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INCREASING REDUCTION OF CO_2 EMISSION IN HYBRID VEHICLES

Summary. This article concerns the issue of reduction of CO_2 emission in hybrid vehicles. External lighting through LED technology was applied to show additional CO_2 savings in these vehicles. The authors propose for hybrid vehicles of M_1 category: conditions of testing external lights, research equipment with measuring system and measuring method in order to determine energy savings obtained by application of external LED light. It enables to calculate saving of CO_2 emission and estimate potential energy and ecological benefits. Computational formulas of CO_2 emission savings and calculated fuel consumption and percentage reduction of CO_2 proposed by the authors were used as a confirmation. Average worktime of lighting and three configurations of sources of lighting of hybrid vehicles were used in the analysis: halogen bulb/bulb, xenon/LED lamp and full electroluminescent external lighting.

1. INTRODUCTION

Based on the directives of European Parliament and Council (WE) no. 443/2009 of April 23, 2009, defining norms of emission for new passenger cars within integrated approach of European community towards reduction of CO_2 emission from light delivery vehicles, European Commission approved the innovative technology of using energy-efficient LED lamps in electrified hybrid vehicles without external charge. An analysis of the impact of new technology of exterior energy-efficient LED lighting confirms that eligibility criteria referred to in art. 12 of directive of EC no. 443/2009 and executive directive of EU no. 725/2011 were met [1-2]. It was also confirmed that it contributes to reduction of CO_2 emission by at least 1g CO_2/km in comparison with reference system of exterior lighting containing identical set of lights in a vehicle. An external source of LED light in vehicles is the following: dipped light, road light, front position light, rear and front fog lights, rear and front indicator, reversing light and number plate. The reduction of CO_2 emission as a result of application of electroluminescent diodes in electrified hybrid vehicles without external charge in all lighting functions or in their appropriate combinations can be determined using a calculation method. The calculation method confirms CO_2 savings owing to exterior energy-efficient LED lighting and verifies conformity in order to obtain certification of approval for energy-efficient products of exterior lighting of vehicles [3-4]**.** Moreover, it would be possible to get repeatable and comparable research results and to indicate credible benefits, in statistical terms, in the form of reduction of CO_2 emission resulting from innovative technology in accordance with art. 6 of executive directive (EU) no. 725/2011. Individual code of eco-innovation that needs to be used with reference to innovative technology in a documentation of type approval is “20”.

2. METHODOLOGY TO DETERMINE THE CO_2 SAVING OF EXTERIOR VEHICLE LIGHTING USING LIGHT EMITTING DIODES (LEDs) FOR THE USE IN M_1 NON – EXTERNALLY CHARGEABLE HIBRID ELECTRIFIED VEHICLES (NOVC-HEV)

In order to determine the CO_2 emission reductions that can be attributed to a package of efficient exterior LED lights consisting of an appropriate combination of vehicle lights for the use in M_1 non-externally chargeable hybrid electrified vehicles, it is necessary to establish the following:

- Testing conditions;
- Test equipment;
- Determination of the power savings;
- Calculation of the CO_2 savings;
- Calculation of the statistical error.

The testing conditions shall fulfil the requirements of Regulation UN/ECE 112 on Uniform provisions concerning the approval of motor vehicle headlamps emitting an asymmetrical passing beam or a driving beam or both and equipped with filament lamps and/or light-emitting diode (LED) modules. The power consumption shall be determined in accordance with point 6.1.4 of Regulation UN/ECE No 112 and points 3.2.1 and 3.2.2 of Annex 10 to that Regulation [15].

Research equipment for certification of approval and calculation of CO_2 savings should include a set of devices:

- Power supply of voltage source that powers measuring system integrated with direct current gauge.
- Two digital multi-meters, one for measuring the DC-current, and the other for measuring the DC-voltage.

Outline and interconnections of equipment are presented in Fig. 1.

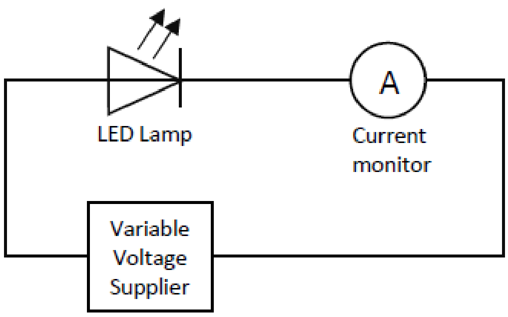

Fig. 1. Test setup for testing (energy-efficient lighting) LED lamps

2.1. Measurements and determination of the power savings

For each efficient exterior LED light included in the package, the measurement of the current shall be performed as shown in the figure at a voltage of 13.2 V. LED module(s) operated by an electronic light source control gear shall be measured as specified by the applicant. The manufacturer may request that other measurements of the current shall be done at other additional voltages. In that case, the manufacturer must hand over verified documentation on the necessity to perform these other measurements to the type-approval authority [16-17]. The measurements of the currents at each of those additional voltages are to be performed consecutively at least five times. The exact installed voltages and the measured current is to be recorded in four decimals. The power consumption has to be determined by multiplying the installed voltage with the measured current. The average of the power consumption for each efficient exterior LED light ($\overline{P_{EI_i}}$) has to be calculated. Each value must be expressed in 4 decimals. When a stepper motor or electronic controller is used for the supply of the electricity to the LED lamps, then the electric load of this component part is to be excluded from the measurement. The resulting power savings of each efficient exterior LED light (ΔP_i) are to be calculated with the following formula (1):

$$\Delta P_i = \Delta P_{B_i} - \overline{P_{EI_i}} \tag{1}$$

where ΔP_{B_i} - Total electric energy taken by the source of light of a reference vehicle [W].

Power consumption of the corresponding baseline vehicle light is defined by Table 1.

Table 1

Power requirements for different baseline vehicle lights

Vehicle light	Total electric power (P_B) [W]
Low-beam headlamp	137
High-beam headlamp	150
Front position	12
Licence plate	12
Front fog lamp	124
Rear fog lamp	26
Front turn signal lamp	13
Rear turn signal lamp	13
Reversing lamp	52

2.2. Calculation of the CO_2 savings

The total CO_2 savings of the lighting package can be calculated by the formula (2):

$$C_{CO_2} = \left(\sum_{i=1}^{m} \Delta P_i \cdot UF_i \right) q_p \cdot \frac{t \cdot k_{CO_2}}{V_{HV_{op}} \cdot \eta_{DCDC}} \tag{2}$$

where *UF* - Usage factor of the vehicle light [–] as defined in Table 2, *t* - Driving duration of the NEDC (New European Driving Cycle) [s], which is 1 180 s, η_{DCDC} - Efficiency of the DC-DC converter [–], k_{CO_2} - CO_2 correction factor [gCO_2/km · Ah], as defined in Regulation UN/ECE No 101, Annex 8, $V_{HV_{op}}$ - Operative voltage of the High Voltage battery (traction battery) [V], defined by the formula (3)

$$V_{HV_{op}} = \frac{V_{HV_{nom}}}{c} \tag{3}$$

where $V_{HV_{nom}}$ - Nominal voltage of the High Voltage battery (traction battery) [V], c - Correction factor for the nominal voltage of the High Voltage battery, which is 0,90 for nickel-metal hydride (NiMH) high voltage batteries [–].

The efficiency of the DC-DC converter (η_{DCDC}) shall be the highest value resulting from the efficiency tests performed in the operative electric current range. The measuring interval shall be equal or lower than 10% of the operative electric current range.

Table 2

Usage factor for different vehicle lights

Vehicle light	Usage factor (UF) [-]
Low-beam headlamp	0,33
High-beam headlamp	0,03
Front position	0,36
Licence plate	0,36
Front fog lamp	0,01
Rear fog lamp	0,01
Front turn signal lamp	0,15
Rear turn signal lamp	0,15
Reversing lamp	0,01

2.3. Calculation of the statistical error

The statistical errors in the outcomes of the testing methodology caused by the measurements are to be quantified. For each efficient exterior LED light included in the package, the standard deviation is calculated as defined by the formula (4):

$$S_{\overline{P_{EI_i}}} = \frac{S_{P_{EI_i}}}{\sqrt{n}} = \sqrt{\frac{\sum_{j=1}^{n}\left(P_{EI_{i_j}} - \overline{P_{EI_i}}\right)^2}{n(n-1)}} \tag{4}$$

where: $S_{P_{EI_i}}$ - Standard deviation of the LED light power consumption [W], n - Number of measurements of the sample, which is at least 5, $P_{EI_{i_j}}$ - energy consumption for each exterior energy-efficient lighting, $\overline{P_{EI_i}}$ - average energy consumption for each exterior energy-efficient lighting

The CO_2-emission correction coefficient k_{CO_2} shall be determined from a set of T measurements performed by the manufacturer, as defined in Regulation UN/ECE No 101, Annex 8. For each measurement, the electricity balance during the test and the measured CO_2 emissions shall be recorded. In order to evaluate the statistical error of $k_{CO_{2_t}}$, all T combinations without repetitions of T-1 measurements have to be used to extrapolate T different values of $k_{CO_{2_t}}$ (i.e. $k_{CO_{2_t}}$). The extrapolation shall be performed according to the method defined in Regulation UN/ECE No 101, Annex 8. The standard deviation of $k_{CO_2}\left(S_{\overline{k_{CO_2}}}\right)$ is thus calculated as defined by the formula (5):

$$S_{\overline{k_{CO_2}}} = \frac{S_{k_{CO_2}}}{\sqrt{T}} = \sqrt{\frac{\sum_{t-1}^{T}\left(k_{CO_2} - \overline{k_{CO_2}}\right)^2}{T(T-1)}} \tag{5}$$

where T - Number of measurements performed by the manufacturer for the extrapolation of the k_{CO_2} as defined in Regulation UN/ECE No 101, Annex 8, $\overline{k_{CO_2}}$ - Mean of the T values of $k_{CO_{2_t}}$.

The standard deviation of the power consumption of each efficient exterior LED light ($S_{\overline{P_{EI_i}}}$) and the standard deviation of the $k_{CO_2}\left(S_{\overline{k_{CO_2}}}\right)$ lead to an error in the CO_2 savings ($S_{C_{CO_2}}$). This error is to be calculated by means of the formula (6):

$$S_{C_{CO_2}} = \sqrt{\sum_{i=1}^{m}\left(\frac{\partial C_{CO_2}}{\partial P_{EI_i}} \cdot S_{\overline{P_{EI_i}}}\right)^2 + \left(\frac{\partial C_{CO_2}}{\partial k_{CO_2}} \cdot S_{\overline{k_{CO_2}}}\right)^2} =$$

$$= \sqrt{\left(\frac{t \cdot k_{CO_2}}{V_{HV} \cdot \eta_{DCDC}}\right)^2 \cdot \sum_{i=1}^{m}\left(UF_i \cdot S_{\overline{P_{EI_i}}}\right)^2 + \left(\sum_{i=1}^{m} \Delta P_i \cdot UF_i\right)^2 \cdot \left(\frac{t \cdot S_{\overline{k_{CO_2}}}}{V_{HV_{op}} \cdot \eta_{DCDC}}\right)^2} \tag{6}$$

2.4. Determining the error of CO_2 savings

It has to be demonstrated for each type, variant and version of a vehicle fitted with the package of the efficient exterior LED lights that the error in the CO_2 savings calculated with the formula (6) is not greater than the difference between the total CO_2 savings and the minimum savings threshold specified in Article 9(1) of Implementing Regulation (EU) No. 725/2011, as represented in formula (7).

$$MT \le C_{CO_2} - S_{C_{CO_2}} \tag{7}$$

where *MT*- Minimum threshold [gCO_2/km], which is 1 gCO_2/km

When the total CO_2 emission savings of the package of the efficient exterior LED lights, as a result of the calculation using the formula (2), and the error in the CO_2 savings, calculated with the formula (6), are below the threshold specified in Article 9(1) of Implementing Regulation (EU) No 725/2011, the second subparagraph of Article 11(2) of that Regulation shall apply.

3. ECOLOGICAL AND ENERGY BENEFITS

The problem of energy consumed by signalling lamps had not been too important before it became mandatory to constantly use dipped headlights in any road vehicles (single-track vehicles and cars) in most of the European countries. The time when daytime running lights became mandatory correlated with interest in reducing the energy consumption of lamps. In case of standard halogen bulbs, power consumption (not taking other lamps powered at the same time into consideration) is at least 2 x 45 W. It results in consumption of 1 kilowatt-hour of energy within 11 hours of driving, that is, 909 kilowatt-hours within 10 000 hours, which is the estimated average life-span of cars produced in our times. Energy consumption within 5000 hours will be 454.5 kilowatt-hours [13-14].

Daylights offered by leading automotive companies that have three LED diodes in every lamp with only 5.5 W, therefore, during 11 hours of driving, 1 kWh is consumed within 182 hours of lighting. Energy consumed within 5 000 hours (it may be assumed that daylights are used for the half mileage of a vehicle) will be 27.5 kilowatt-hours [7-8].

Current consumed for daily lighting is generated by an alternator powered by combustion engine of a vehicle. savings of (454.5 – 27.5) 427.0 kilowatt-hours (about 1537 megajoules [MJ]) can obtained, which can be converted to about 35 kilogrammes (44 litres) of petrol or diesel oil of heating value 44 MJ/kg. Energy efficiency of an engine, alternator and its belt drive must be taken into consideration in these calculations, which allows multiplying calculated amount of fuel by 4. The difference of fuel consumption while using diode daylights is 176 litres in comparison with vehicles without such lights.

This saving gives reduction of CO_2 emission proportional to it. However, it does not make our vehicle less visible for other drivers [5-6]. It is easier to notice diffused, but directed forward, diode light during the day from a longer distance than night dipped headlight shining diagonally to the bottom [18]. Fuel economy and reduction of CO_2 emission in connection with various sources of light are presented in table 3.

Table 3

Fuel consumption and CO_2 emission with average time of lighting operation

Vehicle configuration (headlamp/rear lamp)	Fuel consumption [l/km]	CO_2 Emissions [kg/100km]	Reduction
Halogen/Bulb	~ 0,126	~ 0,297	-
Kesenon/LED	~ 0,077	~ 0,182	39%
LED/LED	~ 0,051	~ 0,120	60%

In total estimation of energy and ecological benefits, energy consumed during production of comparable sources of light and the fact that it is largely created as a result of combustion processes must also be taken into consideration. The unit difference of energy consumption may be omitted here. More important is the fact that life-span of diode is estimated at about 100 000 hours of work, that is, pre-installed element is enough for the whole duration of exploitation of a passenger car (500 000 km of mileage with average speed 50 km/h) [9-10], whereas traditional or halogen bulbs must be replaced many times (life-span of standard bulb P21W is about 500 hours).

4. CONCLUSION

Life-span of LED diode is up to 100 000 hours, that is, eleven years of incessant shining. It means that its life-span is enough for the whole duration of exploitation of a vehicle. Therefore, this element does not have to be replaced or maintained, which eliminates the costs related to periodic servicing or repairing a breakdown. Moreover, in case of similar lighting power, LED diodes consume less energy than bulbs. As a result, fuel consumption and exhaust emission are reduced, which being more perceptible in diode structure of other, more energy-consuming lighting devices in vehicles.

Another important aspect in means of transport is to achieve full efficiency of source of light. In order to achieve full light efficiency, a fibre of conventional bulb must be heated up for 200 ms. There is no phase of gradual heating up in LED diodes. It allows warning other drivers behind our vehicle quicker. In case of brake lights, this relatively small, only one-fifth of a second, difference may be a decisive factor in traffic collision, because a car driving at 80 km/h covers a distance of four meters in this time [11-12].

In other car applications, time of reaction of a lamp to switch activity is less important, however, clarity of light signal is always more important. Lack of heating up phase has an impact on diode indicators because it makes particular light impulses more distinctive. Diode side lights, end-outline marker lights and brake lights are more visible after dark and in conditions of reduced air transparency. On the one hand, diodes do not lose their emission capabilities. On the other hand, the non-demountable and hermetic structure of complete diode lamps leads to their optical elements not needing cleaning from dust periodically and electric connections not needing maintenance from protection against corrosion. You state electrical connections do not need to be maintained, but LED systems still have electrical connections with drivers and other electronic circuitry. These lamps are also completely resistant to vibrations and large temperature differences.

Additional advantage is an option of designing car exterior lights based on any number of LED elements – separately or with miniature reflectors, lens or optical fibres. It allows achieving both original decorative effects and solutions improving effectiveness of signalling the presence of a vehicle on the road and manoeuvres performing by a driver [19]. The multibeam LED system is an example of a combination of useful design and LED reflex control system [6]. Multibeam LED allows to cut out the area from a light beam that should not be illuminated, i.e., other road user. It allow for more precise and efficient road illumination. There will be no necessity to switch on all diodes of driving lights, only these modules, which are not necessary will be switched off.

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