Influence of e-mobility on total impact of the transport means

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Abstract: The lecture shortly introduces a new methodology developing for total impact evaluation of the transportation systems and its application to study the effect of e-mobility on the total impact. The most important novelties of the applying methodology are the followings: (i) all the impact (environmental impact, safety and security, cost, cost benefits and sustainability will be analyzed, (ii) the impacts will be evaluated on the transportation system level, and (iii) as their total value (including all the related sub-systems and elements, i.e. transport infrastructure, transport flow control and (iv) total impact index will be generated. There will be evaluated the hybrid systems, systems with energy recovery and operation of the full electric vehicles. All the major transport means will be examined.

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1. INTRODUCTION

The transport plays determining role in economy (Rohacs, 2005) and its volume increases with growth of GDP (Baninster, Stead, 2002). Transport is a key element of economic growth and competitiveness” (Transport, 2009).

The European practice in emission reduction demonstrates that, for last 15 years (Fig. 1.), only the transport sector emission is greater than the levels of 1990 (Fig.1) due to increasing the number of vehicles and their usage (Statistical, 2016).

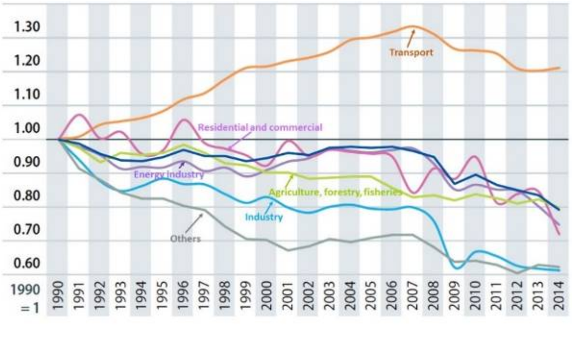

Fig. 1. Changes in CO_2 emission by sectors in Europe

The emission reduction is identified as one of the most important key goals of the future developments. For example, the key goals of the European White (2016) Paper on future transport for 2050 defines as

- no more conventionally-fueled cars in cities.
- 40% use of sustainable low carbon fuels in aviation; at least 40% cut in shipping emissions.
- a 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport.
- all of which will contribute to a 60% cut in transport emissions by the middle of the century.

Ambition plan that seeks for new technologies, new solutions.

The e-mobility seems a key factor in reaching this plan. However, the e-mobility requires energy, too. The question is that, how much energy is needed and how will be generated the required energy.

This paper investigates the possible deployments of the e-mobility, e-vehicles, study the required energy, and evaluates the total impact of e-mobility. After short introduction of a new methodology developing for total impact evaluation of the transportation systems it will be applied to study the effect of e-mobility on the total impact. The most important novelties of the applying methodology are the followings: (i) all the impact (environmental impact, safety and security, cost, cost benefits and sustainability will be analyzed, (ii) the impacts will be evaluated on the transportation system level, and (iii) as their total value (including all the related sub-systems and elements, i.e. transport infrastructure, transport flow control and (iv) total impact index will be generated.

The e-mobility might be introduced by step by step. At first the hybrid vehicles, after that relatively small electric vehicles, and finally all electric transportation system will realized. This paper evaluates the hybrid systems, systems with energy recovery and operation of the full electric vehicles. All the major transport means will be examined.

2. PRELIMINARY CONSIDERATIONS

On the first blink, it seems, the electric vehicles have zero emission. The Figure 2. shows that, in Europe, about half of electric energy is generated by use of combustible fuels (Electricity, 2017).

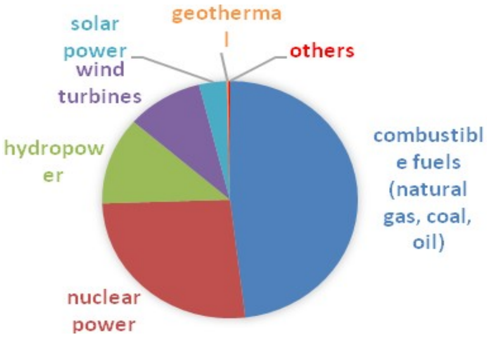

Fig. 2. Net electricity generation in EU28 (Electricity, 2017)

According to the WNA – World Nuclear Association report (Comparison, 2011) the lifecycle greenhouse gas (GHG) emissions in case of using the combustible fuel equal to from 400 up to 1300 tons of CO_2e / GWh depending on the type of fuel (natural gas, oil, coal) and applied technologies. These emissions about 20 – 50 times greater than the GHG emissions in cases of generating the electricity from nuclear, hydro or wind energy. Therefore in Europe, the GHG emission of electric energy generation about 450 tons CO_2e / GWh.

Of course, during production, operation, maintenance or recycling of the electric cars the electric cars large amount of emissions are polluted, too. Even some elements like accumulators call special attention on environmental impact and sustainability.

The transport uses 1/3 of energy (Fig. 3.). The petrol or diesel engines convert a maximum 35 % of energy of burned fuel into driving force, and the total efficiency around 17 – 21 %, only. The electric cars even more than 85 % of electric energy may used for moving the vehicles. That means the conventional cars use directly about 5 times more energy. (Heat of combustion of 1 liter petrol equals to about 10 KWh.)

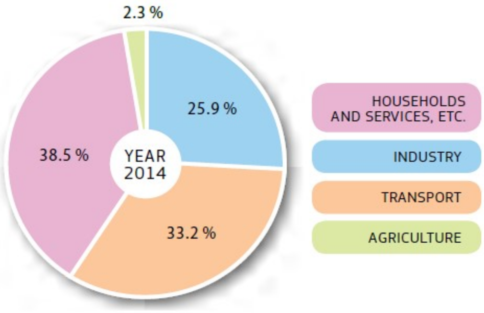

Fig. 3. Energy cuonsumption by sectors (Statistical, 2016)

There is a simple methodology can be applied for the first approximation of required electric energy for the transportation system: each liter of petrol equals to 2 KWh electric energy in case of using electric cars. That means the middle size European cars use about 11 KWh electric energy for 100 km. In 2014, the volume of all the passenger car usage in Europe was 4 766 billion passenger-km (pkm) (Statistical, 2016). Therefore, if all the cars were replace by electric vehicles, then the required energy would be 361 TWh (Table 1.). That equals to 11.3 % of net electric energy generated in EU28 (28 member countries of EU).

Table 1. Simple calculation of the required electric power for full electrification of the passenger car transport

country	use of cars in billion pkm	net generated (available) electricity (TWh)	required electric power* (TWh)	ratio of required and generated energy
EU28	4766,5	3190,773	361,5966	0,113326
Germany	920,8	627,795	72,34857	0,115242
France	815,7	563,694	64,09071	0,113698
Italy	642,9	279,827	48,77172	0,174292
Hungary	52,7	29,392	3,864667	0,131487
Netherlands	145	103,418	11,39286	0,110163
Poland	218,9	159,059	16,05267	0,100923
Sweden	114,9	153,662	9,027857	0,058751
UK	654,2	338,176	49,62897	0,146755

*calculated for case when all the passenger cars is converted to the full electric vehicles and the vehicles are occupied by 1.4, 1.45, 1.5 persons depending on the country economy and car using culture.

Comments: a.) The ratio of required and available energy defines the required increasing in electric production. b.) In cases, when the car usage, namely average annual distance travelled by cars considerable greater and running cars are much more bigger, with greater required power, the ratio in required and available power might be increased up to 25 – 28 %, too.

The replacement of the conventional cars by electric vehicles may results to benefit of air emission reduction up to 1950 MEUR/year (Ayalon, Flicstein, and Shtibelman,2013).

Principally, the methods for evaluation of the environmental impact of the vehicles and transportation systems are well developed (Ntziachristos, et al., 2009; Smit, Ntziachristos and Boulter, 2010; Demir, Bektas and Laporte, 2011) and systemically applicable tools (Upham, et al., 2004; TREMOVE, 2004) are available.

In more general form, the total lifecycle costs can be applied for comparison of the different solutions, vehicles, like conventional, hybrid and electric vehicles. Here total means all the costs associated with using the investigated object, as car, namely design, engineering, production, operation, recycling of the car and - of course - all the impacts on environment, infrastructure, built environment, society, including the short and long term impact on human health and so on. All the impacts can be transferred into the costs as cost of externalities

Externality is the cost or benefit of any actions that is experienced by the unrelated third parties (Buchanan, Stubblebine, 1962). The method is well applicable to investigation of a special aspects (like supporting the electric (Buekers, et al., 2014) and hybrid (Samaras, Meisterling, 2008) vehicles), as well as to study and evaluation of an economic sectors as transport (Friedrich, Rabl and Spadaro, 2001; Mailbach, et al., 2008; van Essen, et al., 2011). A special value of the "Update of the Handbook on external costs of transport" (Korzhenevych, et al. 2014) is generated by (i) good description of methodology, (ii) use of large number of references and real data source and (iii) including the safety (external costs caused by accidents) and congestion into the list of externality. For example, in case of passenger cars, the external costs induced by accidents reaches 50 % of all the externality excluding the congestions, while the congestions increase the external cost for 40 % (Van Essen, et al., 2011). The complexity of evaluation and lack in applicable estimation methods might be characterized by climate change and congestion effects. In case of using the passenger cars in Europe, for example, the climate change effects are estimated as 14,4 and 84,1 million EUR pro year in low and high scenarios, while the costs of road congestions are defined as 98,4 – 161,3 million EUR/year (Van Essen, et al., 2011).

Another interesting and important study published by Chester and Horvath (2009). They had investigated the life-cycle energy, greenhouse gas emissions, namely they had taken into account the emissions caused by infrastructure, fuel production, and supply chains. They founded that the total life-cycle energy inputs and greenhouse gas emissions contribute an additional 63% for on road, 155% for rail, and 31% for air systems over vehicle tailpipe operation. Generally speaking, the inventorying criteria air pollutants shows that vehicle non-operational components often dominate total emissions. Life-cycle criteria air pollutant emissions might be 1.2 – 12 (in case of SO_2 emission for the light rail transport even up to 800) times (!) greater than vehicle operation (Chester, Horvath, 2009).

The total energy consumption for passenger – km – travelled (MJ/pkt) and total greenhouse gas emission in CO_2 equivalent (g CO_2e/pkt) calculated for rail transport (Fig. 4.) demonstrate the meaning and major aspects of this approach in impact calculation. As it can be seen, the ratio of operation and total energy consumption and CO_2 equivalent emission of rail transport are small (actually they are the smallest between the transportation means), because the required large infrastructure. Another important aspect calling the attention is the large differences between the rail transport operated in different regions. The CO2e emitted by the Boston light rail rather greater, than emitted by light rail operated in San Francisco, because in California 49 % of electricity is fuel-based generated, while in Massachusetts the same ratio reaches the 82 % (Chester, Horvath, 2009).

3. METHODOLOGY – TOTAL IMPACT PERFORMANCE INDEX

The Department of Aeronautics, naval Architecture and Railway vehicles at the Budapest University of Technology and Economics has a long term research program developing methodologies for determining the environmental impacts and their application (Rohacs, 2002; Rohacs, Simongati, 2007; Rigo et al., 2007; Bicsak, Hornyak and Veress, 2010; Rohacs et al., 2013).

The Research program has resulted to developing a special total performance index and methodology for its calculations. The simplified and unique index evaluating the total impact is given in form of total cost induced by all life cycle effects of transportation system in form of related to unit of transport work (pkm or tkm):

$$TPI = \frac{TLCC}{TLCW} = \frac{TOLCC}{TLCW} + \frac{TILCC}{TLCW} = \qquad (1)$$

where TPI is the total performance index, TOPI is the total operation performance index, TIPI total impact performance index, TLCC/TOLCC/TILCC are the total / total operational / total impact LCC (life cycle cost) and the TLCW is the total life cycle work.

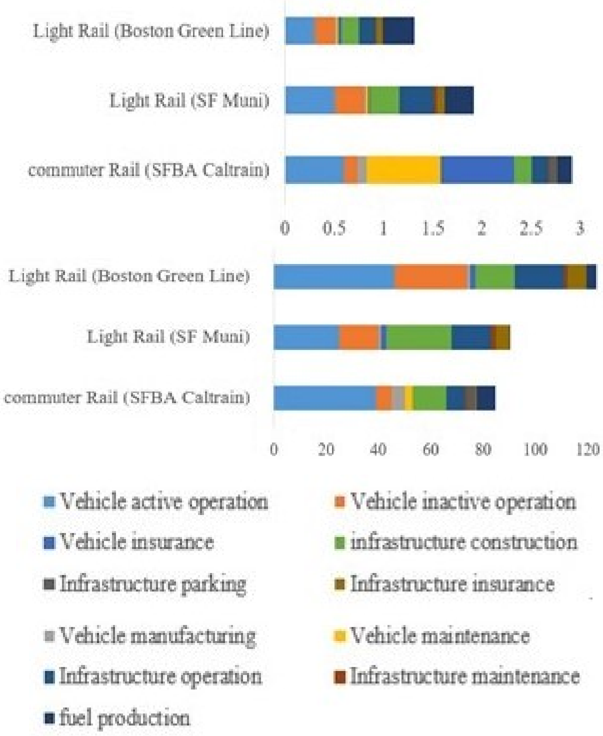

Fig. 4. Total energy consumption (upper figure,in MJ/pkt) and total CO_2e emission (lower figure, g/pkt)) of selected rail

transport (redrawn by use of data from (Chester, Horvath, 2009))

The *TOPI* defining the operational cost of the given vehicle, given transportation mode is well known and applied by owners, operators, service providers. They use it in selecting the aircraft, evaluation of the mixed fleets determining the optimized transportation chain. While, principally, the *TIPI* deals with the externality. This is the index that might be used in impact assessment.

$$TIPI_i = \frac{\sum_{j=1}^{m}\sum_{k=1}^{l}\sum_{q=1}^{r} N_{j,k,q}\, p_{j,k,q}\, I_{j,k,q} \sum_{v=1}^{u} o_{j,k,q,v}\, c_{j,k,q,v}}{TLCW_i} \qquad \forall i \quad ,$$

$$TLCW_i = \sum_{j=1}^{m}\sum_{k=1}^{l}\sum_{q=1}^{r} N_{j,k,q}\, W_{j,k,q} \qquad (3)$$

The *TIPI* summarizes all the impacts:

$$TIPI = \sum_{i=1}^{n} TIPI_i = \frac{\sum_{i=1}^{n} TILCC_i}{TLCW} \;, \qquad (2)$$

where i = 1, 2, … n define the different groups of impacts. According to the transportations systems, i = safety and security; environmental impacts; system peculiarities; system support; use of resources.

The *TIPI* for group of impacts can be determined as sum of the different effects:

where j = 1, 2, … m depicts the subgroups of impacts, while k = 1, 2, … l defines the transport means, q = 1, 2, …, r represents the types or groups of the given transport system, v = 1, 2, …, u identifies the different forms of consequences, N is the number of sub-sub-group elements contributors to the impact, like number of vehicles defined by q, p is the parameter of the given types or group of system elements causes the investigated effects, I is the impact indicator of the given system element, o the outcomes / consequences of impact defined by I or caused by the events, situations associated with the I indicator, c is the conversation coefficient for calculating the (external) cost and W is the work done during the investigated period defined by p. it means, if the p is the parameter of function given in form of average annual unit, then the W should related to the year, too. For example, if the N defines the number of vehicle and p is the annual average running of the vehicles, then the W equals to p.

The p parameter acts as weighting coefficient, or weighting function, too. Of course it depends on goals and level of studies and on the vehicle or system characteristics, parameters defined by the applied indicators. The consequences, o, namely function of consequences take into account the outcomes form the impact characterized by the performance indicator. The consequences might be divided into more forms harmonized with the applied impact indicators. For example, the simple accident may cause damages in (i) vehicle, (ii) transport infrastructure, (iii) buildings, (iv) cultural values, etc. and the human casualty might be classified, too, as fatality, severe and slight injury. The consequences are defined as function of outcomes, because they depend on level of economy and may change during the life cycle frame.

With taking into account the functions of parameters, impact indicators, consequences and conversation coefficients, following to reference [2] the formula (3) can be rewritten in several other forms:

These methods developed for TIPI calculations can be applied to vehicle, equivalent vehicle, fleet, or to the transportation company, transport means, transport sector, etc. Therefore, this methodology developed for calculation of the introduced total impact performance index is structured in hierarchic form and realized in a simplified excel table.

Applying the tool, it must be adapted to the real calculation by (i) definition the goals, (ii) size and (iii) level of investigation, as well as (iv) possible sources of data, (v) economic and (vi) societal conditions.

Principally all the required information might be defined, derived from the existing statistical data, references, research reports (HEATCO, 2006; Bickel et al., 2006; Mailbach, et al., 2008; Chester, Horvath, 2009; van Essen, et al., 2008; IPCC, 2014; Korzhenevych et al., 2014; WRI, 2014; Statistical, 2016). However, the data very sensitive to the real situations including the economy, culture, etc. of the region or country investigated. Therefore, this paper introduces the developing excel table for TIPI calculation and demonstrates it applicability on example e-vehicles. The describing methodology is based on formulas (4).

The developed excel table contains the following columns:

〖TIPI〗 .i = (∑.(j = 1)↑m≡ 〖∑.(k = 1)↑l≡ 〖 〖 ∑.(q = 1)↑r≡N.(j,k,q) f〗 .(p.(j,k,q)) (p.(j,k,q)) 〗 f

- number of rows,
- region or area of investigation (like Europe, or Hungary, or it might be a large or even small company, etc.)
- vode number – completed from the indexes,
- group of impact (GI) (depicted by index “i),
- sub-group of impact (SGI) (identified by index “j”),
- transport means (TM) (indexed by “k”, k = 1, 2, …; namely road, railway, water, and air transport that might be divided into more subgroups, because the road transport contains the city or urban transport highway transport, rural transport, or cars, busses, light and have vehicles, etc., here road transport conventional hybrid and electric passenger cars),
- number of studied elements or merit, i.e. value of the chosen governing parameter,
- applied general parameter describing the aspects or impact calculated,
  - applied parameters, their appellations and values (for each parameter that defines – here – the general average running distance pro year),
  - formula (using for determining the general parameter by use of defined, applied parameters) and calculated values,
- general impact indicator
  - applied indicators, their appellations and values (that defines the general impact),
  - formula (using for determining the general impact indicator) and its calculated value,
- outcomes (determined by use of same methods as it applied to general parameter and general impact indicator calculations),
- cost coefficient (determined by use of same methods as it applied to general parameter and general impact indicator calculations),
- work (two columns: dimension and value),
- results (summarized in 5 columns: $TIPI_{i,j,k,q}$, $TIPI_{i,j,k}$, $TIPI_{i,j}$, $TIPI_{i}$, and TIPI),
- the developing excel table can be used if the parameters, impact indicators, outcomes, etc. will be defined and calculated.

There are two major difference in calculation of the total i8mpact performance index of the conventional car and hybrid or electric cars, namely impact of electric energy generation and impact induced by total using (production, operation, recycling) the electric accumulators. These impacts are considerable depending on mix in electric generation (Comparison, 2011). According to the available information (Ellingsen et al., 2014; Peters et al., 2017, Romare, Dahllöf, 2017) as average 586 MJ energy required for producing the each KWh accumulator capacity. By using this and data on CO_2e emission of electric energy generation, the Figure 5. shows large differences in emission of accumulator production depending on the regions.

Comparing to the production, during recycling of the butteries, the CO_2e emissions are only 1 – 2 kg /Kwh depending on the applied technologies.

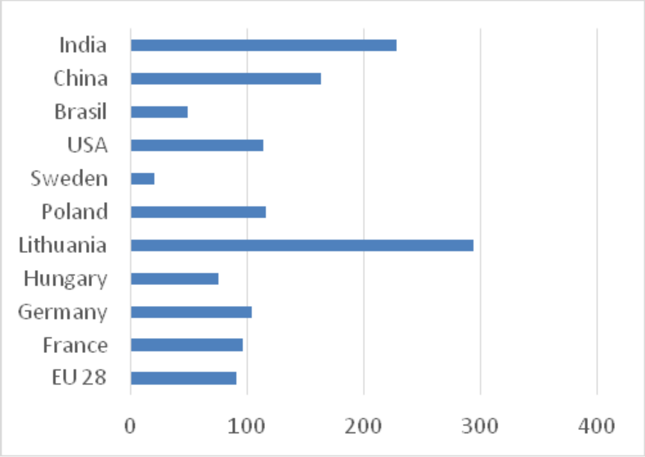

Fig. 5. Batterey production emission (CO_2e - kg/KWh

4. RESULTS AND DISCUSSIONS

There are many references deal with comparison of the environmental impacts of the conventional and electric cars. For instant, a very impressive figure is publish by European Environment Agency (Electric, 2016). As the Fig. 6. demonstrates in case of European average mix of electric energy generation, the use of plug-in hybrid electric and full electric or battery electric vehicles has no too much results. It seems, the introducing the electric vehicles will really reduce the environmental impacts in case of supplying them by electric energy from renewable or clear (nuclear) sources. by the way, the capacity of electric energy generation system should be increased for 10 – 20 % depending on fleet mixing.

The described picture is analog to the figures published by different references, like (Samaras, Meisterling, 2008).

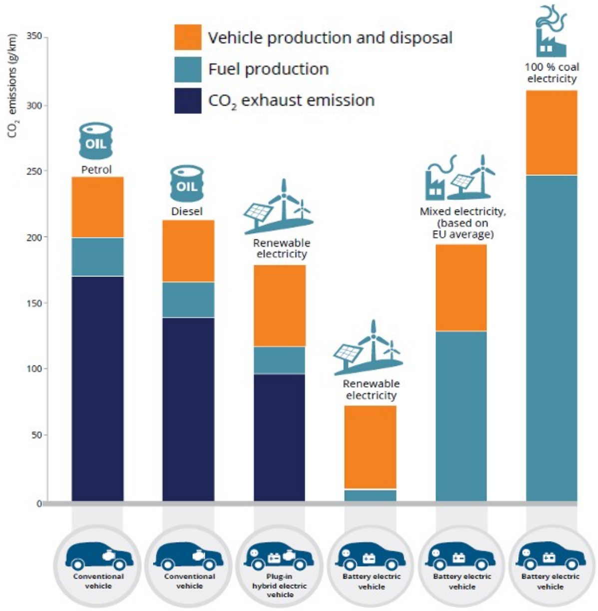

Fig. 6. Life cycle CO_2 emissions for vehicles and fuel types (Electric, 2016)

The described method was applied to calculation and comparison of impacts of average conventional and buttery electric sedan cars operating in US and EU (Fig. 7. 8.).

Some comments to the figures 7, 8.

The mix in energy generations in EU and US rather are rather different, in EU it is "cleaner".

The electric cars are completed by one pocket of battery. Their production requires less energy and the emission during the production considerable less, too. On the other hand, during the life of cars they must be at least one times replaced by new pocket. Therefore, impacts by vehicle maintenance (including the overhauls) are greater in case of electric cars.

The empty mass of electric cars are higher for 150 – 300 kg because the batteries. That means the car dry structure (without battery) should be somewhat higher, and all the effects depending on the mass are higher, too.

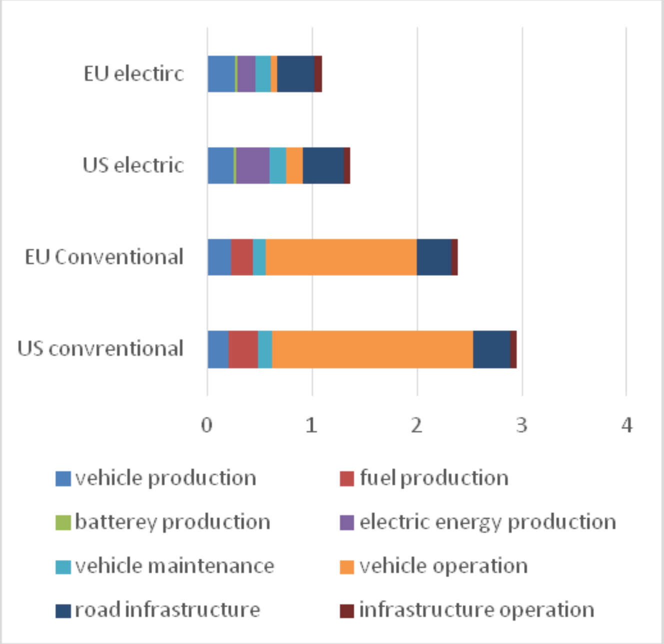

Fig.7. Total energy consumption for average car sedan – MJ/pkm

Some aspects can be identified, but good estimation of their effects are questionable. For example, the electric car weight, power at torque at motion starting are higher, therefor the infrastructure especially road surface must be stronger. So, the impact from infrastructure construction and maintenance should be a bit greater than in case of using the conventional cars.

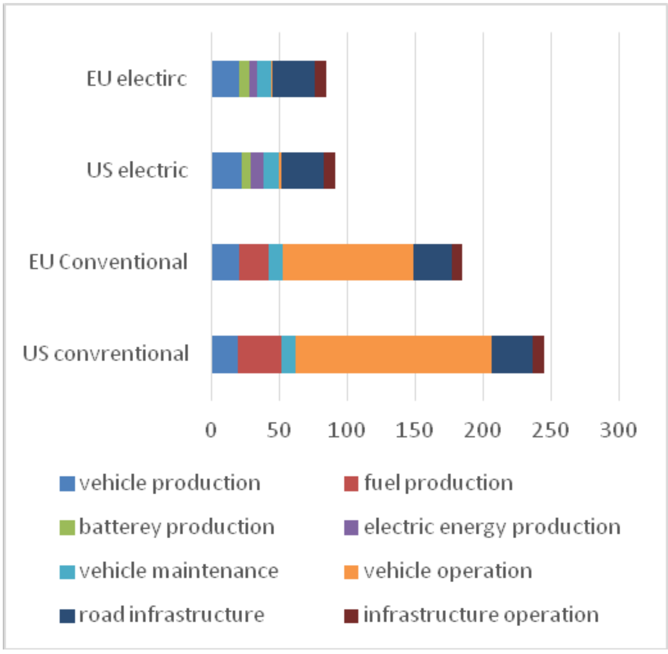

Fig. 8. Total CO2e emission for average car sedan – g/pkm

CONCLUSIONS

Nowadays, the requirements in sustainability and emission reduction becomes to most important problems seek technical, technological and political solutions. One of the most powerful technological solution is replacing the conventional vehicles by hybrid and electric vehicles.

After preliminary and simplified theoretical investigations and short analysis of the available publication, a special methodology was developed. At first the total impact performance impact had been introduced and recommended for evaluation of the total lifecycle impact of vehicles in form of total costs.

There was created a calculation methodology, too, in form of excel table.

The developed method was used for investigation and comparison of total impact of conventional and electric cars operating in US and EU.

The described results show that, the developed methodology is well applicable. The difference in total impacts initiated by operation of conventional and electric vehicles may reach 35 – 50 % depending on sources of electric energy generation.

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