ELECTRIC CARS
Are They Solution to Reduce CO_2 Emission?

by

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Reducing CO_2 emission is one of the major environmental challenges for transportation. One way to solve this problem is to replace old cars that use fossil fuels (petrol, diesel) with new electric cars. In this paper, the existing model for calculating well-to-wheels CO_2 emission during the life cycle of the car (fossil fuel car and electric car) is upgraded. The developed model is used for comparing optimal lifetime and optimal car's kilometers driven during a lifetime in the replacement process of a fossil fuel car with a new electric car. We find that reducing CO_2 emission depends on the type of fossil fuel, and the weight of fossil fuel cars and electric cars. Changing petrol fossil fuel cars with lower weight electric cars have the greatest potential for reducing CO_2 emission. However, the introduction of electric cars does not achieve a significant reduction of CO_2 emission in countries where electricity is primarily produced in thermal power plants, i. e. in countries with a high emission factor of electricity production.

Key words: *emission, CO_2, life cycle, electric car, fossil fuel car*

Introduction

Reducing CO_2 emission is one of the major environmental challenges in the world. This fact is supported by long-term the EU strategy which aims to reduce CO_2 emissions by more than 50% by 2050 [1]. The share of CO_2 emissions from cars in the total emissions in EU is about 12% [2]. In this regard, finding solutions to reduce CO_2 emissions from cars would have a positive effect on solving environmental challenges.

Previous researches proposed a lot of measures and policies to reduce CO_2 emission from the transportation sector. Hickman and Banister [3] identified 122 individual policy measures that could be grouped in follows groups: low emission vehicles, alternative fuels, pricing regimes, liveable cities, information and communications technologies, smarter choices, ecological driving, long-distance travel substitution, freight transport, carbon rationing, and increased oil prices. Within the group of measures alternative fuels, authors recognized electricity as one of the potential alternative fuels. These measures have the second biggest potential for reducing CO_2 emission. Hofer *et al*. [4] defined follows policies for reducing CO_2 emission: increase number of electric cars (EC), ban old cars,

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reduction of work trips due to telecommuting, using car alternatives for short distances (*e. g*. bicycles), increase number of traffic lanes for the most congested road sections, and combinations of these policies. The combination of policies with policy increase number of EC was showed the biggest potential for reducing CO_2 emission. Specifically, for commercial vehicles and buses, improving vehicle load factor, improving vehicle fleet structure, regulatory measures, and introducing alternative fuels were proposed [5-7]. Definitely, EC are recognized as one of the solutions for reducing CO_2 emissions in transportation.

The impact of introducing EC to reduce CO_2 emission was researched by some authors [4, 8-12]. Hofer *et al*. [4] found that increasing the number of EC would lead to reduce CO_2 emission up to 20% but in combination with other policies up to 28%. This research was conducted in Graz, Austria. By comparing eight types of fuels in five countries (Brazil, China, France, Italy, and the United States) was founded that positive impact of EC, in terms of CO_2 emission, depends on the way in which electricity is produced, *i. e*., the emission factor of electricity production [8]. The EC had the lowest emission in Brazil, France, and Italy, but did not have in China and the United States. Namely, China (75.2%), and the United States (42.1%) have produced most of the electricity in thermal power plants with coal. Similarly, Doucette and McCulloch [9] found that the greatest effects of EC introduction can be expected in countries such as France, with a low emission factor of electricity production. Hofmann *et al*. [10] found that only introducing EC would not reduce CO_2 emission in China. Also, these authors stated that a positive impact on CO_2 emission can be expected only if aggressive decarbonization of the electricity sector is implemented. A similar finding was found by Wu *et al*. [11] which concluded that EC are not an ideal solution for solving CO_2 emission problem for China's regions in which electricity is produced in thermal power plants with coal (*e. g*. Jing-Jin-Ji region). However, a study that analyzed four cities in China found that two from four cities would have a positive impact on the environment by introducing EC [12]. Definitely, EC introducing have the potential for reducing CO_2 emission, especially in a region with a low emission factor of electricity production.

Mijailović [13] stated about future research: significant to determine benefit from the replacement of *traditional* fuel car (petrol or diesel) by the other fuel ones, which emit less pollutant". Also, Mijailović *et al*. [14] stated: *Future research should also explore the conditions (economic, infrastructural, legislative, etc.) necessary to reduce the number of fossil-fuelled passenger cars and to increase the number of alternative-fuelled cars. In that sense, a special focus should be put on electric cars*. Are EC the solutions? In order to answer the previous question, the model developed at Mijailović [13] is upgraded in this paper. The upgrade is to introduce well-to-wheels CO_2 emission during the exploitation of a fossil fuel car (FFC) and EC. The developed model is used for comparing optimal lifetime and optimal car's kilometers driven during a lifetime in the replacement process of FFC with a new EC. Also, the paper answers the question of whether the decrease in the weight of new EC can compensate for the high emission factor of electricity production.

Model

The development of the model in this study is realized in two-phases. First, equations for calculating CO_2 emission in each phase of the life cycle of a car are defined. In the second phase, the analytical equation for calculating optimal lifetime and optimal car's kilometers driven during a lifetime in the replacement process of FFC with a new EC is defined based on ecological criteria.

The CO_2 emission during the life cycle of car

As the initial model for calculating total CO_2 emission during the life cycle of a car is used the model developed at Mijailović [13]. Also, this model was adapted for calculating CO_2 emission during the life cycle of turbofan aircraft [15].

The life cycle of each car can be modeled with eight phases: material production, car's parts manufacturing, car's assembling, distribution of the car, use, repair, distribution of car's parts and disposal. Total CO_2 emission during the life cycle of a car is calculated as the sum of partial CO_2 emission during each phase of the life cycle [13]:

$$E = \sum_{\ell=1}^{8} E_\ell \tag{1}$$

The CO_2 emission during material production phase depends on car weight, M, participation of material i in the car weight, qm_i, number of different materials used in production of car, nm, energy consumption per kilogram during material i production breakdown for 100% virgin material, $ec_i^{v.m}$, and for 100% recycled material, $ec_i^{r.m}$, reuse rate during production of material i ($reuse_i$), recovery rate during production of material i ($recov_i$), recycling rate during production of material i ($recym_i$), emission factor for type of energy j, ef_j, participation of type of energy j in the production of material i ($pmp_{j,i}$), number of different types of energy used to produce of material i (ne) [13]:

$$E_1 = \frac{44}{12} M \sum_{i=1}^{nm} \{qm_i [ec_i^{v.m.}(1 - reuse_i - recov_i - recym_i) + ec_i^{r.m.} recym_i] \sum_{j=1}^{ne} ef_j \, pmp_{j,i}\} \tag{2}$$

A car weight can be expressed as the sum of a car's weight without the battery and weight of the battery. The battery in EC is heavier than the battery in FFC. This is one of the reasons because EC has greater weight in comparison with FFC with similar performances. The participation of materials in the car weight has different values at EC and FFC.

The car's parts manufacturing phase follows after the material production sequence. The CO_2 emission during this life cycle phase can be expressed [13]:

$$E_2 = M \sum_{i=1}^{nm} qm_i (1 - reuse_i) \sum_{h=1}^{ntp} ptp_{i,h} em_{i,h} + 889 \tag{3}$$

where ntp denotes the number of different transformation processes used to car's parts manufacturing, $em_{i,h}$ is the CO_2 emission during the manufacturing of material i by type of transformation process h and $ptp_{i,h}$ is participation of type of transformation process h in the manufacturing of material i.

Most of the manufactured car's parts are sent to the next stage of the life cycle car's assembling, while the smaller part is forwarded to the *repair* phase. The CO_2 emission during car's assembling depend on energy consumption per kilogram during car's assembling, ec_{as}, and participation of type of energy j in car's assembling, pas_j [13]:

$$E_3 = \frac{44}{12} M ec_{as} \sum_{j=1}^{ne} ef_j \, pas_j \tag{4}$$

Further, an assembled car is transported to the dealer which sells the car. The equation for determining the CO_2 emission during the distribution of car includes the average transportation distance, S_{dis}, and the specific CO_2 emission during the distribution of car, e_{dis} [13]:

$$E_4 = S_{dis} e_{dis} M \tag{5}$$

The phase *use* is longer in comparison with all other life cycle phases. Each user asks himself a question: *How much is the optimal lifetime and/or optimal car's kilometers driven during a lifetime when I need to substitute the car*? The CO_2 emission during this phase is the product of the car's kilometer driven for the whole life cycle, *S*, and specific CO_2 well-to-wheels emission, $qWtW_{T_N,k}$:

$$E_5 = SqWtW_{T_N,k} \tag{6}$$

The specific CO_2 well-to-wheels emission depends of model year, T_N, and types of fuel, *k*. Types of fuel (petrol, diesel or electric) and engine displacement of the car is described:
– $k = 1$: petrol car, engine displacement < 1400 cm^3,
– $k = 2$: petrol car, engine displacement = 1400 ... 2000 cm^3,
– $k = 3$: petrol car, engine displacement > 2000 cm^3,
– $k = 4$: diesel car, engine displacement < 2000 cm^3,
– $k = 5$: diesel car, engine displacement ≥ 2000 cm^3, and
– $k = 6$: electric car.

Catalogs of cars contain the value of CO_2 emission during the car's exploitation. This CO_2 emission is tank-to-wheels emission, and CO_2 emission is produced during the process of fuel combustion. In addition tank-to-wheels emission, total CO_2 emission contains emissions produced during the production and transportation of raw material, production, and transportation of fuel and all other emissions before fuel combustion. This CO_2 emission is well-to-tank emission. At FFC, term fuel implies petrol and diesel. On the other side, the fuel of EC is electricity. The specific CO_2 well-to-wheels emission is equal to the sum of well-to-tank, $qWtT_{T_N,k}$, and tank-to-wheels, $qTtW_{T_N,k}$, CO_2 emissions:

$$qWtW_{T_N,k} = qWtT_{T_N,k} + qTtW_{T_N,k} \tag{7}$$

By analyzing literature, the values of the specific CO_2 well-to-tank emission of FFC can be found in a wide range. According to Kahn Ribeiro *et al.* [16], well-to-tank emission makes around 13% of well-to-wheel emission petrol FFC and 7% of well-to-wheel emission diesel FFC. Also, according to the research, well-to-tank emission petrol FFC is around 2.5 times higher in comparison with well-to-tank emission diesel FFC. Watabe *et al.* [17] stated that well-to-tank emission petrol FFC is 395 gCO_2 per liter, while for a diesel FFC well-to-tank emission is 208 gCO_2 per liter. Lelli *et al.* [18] found that specific CO_2 well-to-tank emission in Europe fleets of cars in 2020 will 15% of specific CO_2 tank-to-wheels emission. In the United States fleet, this value will amount between 27% and 29%. The specific CO_2 well-to-tank emission FFC can be expressed:

$$qWtT_{T_N,k} = u_1 qTtW_{T_N,k} + u_2\,, \quad for \quad k = 1,2,3,4,5 \tag{8}$$

where coefficients u_1 and u_2 have different values depending on the country and year.

The specific CO_2 well-to-tank emission EC is determined by applying the expression:

$$qWtT_{T_N,6} = \frac{CE \cdot qe}{1 - ellos} \tag{9}$$

where *CE* is the emission factor of electricity production, *qe* – the specific electricity consumption of EC, and *ellos* – the electric power losses during the transmission and distribution of electricity.

The emission factor of electricity production depends on the way (thermal power plants, hydroelectric power plants, nuclear power plants, *etc.*), the technology of electricity production, and the age of plants for the production of electricity. This factor varies depending on the country and year [19]. The lowest value of the emission factor of electricity production is recorded when electricity is produced in hydroelectric power plants and wind power plants [20]. According to this source, the emission factor of electricity production is 2.5 times higher when electricity is made using biomass, and 6.5 times higher in nuclear power plants. The highest value of the emission factor of electricity production is observed when electricity is produced in thermal power plants with coal. Namely, if the electricity is produced in thermal power plants with coal, the emission factor of electricity production will be around 96 times higher in comparison with wind power plants. If lignite is used in thermal power plants, then the emission factor of electricity production will be about 124 times higher.

The specific electricity consumption of EC is one of the car's characteristics. This characteristic can be expressed as a function of the weight of the car [21]:

$$qe = \frac{20.94}{150 - 0.025M} \tag{10}$$

The specific CO_2 tank-to-wheels emission of FFC depends on maintenance type (preventive or corrective) and specific emission when the car was a new [13, 14, 22]. We assume that specific CO_2 emission has not been changed during exploitation. The reason for this assumption is that the technical inspection excludes FFC if these cars have emission over legal limitations [23]. The same assumption is applied to the specific electricity consumption of EC.

The electric power losses during the transmission and distribution of electricity, *ellos*, have different values for each country and year. Based on the data in the [24], in case of Serbia at the scenario *business as usual*, the electric power losses during the transmission and distribution of electricity for the period from 2020-2030 will be between 7.0% and 7.4%.

The specific CO_2 tank-to-wheels emission of FFC is equal the specific CO_2 emission of model T_N year and k-type for a new car and can be calculated applying to follow the equation [13, 25]:

$$qTtW_{T_N,k} = Mw_{1,k}(T_N - 1994)^{w_{2,k}} \quad for \quad k = 1,2,3,4,5 \tag{11}$$

where $w_{1,k} = 0.194$, $w_{2,k} = -0.12$ for $k = 1, 2, 3$ and $w_{1,k} = 0.157$, $w_{2,k} = -0.153$ for $k = 4,5$.

In terms of CO_2 emission, the specificity of EC is zero-emission during the exploitation phase [17]:

$$qTtW_{T_N,6} = 0 \tag{12}$$

Finally, by the implementation expressions (8) to (12) into eq. (7) is obtained the final expression for calculating the specific CO_2 well-to-wheels emission:

$$qWtW_{T_N,k} = \begin{cases} (1+u_1)Mw_{1,k}(T_N - 1994)^{w_{2,k}} & for \quad k = 1,2,3,4,5 \\ \dfrac{CE}{1-ellos}\dfrac{20.94}{150 - 0.025 \cdot M} & for \quad k = 6 \end{cases} \tag{13}$$

The CO_2 emission during the phases *repair* and *distribution of car's parts* depends on the coefficient of repair (*rep*) [13]:

$$E_6 = repS(E_1 + E_2 + E_3) \tag{14}$$

$$E_7 = SrepE_4 \tag{15}$$

The last phase of the car life cycle is *disposal*. The CO_2 emission during this phase is calculated [13]:

$$E_8 = \frac{44}{12} Mec_{di} \sum_{j=1}^{ne} ef_j pdi_j \tag{16}$$

where ec_{di} is the energy consumption per kilogram during the sequence *disposal* and pdi_j – the participation of type of energy j in the sequence *disposal*.

Optimal lifetime and optimal car's kilometers driven during a lifetime

Based on ecological criteria, optimal lifetime and optimal car's kilometers driven during a lifetime is defined as reducing the environmental burden by replacing the old one with a new product is equal to the environmental burden arising from the previous replacement [26]. According to that, if we replace FFC with EC, optimal lifetime and optimal car's kilometers driven during a lifetime is calculated:

$$\begin{aligned} &E_1^{EC} + E_2^{EC} + E_3^{EC} + E_4^{EC} + E_8^{FFC} = \\ &= E_5^{FFC} + E_6^{FFC} + E_7^{FFC} - E_5^{EC} - E_6^{EC} - E_7^{EC} \end{aligned} \tag{17}$$

By the implementation expressions (2)-(6) and (13)-(16) into eq. (17) is obtained an analytical expression for calculating optimal car's kilometers driven during a lifetime of FFC:

$$S_{opt} = \frac{\Delta_2}{\Delta_1} \tag{18}$$

where

$$\begin{aligned} \Delta_1 = {} & M^{FFC}[w_{1,k}(1+u_1)(T_{N,k}-1994)^{w_{2,k}} + rep^{FFC}(S_{dis}e_{dis} + e_{1-2-3}^{FFC})] - \\ & - M^{EC} rep^{EC}[S_{dis}e_{dis} + e_{1-2-3}^{EC}] + 889(rep^{FFC} - rep^{EC}) + \\ & + u_2 - \frac{CE}{1-ellos}\frac{20.94}{150-0.025M^{EC}} \end{aligned}$$

$$\Delta_2 = M^{EC}(e_{1-2-3}^{EC} + S_{dis}e_{dis}) + \frac{44}{12} M^{FFC} ec_{di} \sum_{j=1}^{ne} ef_j pdi_j + 889$$

$$\begin{aligned} e_{1-2-3}^{EC} = {} & \frac{44}{12}\sum_{i=1}^{nm}\{qm_i^{EC}[ec_i^{v.m.}(1-reuse_i^{EC} - recov_i^{EC} - recym_i^{EC}) + ec_i^{r.m.} recym_i^{EC}] \cdot \\ & \cdot \sum_{j=1}^{ne} ef_j pmp_{j,i}\} + \sum_{i=1}^{nm} qm_i^{EC}(1-reuse_i^{EC})\sum_{h=1}^{ntp} ptp_{i,h}em_{i,h} + \frac{44}{12} ec_{as}\sum_{j=1}^{ne} ef_j pas_j \end{aligned}$$

$$\begin{aligned} e_{1-2-3}^{FFC} = {} & \frac{44}{12}\sum^{nm}\{qm_i^{FFC}[ec_i^{v.m.}(1-reuse_i^{FFC} - recov_i^{FFC} - recym_i^{FFC}) + ec_i^{r.m.} recym_i^{FFC}] \cdot \\ & \cdot \sum_{j=1}^{ne} ef_j pmp_{j,i}\} + \sum_{i=1}^{nm} qm_i^{FFC}(1-reuse_i^{FFC})\sum_{h=1}^{ntp} ptp_{i,h}em_{i,h} + \frac{44}{12} ec_{as}\sum_{j=1}^{ne} ef_j pas_j \end{aligned}$$

Moghadam and Livernois [27] found that average annually car's kilometers driven decreasing with the aging car. Relation between average annually car's kilometers driven, S_i, and age, t_i, can be presented as the following equation [13]:

$$S_i = 23613 - 771.653 t_i \tag{19}$$

Optimal car's kilometers driven during a lifetime can be expressed in relation with optimal lifetime:

$$S_{opt} = \sum_{i=1}^{t_{opt}} S_i \, , \; S_{opt} = \sum_{i=1}^{t_{opt}} 23613 - 771.653 t_i \tag{20}$$

The exppressions (18) and (20) are simple for practical use and have practical significance. Numerical values required for the practical application of the exppressions (18) and (20) can be found in references [13, 28-33].

Results

In this paper, the developed model is applied for the values of the emission factor of electricity production ranged between 0 and 800 gCO_2 per kWh. The EU28, countries of EU28 and Serbia have the values of the emission factor of electricity production in this range. The emission factor of electricity production for EU28 countries in 2013 can be found in the report of the European Commission [34]. Serbia represents countries that a major part of electricity produces in thermal power plants. In Serbia, 70% of electricity was produced in thermal power plants (most of the lignite) and 30% was produced in hydroelectric power plants in 2016 [35]. The emission factor of electricity production for Serbia was around 740 gCO_2 per kWh in 2015 [24].

In the model, we assume that conditions required in Directive 2000/53/EC [36] in terms of coefficients of reuse, recovery, and recycling rate are fulfilled. The percentages of material in the total weight of the car, qm_i, for FFC and EC are adopted from Wang *et al.* [37]. Namely, these authors found the values of the percentages of material for 2009, and predict these values for 2020.

The model is applied in case when the specific CO_2 well-to-tank emission FFC amount 15% of specific CO_2 tank-to-wheels emission these cars: $u_1 = 0.15$, $u_2 = 0$. Also, the electric power losses during the transmission and distribution of electricity amount 7%: $ellos = 0.07$. The average age of cars in EU28 was around ten years in 2015 [38]. For that reason, further analysis is made for $T_N = 2009$.

The optimal car's kilometers driven during a lifetime for petrol FFC (k = 1, 2, 3) is lower in comparison with diesel FFC (k = 4, 5) if the values of the emission factor of electricity production and weight of EC is constant, fig. 1. The ratio of optimal car's kilometers driven during a lifetime for diesel FFC and petrol FFC grows with increasing the emission factor of electricity production and weight of EC. This finding is the same for the optimal lifetime.

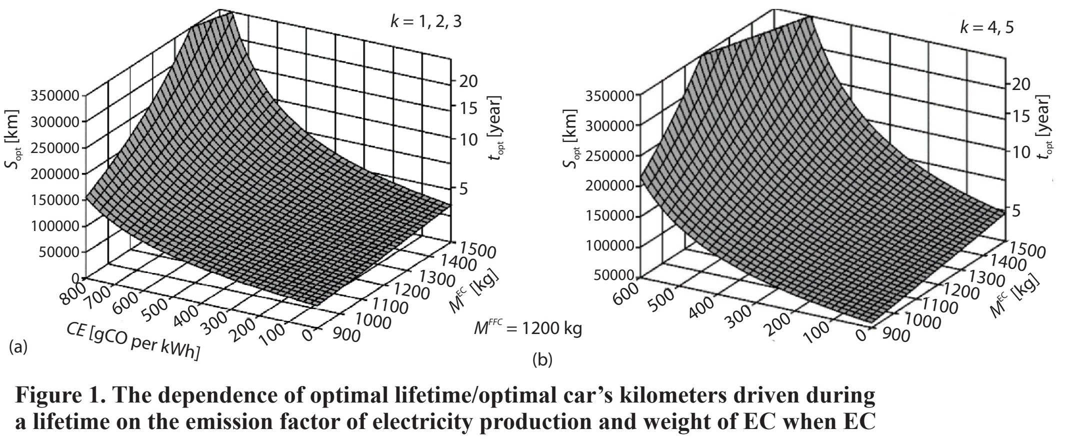

Figure 1. The dependence of optimal lifetime/optimal car's kilometers driven during a lifetime on the emission factor of electricity production and weight of EC when EC replace FFC with; (a) petrol fuel, (b) diesel fuel

We analyze the case when the weight of the cars is the same, $M^{FFC} = M^{EC}$. In the beginning, we analyze the case when all electricity is made in wind power plants in a country: (CE = 10 gCO_2 per kWh): petrol – S_{opt} = 57194 km, t_{opt} = 2.6 year, and diesel – S_{opt} = 77656 km, t_{opt} = 3.5 year. If we consider countries with a low emission factor of electricity production (*e. g.* Belgium and the Slovak Republic) with CE = 200 gCO_2 per kWh, follow results is obtained: petrol – S_{opt} = 70336 km, t_{opt} = 3.2 year and diesel – S_{opt} = 104052 km, t_{opt}=4.8 year. The emission factor of electricity production in EU28 is similar to Slovenian emission factor of electricity production ($CE \approx 400$ gCO_2 per kWh): petrol: S_{opt} = 92774 km, t_{opt} = 4.3 year and diesel – S_{opt} = 162024 km, t_{opt} = 8 year.

Do we achieve reducing CO_2 emission regardless of the emission factor of electricity production if we replace FFC with EC? For this purpose, we analyze the emission factor of electricity production in countries with $CE \approx 600$ gCO2 per kWh (*e. g.* Germany). The optimal car's kilometers driven during a lifetime are 365863 km for diesel FFC. Diesel FFC drove this value of kilometers for the optimal lifetime higher than 25 years, which is higher than the average age of cars in EU. Based on the obtained results, replacing diesel FFC with EC is not environmentally justified in countries with a higher value of the emission factor of electricity production. This conclusion does not apply to petrol FFC – S_{opt} = 136236 km, t_{opt} = 6.6 year. The same finding can be observed in Serbia $CE \approx 740$ gCO_2 per kWh. The car fleet in Serbia was described as follows, in 2015 [14]: petrol – M^{FFC} = 1176 kg, T_N = 2002 and diesel – M^{FFC} = 1225 kg, T_N = 2005. Also, only replacing petrol FFC with EC is environmentally justified, after S_{opt} = 163487 km and t_{opt} = 8.1 year. The case of Serbia is one more example that replacing diesel FFC with EC is not environmentally justified in countries with a higher value of the emission factor of electricity production ($S_{opt} > 800000$ km). This finding is consistent with previous researches [8, 9, 11].

Previous researches [8-12] and our results have proven that the emission factor of electricity production significantly influences the impact of EC on reducing CO_2 emission. Applying the developed model, the value of the emission factor of electricity production for which environmentally justified replacing FFC with EC can be determined. Thus, in the case t_{opt} = 10 year and $M^{FFC} = M^{EC}$ = 1200 kg replacing petrol FFC with EC is environmentally justified in countries where the emission factor of electricity production is lower than 727 gCO_2 per kWh. Also, replacing diesel FFC with EC is environmentally justified in countries where the emission factor of electricity production is lower than 459 gCO_2 per kWh.

Based on fig. 1, reducing the emission factor of electricity production and reducing the weight of new cars should be stimulated by future strategies. Reducing the emission factor of electricity production requires large economic investments. Stimulating the purchase of new low weight EC is a solution that can bring faster positive environmental results.

Further, we will answer the question: *Can reducing the weight of new EC compensate for increasing the emission factor of electricity production*?. We analyze replacing FFC with a weight of 1200 kg. The optimal car's kilometers driven during a lifetime for CE = 200 gCO_2 per kWh is: petrol – S_{opt} = 70336 km, diesel – S_{opt} = 104052 km. By analyzing twice higher the emission factor of electricity production (CE = 400 gCO_2 per kWh) the same values of the optimal car's kilometers driven during a lifetime will be obtained if the weight of EC is reduced for 22% (replacing petrol FFC for EC). If EC replaces diesel FFC, then the weight of EC should be reduced by 30%. Further, by analyzing three times higher the emission factor of electricity production (CE = 600 gCO_2 per kWh), reducing the weight of EC should be 42% if a petrol FFC is replaced or 56% if a diesel FFC is replaced.

In the case of Serbia ($CE \approx 740$ gCO_2 per kWh), reducing the weight of EC should be 43% if a petrol FFC is replaced by EC. On the other side, if a diesel FFC is replaced, then the weight of EC should be reduced by 62%. These results are not realistic in practice. Practically, instead of EC of 1200 kg, these cars are replaced by EC of about 680 kg (replacing petrol FFC) and EC of about 450 kg (replacing diesel FFC).

Conclusions

This paper aims to answer the question of whether the replacement FFC with EC could reduce CO_2 emission. For this purpose, the analytical equation for calculating optimal lifetime and optimal car's kilometers driven during a lifetime in the replacement process of FFC with a new EC are defined based on ecological criteria. The developed model is tested on real data from EU28, EU28 countries, and Serbia. Based on the obtained results, the most important findings of this paper is:

- Greater environmental impact is achieved by replacing petrol FFC.
- Environmental impact is not achieved at the high emission factor of electricity production.
- Replacing petrol FFC with EC is environmentally justified in countries where the emission factor of electricity production is lower than 727 gCO_2 per kWh (assumptions: $t_{opt} = 10$ year and $M^{FFC} = M^{EC} = 1200$ kg).
- Replacing diesel FFC with EC is environmentally justified in countries where the emission factor of electricity production is lower than 459 gCO_2 per kWh (assumptions: $t_{\mathrm{opt}} = 10$ year and $M^{FFC} = M^{EC} = 1200$ kg).

Therefore, EC are a solution for reducing CO_2 emission when the emission factor of electricity production is low and especially when the petrol FFC is replaced. Additional positive impacts would be achieved by reducing the weight of a new EC. This measure has practical limitations because of the ability to reduce the weight of a new EC. Therefore, low weights EC have the greatest potential for reducing CO_2 emission.

In this paper, certain limitations are observed. In order to improve the quality of future researches and eliminate the limitations, certain recommendations are recommended. Methodology for calculating well-to-tank CO_2 emission should be created. Further, the emission factor of electricity production for smaller areas that are more homogeneous in terms of this factor should be analyzed. Such results would be more practical for policymakers. Also, future researches should analyze the potential for reducing CO_2 for other vehicles (*e. g.* commercial vehicles, buses) and other alternative fuels.

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Nomenclature

CE – emission factor of electricity production, [$gCO_2kW^{-1}h^{-1}$]
E_l – emission during l^{th} phase of life cycle, [gCO_2]
e_{dis} – specific CO_2 emission during distribution of car, [$gCO_2km^{-1}kg^{-1}$]
ec_{as} – energy consumption during car's assembling, [Jkg^{-1}]
$ec^{r.m.}$ – energy consumption during production breakdown for 100% recycled material, [Jkg^{-1}]
$ec^{v.m.}$ – energy consumption during production breakdown for 100% virgin material, [Jkg^{-1}]
ec_{di} – energy consumption during the sequence *disposal*, [Jkg^{-1}]

ef – emission factor for type of energy, [gCO_2J^{-1}]
ellos – electric power losses during the transmission and distribution of electricity, [-]
em – emission CO_2 during the manufacturing of material, [gCO_2kg^{-1}]
k – car types, [–]
M – car weight, [kg]
ne – number of different types of energy used to produce of material, [–]
nm – number of different materials used in production of car, [–]
ntp – number of different transformation processes used to car's parts manufacturing, [–]
pas – participation of type of energy in car's assembling, [–]
pdi – participation of type of energy in the sequence *disposal*, [–]
pmp – participation of type of energy in the production of material, [–]
ptp – participation of process in the manufacturing of material, [–]
qe – the specific electricity consumption of EC, [$kWhkm^{-1}$]
qm – participation of material in the car weight, [–]
qTtW – specific CO_2 tank-to-wheels emission, [gCO_2km^{-1}]
qWtT – specific CO_2 well-to-tank emission, [gCO_2km^{-1}]
qWtW – specific CO_2 well-to-wheels emission, [gCO_2km^{-1}]
recov – recovery rate during production of material, [–]
recym – recycling rate during production of material, [–]
rep – coefficient of repair, [km^{-1}]
reuse – reuse rate during production of material, [–]
S – car's kilometer driven for whole life cycle, [km]
S_{dis} – the average transportation distance, [km]
S_{opt} – optimalni pređeni put, [km]
T_N – car's model year, [–]
t – car's age, [year]
t_{opt} – optimal car's kilometers driven during a lifetime, [year]
u_1 – coefficient for calculating *qWtT* emission, [–]
u_2 – coefficient for calculating *qWtT* emission, [gCO_2km^{-1}]
w_1 – coefficient for calculating *qTtW* emission, [–]
w_2 – coefficient for calculating *qTtW* emission, [–]

Acronyms

EC – electric car
FFC – fossil fuel car

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