A method of calculating CO₂ savings obtained by external lighting of vehicles that use electroluminescent diodes

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Abstract. LED vehicle lighting is developing very fast and it is becoming more and more available. Due to new EU regulations, it is installed in all new cars. They are also selected by the owner of older models of cars. LED revolution has brought not only better visibility, but also allowed to save money and protect environment. In order to support development and quick implementation of new advanced technologies reducing CO₂ emission coming from vehicles, EC directive had to be introduced and it enables producers and suppliers to submit applications for approval of innovative technologies contributing to reduction of CO₂ emission coming from passenger cars. Therefore, it was necessary to explain criteria for determination of which technologies should be qualified as eco-innovations and based on what rules and calculation methods, the level of reduction of CO₂ emission may be determined. Total demand for energy of a vehicle equipped with bulbs (rear lamps) and halogen lamps (headlights) is about 60% of demand for energy for dipped headlights and 14% demand for rear position lights. If we use combination of xenon lamps and LED lamps for configuration of vehicle lighting, demand for energy will be reduced by 39%. If we used only LED lamps, energy consumption would be reduced by 60%.

In this article, the authors presented a method of calculation of CO₂ savings obtained by application of exterior lighting with LED diodes. Moreover, they presented optimization of energy consumption and savings thanks to application of LED technology and percentage reduction of CO₂ emission.

1. Introduction

In the years 2014–2016, European Commission approved three applications concerning new technologies, which largely contributed to improvement of energy efficiency of the systems of external lighting of M1 vehicles. An analysis of the impact of new technology of exterior energy-efficient lighting LED allowed to confirm that eligibility criteria referred to in art. 12 of the directive of EC no. 443/2009 and executive directive of EU no. 725/2011 were met [2,3]. It was also confirmed that it contributes to reduction of CO₂ emission by at least 1g CO₂/km in comparison with reference system of exterior lighting with identical set of vehicle lights [4,5]. An external source of LED light in the vehicles is the following headlights: dipped light, road light, front position light, rear and front fog lights, rear and front indicator, reversing light and number plate. Therefore, we should enable producers to certify CO₂ savings obtained by exterior energy-efficient lighting LED and to verify conformity in order to obtain certification of approval for energy-efficient products of exterior lighting of the vehicles [6,7].
In order to determine CO2 savings obtained by LED external lighting, it was necessary to determine research method and reference technology to assess energy consumption of LED lighting. Based on technology development and experiences with external lighting of vehicles, halogen lighting has been accepted as a reference technology[12]. A producer who wants to certify CO2 savings obtained from a few sources of external lighting must submit an application confirming an offer of the highest energy efficiency[8,9]. According to the EC Order no. 443/2009, thanks to application of innovative technologies, total share of these technologies in reduction of target individual level of emission can’t be higher than 7g CO2/km. Certified CO2 savings resulting from application of eco-innovations indicated in accordance with an executory order of European Commission no. 725/2011 are given separately for documentation of type approval, as well as for certificate of conformity in accordance with directive 2007/46/EC. It is possible based on tests made in accordance with approved methodology and entering code of eco-innovation, number 19 for such documentation.

2. Methodology to determine the CO2 savings of exterior vehicle lighting using light emitting diodes (LED)

In order to determine savings of CO2 emission that may be ascribed to the system of energy-saving LED external lighting, consisting of appropriate set of vehicle lights, in a vehicle M1, it must be defined:

- Testing conditions.
- Test equipment.
- Determination of the power savings.
- Calculation of the CO2 savings.
- Calculation of the statistical error.

The testing conditions shall fulfil the requirements of Regulation UN/ECE No 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.

Research equipment for certification of approval and calculation of CO2 savings should include a set of devices:

- Power supply unit (i.e. variable voltage supplier).
- Two digital multimeters, one for measuring the DC-current, and the other for measuring the DC-voltage. In the figure, a possible test set-up is shown, when the DC-voltage meter is integrated in the power supply unit.

Outline and interconnections of equipment are presented on figure 1.

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
To perform these other measurements to the type-approval authority. 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 \( P_{EI} \) 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 \( \Delta P_i \) are to be calculated with the following formula (1):

\[
\Delta P_i = \Delta P_{Bl} - P_{EI_i}
\]

\( \Delta P_{Bl} \) - total electric energy taken by the source of light of a reference vehicle [W].

The 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 \( (P_0) \) [W] |
|---------------------|--------------------------------------|
| Low beam headlamp   | 137                                  |
| High beam headlamp  | 150                                  |
| Front position      | 12                                   |
| License plate       | 12                                   |
| Front fog lamp      | 124                                  |
| Rear fog lamp       | 26                                   |
| Front turnsignal lamp | 13                                |
| Rear turnsignal lamp | 13                                |
| Reversing lamp      | 52                                   |

3. Calculation of the CO₂ savings

The total CO₂ savings of the lighting package are to be calculated by formula (2):

\[
C_{CO_2} = \left( \sum_{i=1}^{m} \Delta P_{Bl} \cdot UF_{i} \right) \cdot \frac{V_{Pe} \cdot CF}{\eta_A \cdot v}
\]

\( v \) - mean driving speed of the New European Driving Cycle NEDC [km/h], which is 33.58 km/h, \( \eta_A \) - alternator efficiency [%], which is 67%, \( V_{Pe} \) - consumption of effective power [l/kWh] as defined in Table 2, \( CF \) - conversion factor (l/100 km) – (g CO₂/km) [gCO₂/l] as defined in Table 3, \( UF \) - usage factor of the vehicle light [-] as defined in Table 4.

### Table 2. Consumption of Effective power.

| Type of engine | Consumption of effective power \( (V_{Pe}) \) [l/kWh] |
|----------------|---------------------------------------------|
| Petrol         | 0.264                                       |
| Petrol Turbo   | 0.280                                       |
| Diesel         | 0.220                                       |
Table 3. Fuel conversion factor.

| Type of fuel | Conversion factor (l/100 km) – (g CO$_2$/km) (WK) |
|--------------|--------------------------------------------------|
| Petrol       | 2 330                                            |
| Diesel       | 2 640                                            |

Table 4. 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                  |
| License 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                  |

4. 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 formula (3):

\[
S_{P_{E_i}} = S_{P_{E_i}/n} = \left( \sum_{j=1}^{n} (P_{E_i,j} - \bar{P}_{E_i})^2 \right)^{1/2} / n(n-1)
\]

\[\text{(3)}\]

\(S_{P_{E_i}}\) - standard deviation of the LED light power consumption [W], \(n\) - number of measurements of the sample, which is at least 5, \(P_{E_i,j}\) - energy consumption for each exterior energy-efficient lighting, \(\bar{P}_{E_i}\) - the average of the power consumption for each efficient exterior LED light [W].

The standard deviation of the power consumption of each efficient exterior LED light (\(S_{P_{E_i}}\)) leads to an error in the CO$_2$ savings (\(S_{C_{CO2}}\)). This error is to be calculated by means of formula (4).

\[
S_{C_{CO2}} = \sum_{i=1}^{m} \left( \frac{\partial C_{CO2}}{\partial P_{E_i}} \cdot S_{P_{E_i}} \right)^2 = \sum_{i=1}^{m} \left( UF_i \cdot S_{P_{E_i}} \right)^2 \cdot \frac{V_{pe} \cdot CF}{\eta_A \cdot v}
\]

\[\text{(4)}\]

\(C_{CO2}\) - CO$_2$ savings [gCO$_2$/km], \(\frac{\partial C_{CO2}}{\partial P_{E_i}}\) - sensitivity of calculated CO$_2$ savings related to the LED light power consumption.

It has to be demonstrated for each type, variant and version of a vehicle fitted with the combination of the efficient exterior LED lights that the error in the CO$_2$ savings calculated with Formula 4 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 (see Formula 5). This Minimum threshold is to be calculated by means of formula (5).

\[
MT \leq C_{CO2} - S_{C_{CO2}}
\]

\[\text{(5)}\]

\(MT\) - minimum threshold [gCO$_2$/km], which is 1gCO$_2$/km
Where the total CO₂ emission savings of the package of the efficient exterior LED lights, as a result of the calculation using Formula 5, 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.

5. Optimization of energy consumption and savings thanks to application of LED technology

Environmental protection and growing fuel prices are two key issues, therefore, the issue of saving energy is now more important than ever. Fuel consumption is a basic criterion taken into consideration while buying a new vehicle. Unfortunately, the reduction of energy consumed by lighting of a vehicle is too often ignored.

Total demand for energy of a vehicle equipped with bulbs (rear lamps) and halogen lamps (headlights) is about 60% of demand for energy for dipped headlights and 14% demand for rear position lights. If we use combination of xenon lamps and LED lamps for configuration of vehicle lighting, demand for energy will be reduced by 39%. If we used only LED lamps, energy consumption would be reduced by 60%[1]. Figure 2 shows 100% demand of a vehicle equipped with incandescent lamps. Figure 3 and figure 4 show economical variants equipped with xenon lamps and LED lamps and only with LED lamps [1].

![Vehicle equipment with halogen lamps / bulbs.](image1.png)

**Figure 2.** Vehicle equipment with halogen lamps / bulbs.

![Vehicle equipment with halogen xenon lamps / LED lamps.](image2.png)

**Figure 3.** Vehicle equipment with halogen xenon lamps / LED lamps.
Fuel economy and reduction of CO\textsubscript{2} emission in combination of various sources of light and with average working time of lighting were presented in Table 5.

**Table 5.** Fuel consumption and CO\textsubscript{2} emissions at average lighting time.

| Vehicle Configuration (Headlamp/rear lamp) | Fuel consumption [l/km] | Emission CO\textsubscript{2} [kg/100km] | Reduction |
|--------------------------------------------|--------------------------|----------------------------------------|------------|
| Halogen/Bulb                               | ~ 0.126                  | ~ 0.297                                | -          |
| Xenon/LED                                  | ~ 0.077                  | ~ 0.182                                | 39%        |
| LED/LED                                    | ~ 0.051                  | ~ 0.120                                | 60%        |

For daytime running lights, vehicle lighting used only to drive in bright conditions during the light day, on condition that different light is used, additional fuel consumption is presented in Table 6.

**Table 6.** Additional fuel consumption and CO\textsubscript{2} emissions for daytime running lights.

| Daytime running light system                | Fuel consumption [l/km] | Emission CO\textsubscript{2} [kg/100km] | Reduction |
|--------------------------------------------|--------------------------|----------------------------------------|------------|
| Halogen head lamps                         | ~ 0.138                  | ~ 0.326                                | -          |
| LED (Day time Running Lights)              | ~ 0.013                  | ~ 0.031                                | 91%        |

Moreover, fuel consumption and CO\textsubscript{2} emission depend also on configuration of sources of external lighting and for a truck equipped with the parts of a producer of Original Equipment Manufacturer (OEM), this consumption is presented in Table 7.

**Table 7.** Fuel consumption depending on lighting configuration (truck with OEM).

| Comparision of light sources               | Fuel consumption [l/100km] |
|--------------------------------------------|----------------------------|
| Combination of Halogen lamp/Bulb           | 0.10 – 0.25                |
| Combination of Xenon lamp/LED              | 0.05 – 0.15                |
| Only lighting LED/LED                      | 0.03 – 0.09                |

6. **Summary**

Due to high costs, LED technology has been available only in the segment of the most expensive vehicles of premium class so far. Currently, it is also applied in other segments of vehicles, also in the trucks and buses [10,11]. The diodes are very functional and have good technical performance. They allow to save energy. Moreover, they have a colour similar to daylight.
In the longer perspective, the market of lighting and reflectors in LED technology will be developing in two directions. On the one hand, the segment of premium vehicles will become more important and it will require high efficiency and perfect light energy. On the other hand, the emphasis will be put on economic and ecological aspect, of which condition, apart from lower energy consumption, is application of solutions favourable in terms of costs and functionality. Modern, functional and economic LED diodes give many options. One of them is greening of vehicle lighting, which will allow to reduce CO2 emission. Therefore, the introduction by the EU of calculation method of CO2 savings obtained by external lighting of vehicles that use electroluminescent diodes has become a necessity and cost analysis showed that LED lighting allows to save energy and provides higher level of environmental protection.

The diode lamps to drive in the daylight do not only allow to save fuel and reduce CO2 emission, but also make driving safer. Colour temperature of light of white LED diode is 6000 K, that is, three time more than in case of standard halogen bulbs and xenon lamps. The modules consisting of LED diodes emit very bright light that make driving safer both in full sun and in poor weather conditions.

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