. The IUF is calculated by the arithmetic average over all the vehicles in the database and therefore, each vehicle's (individual) UF has the same weight. In Figure 2, a comparison of both methods is shown.

vehicle	daily miles traveled [km]	vehicles total mileage [km]	total mileage fleet [km]	daily electric range [km]	vehicles total electric range [km]	total electric range [km]	daily cs range [km]	vehicles total cs range [km]	total cs range [km]	vehicles Individual UF	Individual UF	Fleet UF
1	50	175	545	40	145	305	10	30	240	83%	63%	56%
	30			30			0					
	60			40			20					
	35			35			0					
2	80	370		40	160		40	210		43%		
	90			40			50					
	80			40			40					
	120			40			80					

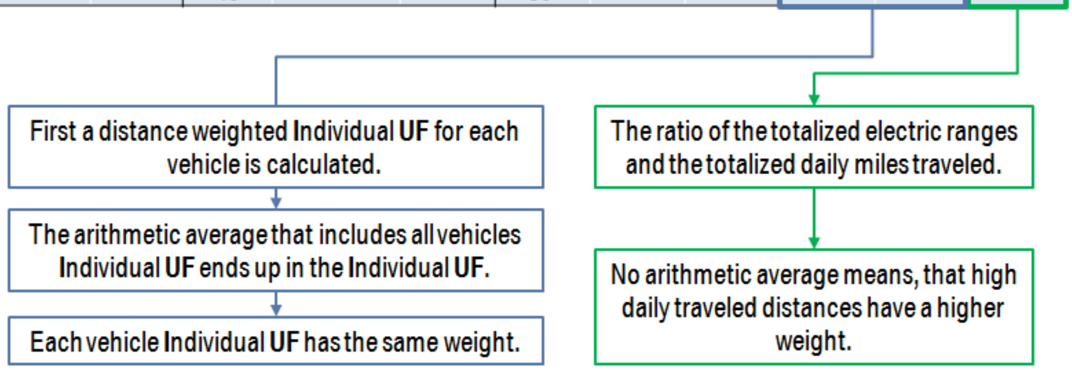

Figure 2: Comparison of Individual UF (IUF) and Fleet UF (FUF) calculation methods (cs range = driven distance in charge sustaining mode). In this example, the assumed max. electric range of a vehicle is 40 km.

The databases available today contain a very high share of conventional vehicles (see Sect. 3). As a result the individual UF method has been used for the current evaluation of the European UF, whereas for a recommended re-evaluation of the UF curve with a pure OVC-HEV database, the fleet UF is regarded as the more accurate calculation method. However some preparatory work would be required in order to have a representative data set available for such a re-evaluation (see Sect. 5).

Another assumption necessary for the determination of UF is the charging frequency of the OVC-HEV performed by the customers. As it is currently not possible to evaluate the future OVC-HEV customer charging behaviour, the assumption of one charging event per day (overnight charge), according to SAE J2841, is used for the further analysis. In the future this charging frequency might be modified if more accurate data is available.

3. Database for the calculation of European Utility Factor

The main influence on the UF curve by using the methodology from SAE J2841 is the quality and resolution of input data. In order to get the most representative IUF, regional differences such as in customer behaviour (e.g. utilization, daily driven distance, shares of different vehicle classes) or infrastructure conditions (e.g. density and practicality of opportunities to charge the vehicle) cause the need to focus on a special weighting of the input data to correct imbalances within a data base.

Since OVC-HEVs are fairly new vehicle types on the European market, there is currently no representative statistical data available in Europe about their practical use. Therefore it was decided to use statistics about the use of conventional vehicles instead. Two comprehensive databases are currently available. One is the European WLTP database [2] that had already been used for the development of the WLTC speed profile. The second one is a database that was provided by FIAT [3]. After the exclusion of erroneous data (e.g. implausible start or end dates of recorded trips that leads to unrealistic trip durations), the databases combined contain in total about 1,400 conventional vehicles within the European Union.

A comparison of both databases is shown in Figure 3. The EU WLTP database shows a very wide distribution of driving data and consists of a high share of diesel vehicles. Some of the vehicles have travelled very long daily distances on average (> 100 km/day) which is – at least from today's perspective - considered to be not representative for an OVC-HEV use in the near future, as these long-distance driving customers would have significantly lower total cost of ownership with a conventional diesel vehicle compared to an OVC-HEV. As the absolute number of vehicles, especially in some segments, is relatively low, the distribution of average daily travelled kilometres is very heterogeneous, but on the other hand, all relevant vehicle segments for Europe are represented at least once in the database.

In contrast, the FIAT database consists of a four times higher total fleet mileage and a high share of petrol vehicles, but covers only the mid-to-small vehicle segments. Due to the high number of vehicles in this database and the limited available vehicle segments, the distribution of the daily travelled kilometres is very homogeneous.

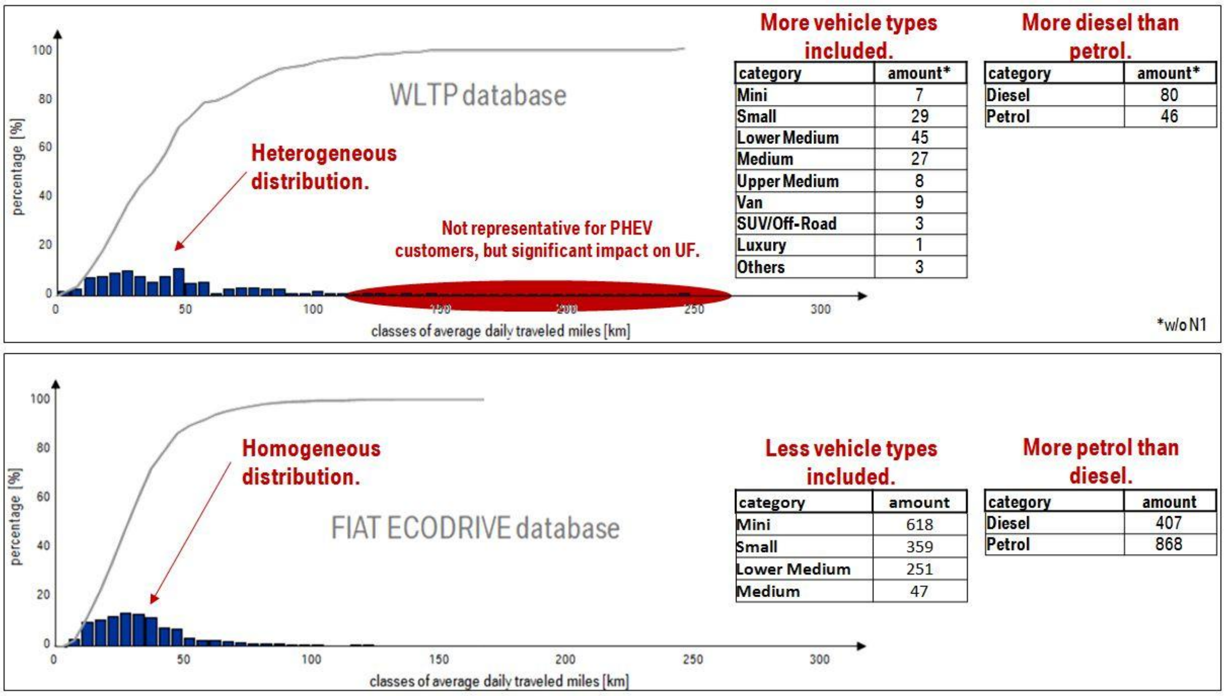

Figure 3: Percentage composition of average daily travelled kilometres and vehicle types of WLTP and FIAT database

Neither database reflects the situation in Europe to the full extent with respect to vehicle segments and mileage distributions. Therefore both databases were consolidated for further evaluation, with the following steps being taken to improve the representativeness of the combined database. In a first step, the N1 vehicles were excluded from the EU WLTP database, as OVC-HEVs as replacements for conventional N1 vehicles are not currently in wide use. In a second step different weighting procedures based on mileage and statistics about new registrations were applied. This weighting makes sure that the distribution of different categories, e.g. vehicle types and/or engine types, can be corrected to be representative of the vehicles on the European market (see Sect. 4).

The UF curves developed on the basis of the databases are shown in Figure 4.
The red dashed curve is based on a simple merge of both databases, however in this curve the Fiat data is dominating due to the significantly higher total fleet mileage in the Fiat database compared to the EU WLTP database.

In order to compensate for this effect, a 50 % / 50 % weighting approach was applied. For each electric range the respective UF was calculated for both databases and weighted by 50 % for the calculation of the total UF (dashed purple line).

For comparison, the UF curve from the NEDC regulation UN/ECE R101 [4] is also shown in this graph (black solid line – "NEDC corrected to WLTP"). This curve was adjusted to the reduced electric range in WLTP (due to the higher energy demand of the WLTP) in order to ensure the comparability of all curves depicted against the electric range of a vehicle driving the WLTP driving cycle. The corrected NEDC–UF curve that is shown in Figure 4 was developed using the assumption that the electric range of a vehicle in NEDC is reduced by about 25% due to driving the WLTC, similar to the reductions found from simulations of electrified vehicles. Hence, the NEDC-UF is plotted to the WLTP electric range, which leads to a compression in the electric range (e.g. the UF of 0.5 in NEDC @ 25 km electric range moves back to 18.75 km electric range in WLTP).

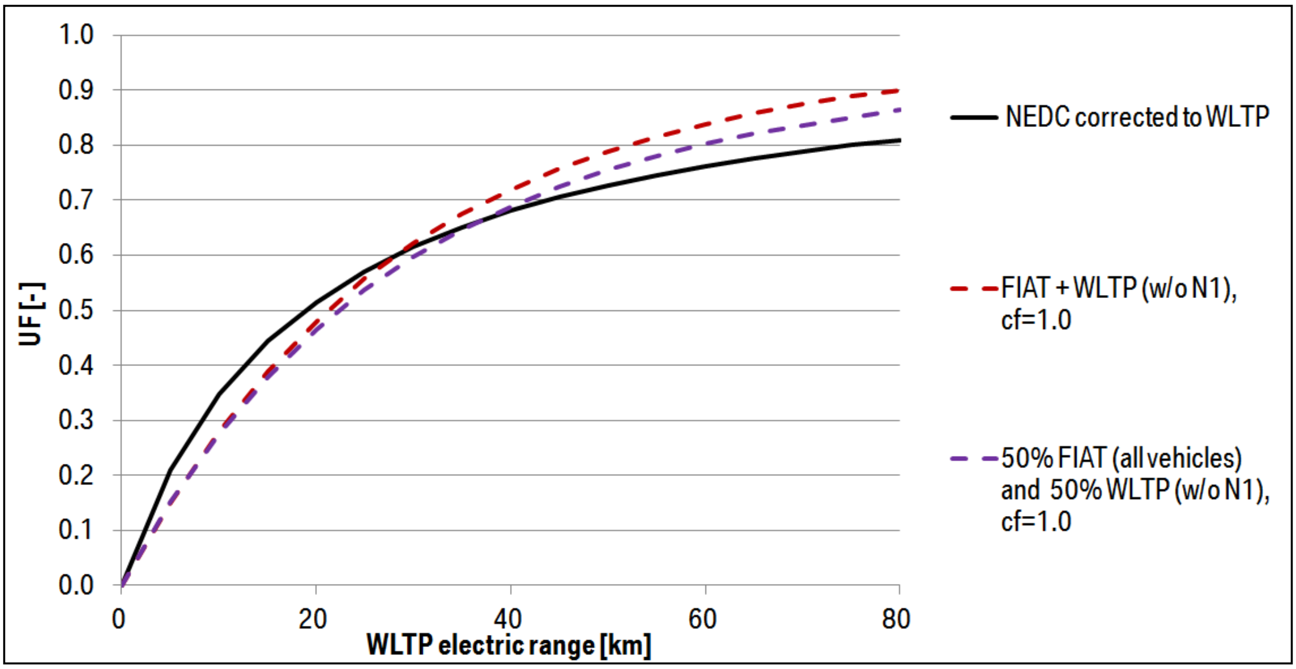

Figure 4: Comparison of NEDC UF and WLTP UF scenarios based on different weightings; cf=1.0 means charging frequency of one (full) overnight charge per day (see Sect. 2).

4. Scientific Analysis of European UF Curves

As mentioned above, the analysis of the composition of the databases shows that both databases neet to be further complemented in relation to the following aspects:

- The number of vehicles from each country in the database, compared to the number of new registrations in the EU,
- The average annual vehicle mileage driven within each country,
- The percentage split of the different vehicle classes within the EU (mini, subcompact, compact, middle, luxury …),
- The percentage of conventional vehicles with diesel- and petrol combustion engine within each country,

. In order to achieve this, statistics from the European Environment Agency, as well as data from representative institutes, were applied European Environment Agency [5], ICCT [6], and Transport & Mobility Leuven [7]. As an example, Figure 5 illustrates the differences between the amounts of new passenger car registrations for each country compared to the amount of vehicles from each country within the data base.

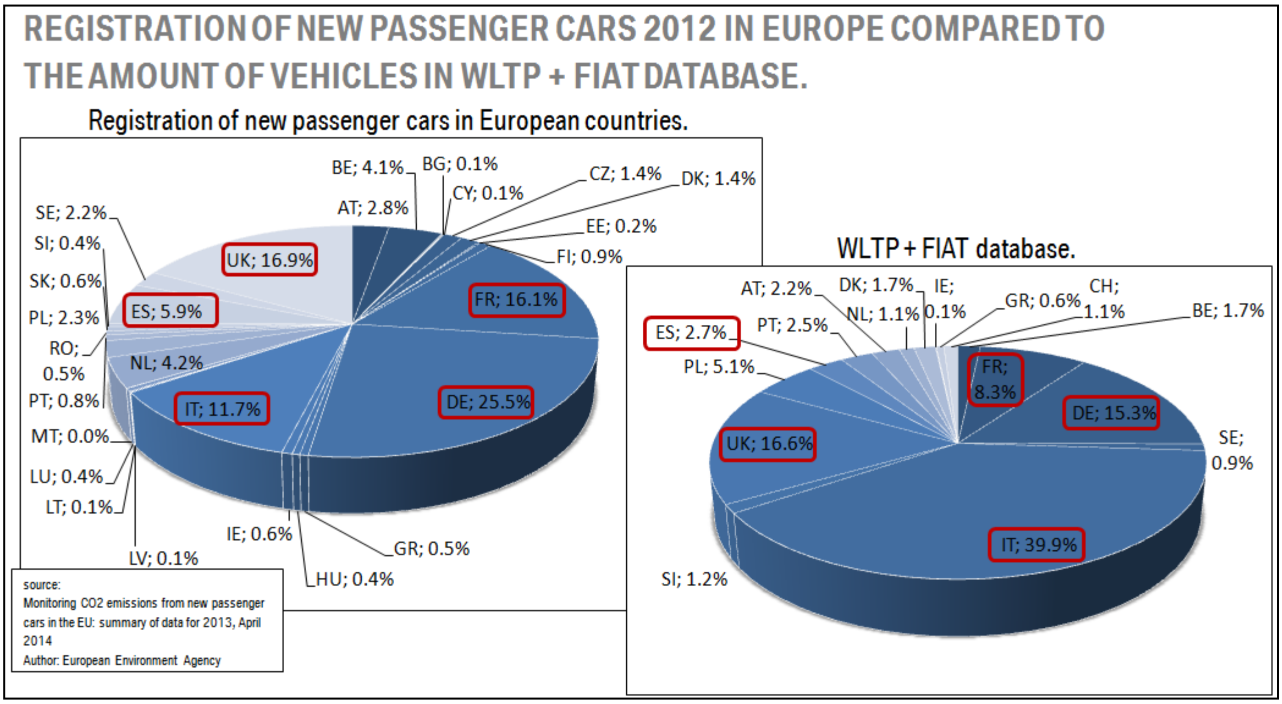

Figure 5: Comparison of registrations of new passenger cars and amount of vehicles in each country within WLTP and FIAT database

Three different approaches were applied to determine the consolidated European UF curve:

a) New vehicle registration numbers

The first step of the process was to identify the intersection of countries in the database and in the European Union. If there is only data available for a number of the countries, the percentage shares for country specific data should be normalized to receive a total of 100%. Afterwards each vehicle belongs to a country specific sub-database.

The second step is to divide the vehicles of each sub-database into categories of engine types (e.g. diesel, petrol, etc.). Accordingly country and engine type specific UF curves can be determined in the third step.

The last two calculations of the balancing process are to consolidate the number of UF curves to a corrected European UF curve. Therefore the engine type specific UF curves of each country are weighted according to the country specific engine type percentages. Finally the engine type balanced, but country specific, UF curves are consolidated by applying the country specific percentages of new vehicle registrations.

b) Sum of annual vehicle mileage

Consolidation of the country-specific curves is done according to the sum of annual vehicle mileage instead of new vehicle registrations.

c) Vehicle segments

Before consolidation of the UF, the database was separated into different vehicle segments and then weighted according to the distribution of vehicle types in the European Union.

The different weightings described above result in three UF curves that are shown in Figure 6.

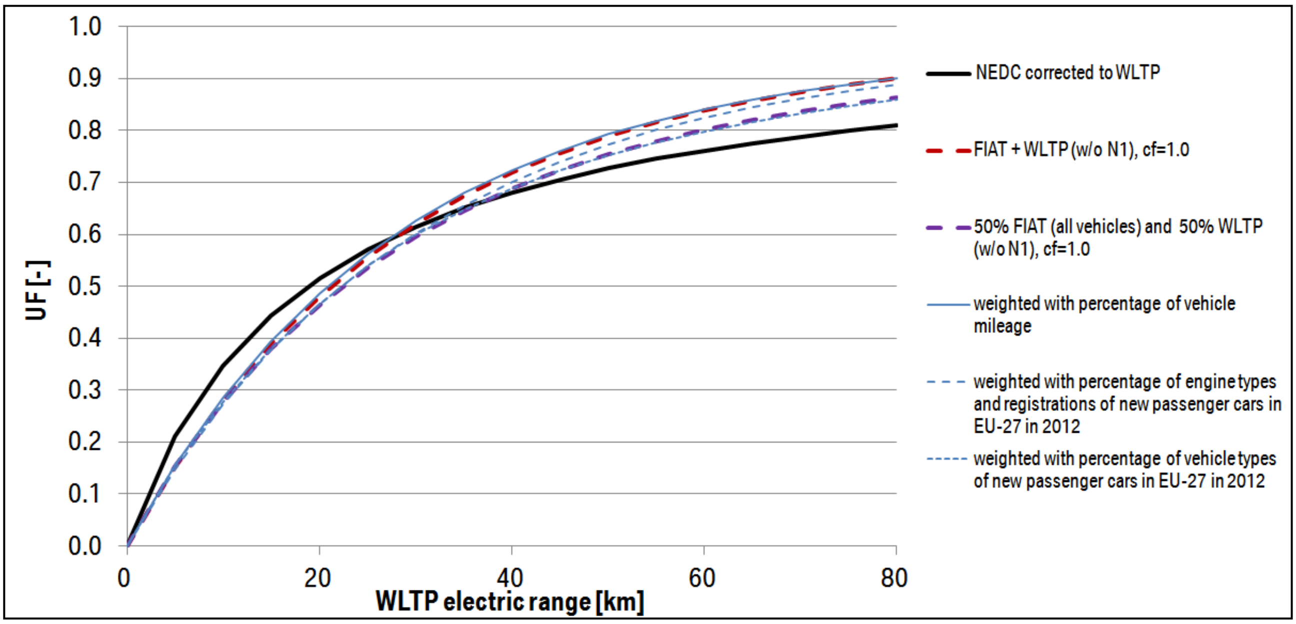

Figure 6: Comparison of different UF balancing approaches

All three curves are located between the uncorrected UF that is represented by the dashed red line (approach that consolidates both data bases without any weighting) and the 50/50 approach represented by the dashed purple line (approach that weights the WLTP UF curve and the FIAT UF curve each with 50 %).

A further option would have been to apply a combined weighting for each of the above mentioned criteria. However, there is not enough statistical data available to cover all vehicle segments and therefore this option was not further evaluated.

From Figure 6 it can be seen that the 50/50 UF curve is a good fit for the trend line which was weighted to the vehicle type percentages. Based on this analysis, it was decided and agreed in EU WLTP Meeting in June 2014 that the 50/50 UF curve should be used in Europe until more representative data are available (see Sect. 5).

The SAE J2841 also provides a method for how to describe the curve in a mathematical way. Therefore the following exponential approach can be used. A number of coefficients are provided to fit the curve towards an acceptable accuracy.

The described process to determine the coefficients ensures that several mathematical requirements and characteristics are fulfilled.

For the calculation of a specific UF for each of the 4 cycle phases in the WLTC, the following equation is applied:

$$UF_i(d_i) = 1 - \exp\left(-\left(\sum_{j=1}^{k} C_j * \left(\frac{d_i}{d_n}\right)^j\right)\right) - \sum_{l=1}^{i-1} UF_l$$

Where:

UF_i	- Utility factor for phase i.
d_i	- Distance driven from the beginning of the charge depleting test up to the end of phase i (phase i is the phase for which the delta UF is calculated) in km.
C_j	- j^{th} coefficient (see Table 1)
d_n	- Normalized distance (see Table 1).
k	- Amount of terms and coefficients in the exponent (see Table 1).
i	- Number of considered phase.
j	- Number of considered term/coefficient.
$\sum_{l=1}^{i-1} UF_l$	- Sum of calculated utility factors up to phase (i-1).

For the approximated curve, terms and coefficients in the exponent are applied up to the tenth order. The coefficient values shown in Table 1 are determined according to the process described in SAE J2841 and fit the 50/50 curve with a maximum error of 0.001 (ΔUF_{max} = 0.1 %).

C_1	26.25
C_2	-38.94
C_3	-631.05
C_4	5964.83
C_5	-25094.60
C_6	60380.21
C_7	-87517.16
C_8	75513.77
C_9	-35748.77
C_{10}	7154.94
d_n[km]	800
k	10

Table 1: Coefficients for the UF calculation equation

5. Review and recommended application of the European Utility Factor

As this UF was derived from data based on conventional vehicles it is planned to re-evaluate UF and charging frequencies by a customer study once a significant number of OVC-HEV has been placed in the European market, see Figure 7.

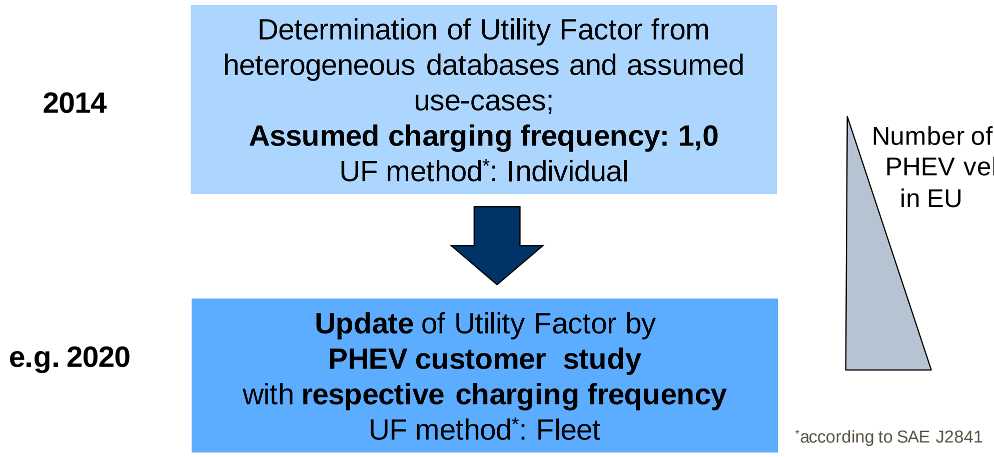

Figure 7: Schematic representation of re-evaluation

It is recommended that UFs are continuously checked for their robustness concerning the application of future OVC-HEVs. In order to have a representative UF-study, it is recommended to use a fundamental robust and scientific approach as described in Sampath [8]. An established method that could be used is the stratified sampling. This methodology can be applied if it is necessary to divide a population into sub-populations.

Generally there are two main tasks: The first one is the sampling of vehicle data itself and the second one the determination of weightings of sub-populations according to important criteria concerning the evaluation of the UF-curve. The choice of customers that are considered to represent a sub-population shall fulfil special criteria like a minimum annual mileage and should be measured continuously during a minimum duration. It is recommended to use a survey as outlined in Reiser [10] in order to select appropriate customers for the re-evaluation of real-life UFs.

In addition to each specific OVC-HEV having to be analysed in each specific market (including the separation of manufacturers, diesel- or petrol-OVC-HEV, different electric ranges, vehicle-type (from mini to luxury), etc.), the following criteria could also be indicators for different sub-populations of customers:

- Road category mainly used (highway, A-road, B-road) and home environment (urban, suburban, rural);
- Driving style (more economic or more sporty); and
- Daily access to public and non-public charging infrastructure.

In order to get representative sub-populations, it is recommended that at least 20 vehicles are available per survey for the re-evaluation described above. It is also important, that the driving behaviour is recorded comprehensively for each driving mode (charge depleting and charge sustaining) for at least 5,000 km per vehicle, in order to ensure that the whole variety of driving states has been captured (see Reiser [10]).

The main focus of the Utility Factor approach described above is to calculate average values which are mainly used for fleet monitoring. In contrast to conventional vehicles, the OVC-HEV customers' fuel consumption depends not only on driving behaviour and ambient conditions, but also on driven range and charging frequency.

It is therefore recommended for customer information to provide not just a single fuel consumption value, but instead to provide, for example, information on consumption depending on the driven distances.

6. References

[1] SAE International J2841 "Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data", Revision from 2010/09, Issued 2009/03

[2] For access to database, please contact Heinz Steven, heinz.steven@t-online.de

[3] For access to database, please contact Luigi Orofino, Luigi.orofino@fiat.com.

[4] ECE/TRANS/WP.29/343 "Uniform provisions concerning the approval of passenger cars powered by an internal combustion engine only, or powered by a hybrid electric power train with regard to the measurement of the emission of carbon dioxide and fuel consumption and/or the measurement of electric energy consumption and electric range, and of categories M1 and N1 vehicles powered by an electric power train only with regard to the measurement of electric energy consumption and electric range",
http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29fdocstts.html (2014/07/21)

[5] European Environment Agency "Monitoring CO_2 emissions from new passenger cars in the EU: summary of data for 2013", 2014/04

[6] ICCT "European vehicle market statistics 2013", 2013

[7] Transport & Mobility Leuven, "TREMOVE - economic transport and emissions model", http://www.tmleuven.be/methode/tremove/home.htm (2014/07/21)

[8] S. Sampath "Sampling theory and methods", 2001, Narosa Publishing House

[9] Riemersma I., "Review of Utility Factor development", Library of WLTP on CIRCABC - https://circabc.europa.eu (2014-04-17)

[10] Reiser C.: Kundenverhalten im Fokus der Fahrzeugentwicklung ("Customer behaviour in the context of vehicle development"), Technical University Dresden, Germany, PhD Thesis, 2010