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TOTAL LIFE CYCLE COST AND EMISSION OF ELECTRIC, HYBRID-ELECTRIC AIRCRAFT

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Abstract

The estimated total life cycle costs and emissions are essential indicators in evaluating developments, as developing the electric, hybrid electric aircraft. The total means consider all the impacts associated with developing, producing, and operating the investigated items, including the infrastructure construction, operation, and externalities as caused by health problems. The proposed approach introduces three new specific features in the impact analysis: (i) the impact is evaluated on the air transportation level, (ii) the impact is estimated in their total value (including all the related subsystems and elements, like vehicles, transport infrastructure, transport flow control, externalities), and (iii) proposes a unique index to describing the total impact. The paper describes the general formulas and developing methodology for estimating the total impact, namely in the form of estimation of the total costs and emissions. The estimated total life cycle costs and emissions depend on the applied price policy and mix of energy sources. The differences in total life cycle emissions and costs of fossil fuel burning and electric, hybrid – electric aircraft are about 12 – 27 %, respectively.

Keywords: total life cycle cost, total life cycle emission electric aircraft hybrid-electric aircraft.

1. Introduction

Nowadays, impact analysis is a necessary, meaningful, and integrated part of developing new technologies or solutions. However, impact analysis often deals only with the environmental impact. Global GHG emissions already reached 46 Gt (given in CO2 equivalent) in 2013 [1]. The transportation segment is a significant contributor factor by emitting 14 % of GHG [2]. The global transportation system uses more than 100 EJ (100 Exajoule, i.e., 100·1018 J) energy, 95 % of which comes from petroleum-based fuels, primarily gasoline and diesel. One-third of the vehicles' energy consumption in the transportation system relates to kinetic energy, while 2/3 to heat losses.

Transportation plays a determining role in the economy [3], and its volume increases with GDP growth [4]. The European practice in emissions reduction [5] demonstrates that for the last 15 years only, the transportation sector's emission is greater than the total emission levels of 1990 due to the increasing number of vehicles and their usage.

The transportation-related white papers and vision documents define the future KPIs and goals from an emission reduction perspective. For example, the European White Paper [6] on the future of transportation defines its critical goals for 2050 as the following:

- no more conventionally-fuelled cars in cities.
- 40 % use of sustainable low carbon fuels in aviation; at least 40 % cut in shipping emissions.
- 50% shifting 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.

Generally, the methods of the environmental impact assessment of the vehicles and transportation systems are well developed and with systemically practical tools [7], [8], [9], [10].

On a higher management level related to sustainable development, the effects of environmental impact are defined in the form of externalities. An externality is the cost or benefit of any actions experienced by unrelated third parties [11]. This approach converts all the effects to a cost value. The method is well applicable to investigate particular aspects, like the support of electric [12] and hybrid vehicles [13]. It is also used to study and evaluate an economic sector, such as transportation [14]. The special value of the "Update of the Handbook on external costs of transport" includes (i) the good description of the methodology, (ii) the use of a large number of references and real data sources, and (iii) the use of the safety (external costs caused by accidents) and congestion factors in the list of externalities [15], [16]. For example, in passenger cars, the external costs induced by accidents reach 50 % of all the externalities, excluding congestions. Congestions increase the external cost by 40 %. The complexity of the evaluation and the lack of applicable estimation methods might be characterized by the example of climate change and congestion effects. For passenger cars in Europe, the climate change effects are estimated at 14,4 and 84,1 million EUR / year for the low and high scenarios, respectively. The costs of road congestions are defined as between 98,4 and 161,3 million EUR / year.

As seen, (i) numerous studies and papers are describing the possible translation of the impacts into costs or cost-benefits, while (ii) the results are not so accurate (such as previously cited costs of road congestions).

Another interesting study was published by Chester and Horvath [17]. They investigated the life-cycle energy use and GHG emissions, considering the emissions caused by infrastructure, fuel production, and supply chains. They found that the total life-cycle energy use and GHG emissions contribute 63% for road, 155 % for rail, and 31 % for air transportation systems over the vehicle tailpipe values. The total energy consumption for passenger-km-traveled (MJ/pkt) and total greenhouse gas emission in CO_2 equivalent (g CO_2e/pkt) calculated for rail transport (Fig. 1.) demonstrate the meaning and significant aspects of this approach in impact calculation. 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 of the required extensive infrastructure. Another important aspect of calling the attention is the significant differences between rail transport operated in different regions. The CO_2 emitted by the Boston light rail somewhat more excellent than emitted by light rail operated in San Francisco. In California, 49 % of electricity is fuel-based generated, while in Massachusetts, the same ratio reaches 82 %.

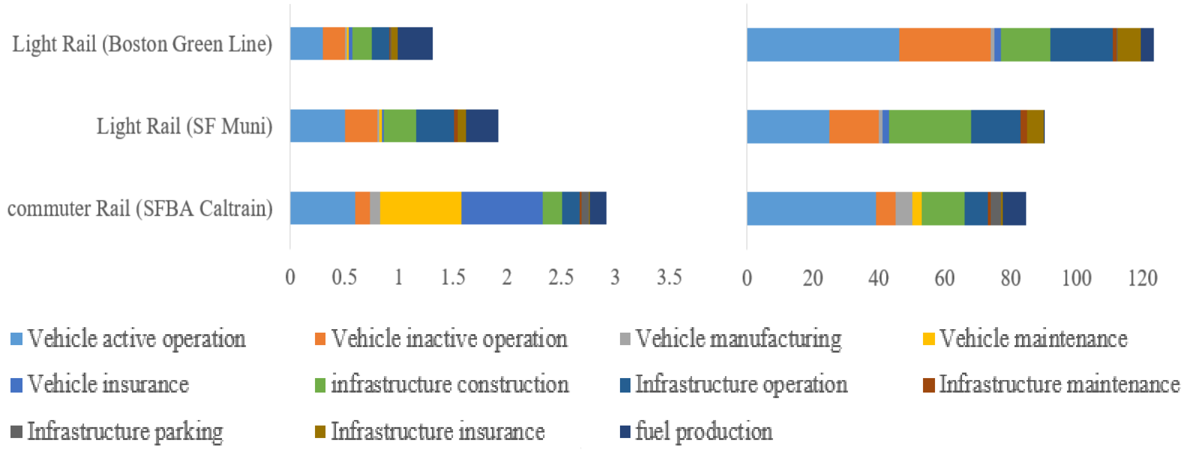

Figure 1 - Total energy consumption (left side, in MJ/pkt) and total CO_2 emission (right side, g/pkt) of selected rail transport [17]

Generally, investigating criteria, air pollutants shows that the non-operational vehicle components often dominate the total emissions. The life-cycle criteria air pollutant emissions might be 1.2 to 12 (in case of SO_2 emission for the light rail transport even up to 800) times higher than those related to vehicle operation. So, the total impact (considering the infrastructure development, energy generation) may "change the game." This point of view may show that even electric cars are not such a clear and green transport system as it looks at first glance.

The authors intend to make a further step and consider all the costs related to the use of transportation systems, such as the costs associated with vehicle production, road infrastructure, or transport flow management. Also, the externalities are included in the total impact evaluation. The total impact must be determined for the life-cycle related to the unit of usages, such as passenger-km or tonne-km.

This conducting study aims to create an index for total impact evaluation and develop a new methodology. This paper generalizes the impact analysis, which introduces three new specific features in impact analysis: (i) the impacts are evaluated on the transportation system level (ii) the impacts are estimated as their total value, including all the related subsystems and elements, like vehicles, transport infrastructure, transport flow control, and (iii) defines a unique index describing the total impact in the form of a total cost function.

2. Methodology

2.1 Total impact assessment

The impact is defined as the effect of a system or concept on a measured variable or other systems. In the case of transportation, this means, for example, the effects of the vehicles, transportation means or transportation systems on society, nature, built environment, or large technical systems (as shown in Fig. 2). The impact can be described in various forms, from direct and short time (such as transport accidents) to indirect and long-term (like health problems caused by climate change) effects. The impact influences nature through direct (damage of trees, forests due to chemical emissions) and indirect effects, such as the changes initiated by climate change. The short, direct impacts might damage the built environment and technical systems (like accidents, for example, airplane crash into electric power station) and long term effects (such as corrosion of the technical systems caused by chemical emissions).

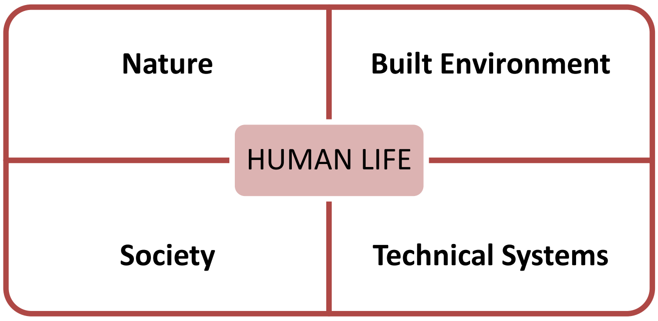

Figure 2 - Tetrahedron of the total impact

The demand for sustainable systems design catalyzed the development of indicator identification, evaluation, and selection methods. Sustainability is characterized by factors, performance, indicators, and indexes [18], [19], [20]; and depends on various factors, including economic and societal considerations. The vehicles, fleets, and transportation means have their characteristics and performance measures (including, for example, the geometrical characteristics, weight, maximum speed). The indicators are variables selected and defined to measure the progress towards an objective, such as sustainable transportation development (see Fig. 3). They are usually expressed in the following framework:

- indicator data – values used in indicators;
- indicator type – nature of data used by the indicator (qualitative or quantitative, absolute or relative);
- indicator system – a process to define the indicators, collect and analyze data and apply the results;
- indicator framework – conceptual structure linking indicators to a theory, purpose, or planning process;
- indicator set – a group of indicators selected to measure comprehensive progress toward goals;
- index (sustainable transportation performance index – STPI) – a group of indicators aggregated into a single value.

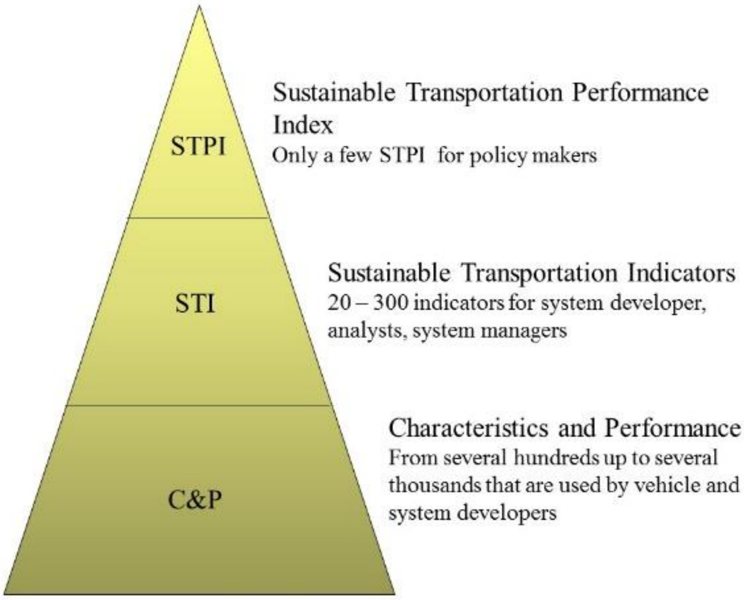

Figure 3 - The pyramid of indicators [19]

Policymakers need objective information on the general impact, including all effects. Therefore, during the last 40 - 60 years, new approaches were introduced and applied in impact analysis. There are three major groups of new methods being developed:

- life-cycle (total life-cycle) effect (emissions, cost) calculations – that is used to analyze and evaluate the impact of the product (in this context, the vehicle);
- calculation of externalities – the external cost of using or operating a given type of product, in this case, transportation means, or a type of vehicles;
- sustainability – that evaluates the use of resources as a long-term effect limiting or reducing future generations' possibilities.

There are numerous high level, sophisticated solutions to calculate life-cycle emissions costs [21], [22], [23], [24], [25], to determine externalities [11], [16], study the interactions of transport externalities and transport economy [26], and interconnections of externalities and environmental assessment [27], [28]. However, there are no well-developed and suitable solutions for evaluating these groups of effects together with the use of a general or integrated performance index.

The authors investigated sustainable transportation and its development from various points of view. The combustion process and its effects were studied using numerical methods [29]. A new, simple dynamic model was suggested to dispersion motorway traffic emissions [30]. A general estimation method was elaborated for transport mode emission evaluation [31]. Sustainable transportation strategic development was defined [32]. The link between climate change and Hungarian road transport was investigated in-depth [33]. Transport efficiency [34], intermodal change [35], and multi-criteria decision-making were investigated for an adequate understanding of the primary transportation systems. A unique, sustainable transport performance index was developed [20], [36]. The role of high-level state management in environment sustainability was studied. The developed competencies were utilized to evaluate the impact of new technologies [37], [38]. Estimating environmental impact reduction in airport areas by introducing new small electric / hybrid aircraft into operation was preliminary investigated [39].

These methods work together with the life-cycle impact estimation methodologies, the available input data [5], and also the additional information on the impact of the infrastructure or specific system elements. For the latter, see, for example, the effect from transport infrastructures [17], life-cycle assessment of pavements [40], or – as a notable example – the toxic effects of brake wear particles [41]. These studies allow a further step in the generalization of the impact evaluation and use the total impact calculation to impact life-cycle cost (TILCC).

2.2 Total impact performance index

The total impact might be classified into five major groups:

- safety and security – inducing the direct and short-time impact, such as accidents;

- environmental impact (chemical emission and noise) – generating direct and indirect medium- and long-term impact on people, nature, and the living world in general;
- system characteristics – system management, management of the transport operation processes that, for example, cause congestions;
- system support – infrastructure, supply chains, upstream and downstream processes that have a considerable effect on the environment and society;
- use of resources – that might be defined as perishable effects, e.g., use of land, minerals sources.

The last group of impacts is related to economic effects that take into account the perishable nature of given resources, such as loss of time when waiting for transport, loss of agricultural or natural land, use of oil, reduction in the value of real estate due to emissions, noise or vibration originating from the transportation systems.

The proposed and introduced new approach generalizes the impact analysis: (i) it takes into account all types of impact (safety, security, environmental impacts, system management, system support, use of resources), and (ii) it summarizes all the impact related to the transportation systems, e.g., the manufacture, operation, and recycling of the vehicles, the required infrastructure, surveillance and control systems, and so on.

The authors recommend the use of a simplified and unique index to evaluate the total impact, in the form of total costs induced by all life-cycle effects of transportation system related to a unit of transportation work (pkm, or tkm):

$$TPI = \frac{TLCC}{TLCW} = \frac{TOLCC}{TLCW} + \frac{TILCC}{TLCW} = TOPI + TIPI, \tag{1}$$

Where, TPI (or STPI) is the total performance index (or sustainable transportation performance index);

TOPI is the total operation performance index,

TIPI is total impact performance index,

TLCC/TOLCC/TILCC are the total/total operational/total impact LCC (life-cycle cost),

TLCW is the total life-cycle work.

The TOPI is evident as the operational cost of a given vehicle in a given transportation mode is well known and is already used by the owners, operators, and service providers. It plays the determining role in the users' selection of the vehicle, transportation mode, and transportation chain. On the other hand, the TIPI deals with the externalities. This is the index that can be used in impact assessment.

The authors aim to introduce a generalized index to evaluate the total impact of transportation systems and compare various transportation means. As TOPI is assumed to be known, the following sections only describe the calculations of TIPI.

The TIPI summarizes all impact:

$$TIPI = \sum_{i=1}^{n} TIPI_i = \frac{\sum_{i=1}^{n} TILCC_i}{TLCW}, \tag{2}$$

where *i = 1, 2, … n* define the different groups of impact. In the case of transportations systems, *i* can be defined as safety and security; environmental impacts; system peculiarities; system support; use of resources.

2.3 Total impact performance index calculation

The individual $TIPI_i$ in Eq. (2) can be expressed as the sum of the different effects:

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

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

Where:

j = 1, 2, … m describes the subgroups of impact,

k = 1, 2, … l defines the transport means,

q = 1, 2, … r represents the types or groups of the given transportation system,

v = 1, 2, …, u identifies the different forms of consequences,

N is the number of sub-group elements contributing to the impact, q, p is the parameter of the given types or groups of system elements that cause the investigated effects,

I is the impact indicator of the given system element

o the outcomes/consequences of the impact defined by I or caused by the events, situations related to the I indicator,

c is the conversion coefficient to assess the (external) cost

W is the work done during the investigated period defined by p.

As it can be seen, Eq. (3) includes many terms. That is intentional, as the TIPI must take into account all the effects. There is the reason while Eq. (3) is defined as a “hierarchical sum”. After a short study of this formula, a systematic model hierarchy might seem to appear that could be supported by using a set of unique tables. However, that approach has a weakness. There are no well-applicable formulas for the calculation of all the effects in cost format. Generally, developed cost models depend on economic, ecologic, and societal conditions.

Let us examine the use of Eq. (3) through an example. Parameter i = 1 means impact group relating to safety and security. In both cases, safety or security events, such as a car accident, may cause delay and repair expenses, but possible additional personal injuries can result in high extra external costs. Of course, the safety and security group presents a broad range of events based on size and outcomes. They must be estimated separately using models appropriate to the events’ class. Therefore, as a first approximation, j = 1 defines the safety aspects, while j = 2 deals with security. The parameter k identifies transportation means, such as road, water transports. The q parameter depicts the type of vehicles, for example, in road transport, a personal car, or even the personal car type depending on the level of TIPI calculation. In this last case, $N_{j,k,q}$ means the number of different cars in the investigated sectors or regions. The p parameter might be given as the annual (or life-cycle) averaged running distance of the given car category in the given regions. Naturally, numerous safety indicators could be used, basically any related to causes of safety problems or risks [49]. In this case, they can be classified as the following:

- external factors not directly related to the vehicle (or transport system) like bad weather conditions;
- risks depending on the vehicle structure (transport systems organization and structure) like maneuvering characteristics;
- technical failures, such as engine failure or increase in fuel consumption due to engine failure;
- failures in control and management, such as failure in traffic control systems;
- errors caused by the human controlling the vehicle;
- errors, failures caused by passengers or transported goods.

Each sub-sub-group may contain several up to 20 indicators. As a first approximation, the indicator, I, can be harmonized with the p parameter. For example, the impact indicator can be defined as a risk of accident-related to the given unit of p parameter, namely the risk of accident-related to unit distance. Depending on the required accuracy and available preliminary information (e.g., statistical data on the operational history), the safety performance indicators, such as failure rates, can be integrated into a few indicators. Even in a simple case, three indicators can be applied, such as accident, complex accident with human injuries, and severe accidents with fatalities. If these three indicators are integrated into one, as a single risk of accidents, then the accident outcomes, such as severe and complex accidents, might be defined by weighting coefficients, o. The coefficient c is the cost related to one unit of outcome o.

The p parameter also plays a weighting function that depends on the vehicle or system characteristics and parameters since the indicators depend on the actual characteristics of the real vehicles, systems, or environment. For example, the accident rate depends on the car's color, the GDP of the country or region, the driving culture, or the driver assisting systems. Therefore, the given car category could be further specified, for example, petrol or diesel engine, being black, white or yellow and so on. The consequences, o, describe the function of consequences that consider the outcomes from the impact characterized by the performance indicator. The consequences might be divided into more categories harmonized with the applied impact indicators. For example, a simple accident might cause damages in (i) the vehicle, (ii) the transport infrastructure, or (iii) the cultural values. The consequences are defined as a function of outcomes, as they depend on the economic level and thus might change over the life-cycle frame.

By taking into account, the functions of parameters, impact indicators, consequences, and conversion coefficients, Equation (3) can be rewritten in several other forms:

$$TIPI_i = \frac{\sum_{j=1}^{m}\sum_{k=1}^{l}\sum_{q=1}^{r} N_{j,k,q} f_{p_{j,k,q}}(p_{j,k,q}) f_{I_{j,k,q}}(I_{j,k,q}) \sum_{v=1}^{u} f_{o_{j,k,q,v}}(o_{j,k,q,v}) f_{c_{j,k,q,v}}(c_{j,k,q,v})}{TLCW_i} \quad \forall i \;, \tag{4a}$$

$$TIPI_i = \frac{\sum_{j=1}^{m}\sum_{k=1}^{l}\sum_{q=1}^{r} N_{j,k,q} f_{p_{j,k,q}}(p_{j,k,q}) \sum_{v=1}^{u} f_I(I_{j,k,q,v}) f_{o_{j,k,q,v}}(o_{j,k,q,v}) f_{c_{j,k,q,v}}(c_{j,k,q,v})}{TLCW_i} \quad \forall i \;, \tag{4b}$$

The developed methodology can be applied, for example, to a given vehicle, equivalent (average) vehicle, fleet, or a transportation company or transport means. Therefore, this methodology is structured in a hierarchic form. For example, as a first approximation, the safety impact of the accidents as external costs can be determined by the following simple formula, applicable for a small taxi company:

$$TIPI_{safety,accident} = \frac{\sum_{i=1}^{n} N_i p_i I_{sa,i} \sum_{j=1}^{k} o_{i,j} c_{i,j}}{\sum_{i=1}^{n} N_i p_i} = \frac{\sum_{i=1}^{n} N_i p_i I_{sa,i}(o_{i,d}c_{i,d} + o_{i,in}c_{i,in} + o_{i,f}c_{i,f})}{\sum_{i=1}^{n} N_i p_i}. \tag{5}$$

In this case:

i = 1, 2, …, n defines the car categories used by the taxi company,

N_i number of cars of the given category,

p_i is the annual average mileage of the i category of cars,

$I_{sa,i}$ safety accident rate (risk) of the given category of the cars,

o_d, o_{in}, o_f are the weighting coefficient, ratio of damage, injure and fatal accidents taking into account the third parties involved in the accidents. Therefore, the sum of the weighting coefficients is more than 1.

c_d, c_{in}, c_f are the cost conversion coefficients of damage, injuries, and fatalities.

As it can be understood, the hierarchy of the methodology allows the use of the created TIPI or (TPI) index on different levels; as individual cars, transport companies, city transport, and on the different segments (evaluating only the safety aspects or only the greenhouse effect).

3. Investigation and evaluation

3.1 Developing an excel tool for index calculation

After an investigation of the possible use of the developed model, an excel table model was created. Excel software was considered a simple, helpful tool for statistical analysis when dealing with extensive data set and was readily available. It is to create a user-friendly tool, which must adapt to the actual calculation by (i) defining the goals, (ii) size and (iii) level of investigation, as well as (iv) possible sources of data, (v) economic and (vi) social conditions.

Principally, all the required information might be defined, derived from the existing statistical data, references, research reports. However, the data susceptible to real situations, including the economy, the culture of the region or country investigated. The excel table developed for TIPI calculation demonstrates its applicability to an example of the TIPIs (TIPIsafety). The describing methodology is based on formulas (4) and (5).

The developed excel table contains the following columns:

- Number of rows,
- Region or area of investigation,
- Code number – completed from the indexes,
- Group of impact (GI) (depicted by index “i”, in this example i = 1 mean safety and security),
- Sub-group of impact (SGI) (identified by index "j", where j = 1 is safety),
- 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 rail transport consists of urban or inter-urban rail, passenger and cargo rail, the road transport contains the city or urban transport, highway transport, rural transport, or cars, buses, light and have vehicles, the water transport can be classified as inland water navigation and marine transport, passengers and cargo ship transport),
- Several studies focused on elements or merit, i.e., the value of the chosen governing parameter (for example, number of cars in the given regions-it is well understood, the number

of elements can usually be derived from the available statistics references).

- Applied general parameter (in this first application, the safety can be characterized by a number of the accident of the investigated cars in defined regions, that can be calculated as the multiplication of the number of cars by general parameter as an average running distance by general impact factor as the average risk of accident)
- Applied parameters, their appellations, and values (for each parameter that defines – here – the general average running distance per 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 the general parameter and general impact indicator calculations),
- Cost coefficient (determined by use of same methods as it applied to the 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, will be defined and calculated. During the adaption of the methodology into the excel table, it was found that it's also possible to add specific indicators/parameters columns. It is user-friendly and can be applied for evaluating the total impacts of transport vehicles, transport companies, regional transport systems, and transport means. Sub-groups of impact for different modes of transport may be analyzed, for example, noise and emissions under environmental impacts.

3.2 Investigation of road transport safety aspects

Several scientific reports presented the investigation of road transport safety and safety aspects. However, most of these researches use the statistical approach that may not identify the required most important parameters and indicators.

For example, the most common indicator for road transport accidents is the number of death in traffic accidents per million km (miles) of driven (Fig. 4. redrawn from [50]. This indicator demonstrates the excellent work done by developers; the safety is increasing. Another representation of the data shows no such a lovely picture (Fig. 4.). So, the new, more dynamic, and safer cars are driven by users not so carefully.

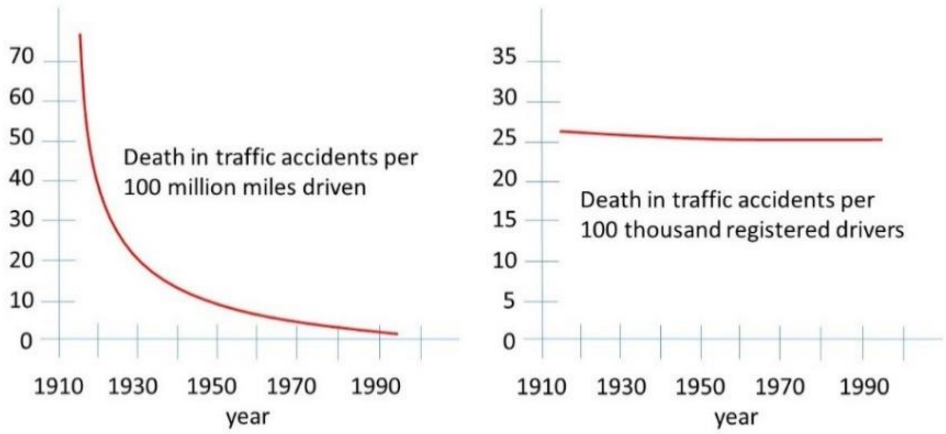

Figure 4 - Changes in road transport safety indicators depending on proportion to different basis

In any case, it seems, the number of driving licenses is the best road traffic safety indicator.

By using the traditional approach, road traffic accidents can be determined as a multiplication of the number of cars (N), average driven distance (p), and safety indicator (I): The driven distance, of course, depends on many different aspects. In this study, the driven distance was determined by using three major parameters: p_1 - travel money budget or personal net income, p_2 - population density, and p_3 – level of urbanization. The risk of accident of passenger cars was calculated by applying the following impact indicators: I_1 - GDP, I_{2a}, I_{2b} - the ratio of highway and city roads in total road system and I_{3a}, I_{3b} - the ratio of young (less than 25 years) and old (more than 70 years old) car drivers. These parameters and impact indicators can be estimated by use of public statistical data [42], [43].

Figure 5. shows several examples explaining the selection of the given parameters and impact indicators. As can be seen, the average passenger-km traveled (pkm) is not so correlated with GDP or expenditure per head-on car transport (including the purchase of vehicles, operational and services costs). Possible correlation of the fatalities (death per 100 million pkm) was investigated with the level of urbanization, road density (total road in km related to the land km2, ratio of motorways length per total road length, ratio of motorways, and main national road length to total road length.

As upper figures in Fig. 5. demonstrates, too, a considerable correlation of average passenger-km (pkm) traveled related to GDP or expenditure was not found. At the same time, a relatively good correlation can be estimated between the fatalities and GDP or expenditure per head-on car transport.

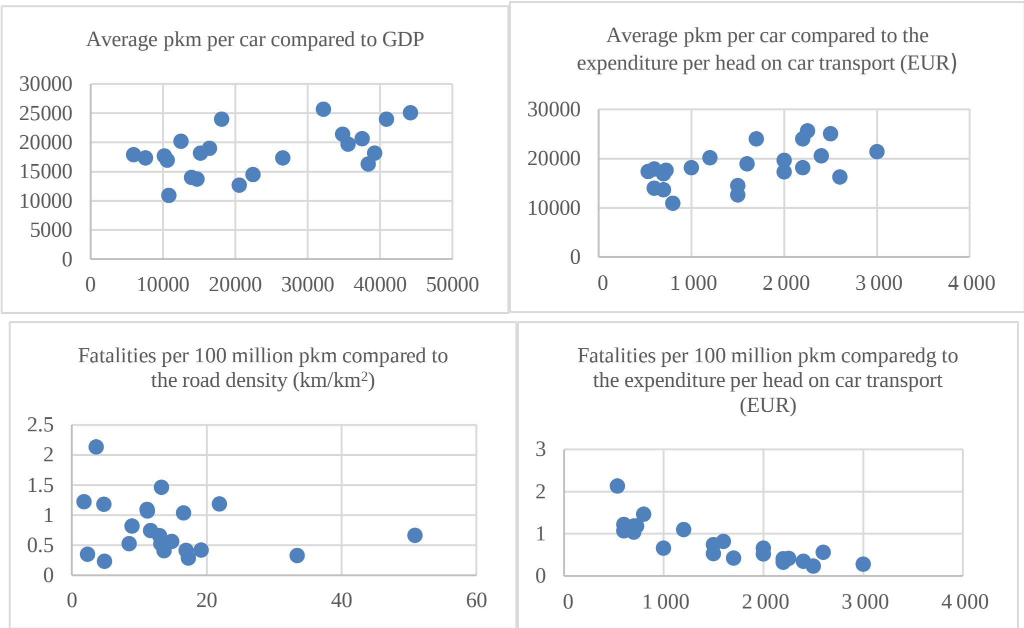

Figure 5 - Several examples of the impact indicator selection studies (figures are based on data published by Rigo [38]

Another example is shown in Fig. 6, which explains why the indicators ratio of young (less than 25 years) and old (more than 70 years old) car drivers were selected in this study. Interestingly, the young and old drivers are involved in more fatal accidents (The number of fatalities per 1000 accidents is slightly higher, only, while the other indicators are more significant).

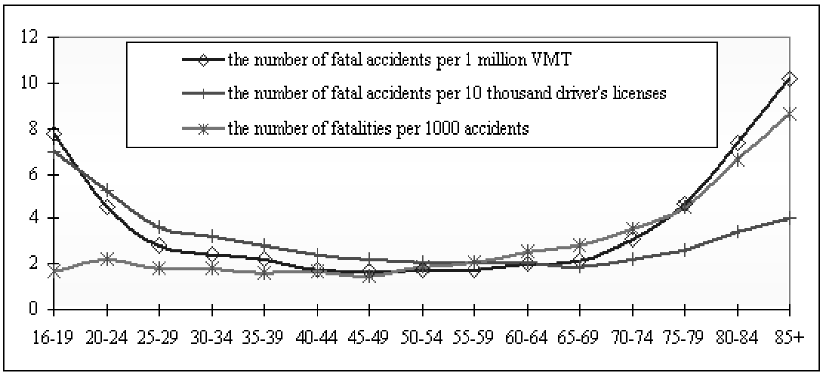

Figure 6 - Fatal accidents according to the age distribution of drivers [39]

Several available reports show no unique and well-applicable methods for estimating the transport safety accident risks and causing external costs - the first problem of predicting them. Even if the country had useful accident statistics, the initial data must be corrected because of the non-reported accident (see Table 1).

Table 1. Correction factors for the unreported number of accident ([44]

	Fatality	Severe Injury	Slight injury	Average injury	Damage only
Car	1.02	1.25	2	1.63	3.5
Motorbike/moped	1.02	1.33	3.2	2.38	6.5
Bicycle	1.02	2.75	8	5.38	18.5
Pedestrian	1.02	1.35	2.4	1.88	4

3.3 Investigation of the accident outcomes

As outcomes of traffic accidents, the consequences might be defined relatively quickly, while calculating the costs associated with these outcomes is a sufficiently more complex challenging problem.

The accident consequences might be classified into three groups:

- human injuries, namely fatality, severe injury, and slight injury,
- damages including the damages in cars, in transport infrastructures, as structural road damages, damages in traffic control systems, losses of products or production capacity (for example, due to damage to the electric supporting system, damage of production supplying materials), and other damages like damages inbuilt (houses, electric lines) and natural environments, cultural heritages,
- societal consequences are the cost of accident investigation, medical costs, administrative and juridical processes' costs, traffic congestions, extra expenditure of relatives and friends of the injured people.

Here some thoughts about the estimation of the costs associated with human injuries.

There is a covenant in references; the injuries are classified as a fatality, severe and slight injuries. Probably the most common and well used [17], [31], [42], [43].

- Fatality: death during the accident or within 30 days after an accident.
- Serious injury: casualties require hospital treatments and have lasting injuries.
- Slight injury: casualties whose injuries do not require hospital treatment or only a short staying in hospitals.
- Damage-only accident: accident without casualties.

The Commission Directive (2014/88/EU) defines the conventional safety indicators (for railway transport) and standard methods of calculating accident costs [45]. For example, it introduces the following indicators to calculate the economic impact of accidents as total in euro and relative (to train-kilometres):

- number of deaths and serious injuries multiplied by the Value of Preventing a Casualty (VPC),
- cost of damages to the environment,
- cost of material damages to rolling stock or infrastructure,
- cost of delays as a consequence of accidents.

The Commission Directive (2014/88/EU) states that "safety authorities shall report the economic impact of significant accidents. The VPC is the value society attributes to the prevention of a casualty and as such shall not form a reference for compensation between parties involved in accidents."

The Commission Directive (2014/88/EU) defines the other relevant indicators and terms. For instance, the "significant damage to stock, track, other installations or environment" means that damage that is equivalent to EUR 150 000 or more, or "extensive disruptions to traffic" means that train services on the main railway line are suspended for six hours or more.

The costs associated with transport accidents might be estimated by the Value of Preventing a Casualty (VPC). The Commission Directive (2014/88/EU) states the VPC is composed of

- value of safety per se: that can be estimated by Willingness to Pay (WTP) values, and
- direct and indirect economic costs are containing the (i) medical and rehabilitation costs, (ii) legal court cost, the cost for police, private crash investigations, the emergency service and administrative costs of insurance, and (iii) production losses: value to society of goods and

services that the person could have produced if the accident had not occurred.

This approach is well similar with the methodology applied by the European international studies [17], [31], [42], [43]. One of the latest excellent cost estimation uses the following costs are related to the accident risk:

- expected cost (of death and injury) due to an accident for the person exposed to risk,
- expected cost for the relatives and friends of the person exposed to risk,
- accident costs for the rest of the society (output loss, material costs, police and medical costs).

These costs can be determined even for the risk of each vehicle and road type with taking into account the traffic flow intensity and internal costs.

The costs related to death as cost for relatives and friends are usually estimated using the Willingness to Pay method. As it can be seen (Table 2), the costs of fatalities that the people willing to pay for avoiding fatal accidents are not harmonized with the net income of people or GDP per capita (Fig. 7).

It has not been identified any economic drivers that might be applied for determining the values of accident fatality avoidance or, as it is called, too, the value of statistical life. On the other hand, the fatality cost reaches the net income of 70 up to 200 years. People are having smaller incomes, willing to pay a larger sum for their life. It is interesting, and the willingness is somewhat more significant in countries with less GDP. It seems the fatality costs are overestimated. The people are willing to pay money that they have not in their hands. Another interesting question is whether the people traveling as usually by train or people using their car are willing to pay the same amount of money to avoid the fatal accident?

Table 2. Some economic drivers and estimated values for casualties avoided [40] data retrieved, 2017) for the year 2010

Country	*GDP per capita (USD)*	*Net in-come (USD)*	*Gini in-dex*	*Fatality (EUR)*	*Severe injury (EUR)*	*Slight in-jury (EUR)*
Latvia	10743	8779	35,27	1034000	140000	10000
Estonia	14062	10683	32,16	1163000	155800	11200
Slovakia	16062	10897	24,94	1593000	219700	15700
Slovenia	22942	21572	35,79	1989000	258300	18900
Greece	25851	21382	34,48	1518000	198400	15100
Spain	29956	27052	26,81	1913000	237800	17900
Italy	33761	27809	34,41	1916000	246200	18800
France	39186	33892	33,78	2070000	289200	21600
Germany	40164	32754	31,14	2220000	307100	24800
Belgium	43000	38879	28,53	2178000	330400	21300
Finland	43864	36693	27,74	2213000	294300	22000
Austria	44916	36416	30,25	2395000	327000	25800
Ireland	46019	46917	32,3	2412000	305600	23300
Nether-lands	46623	42711	28,73	2388000	316400	25500

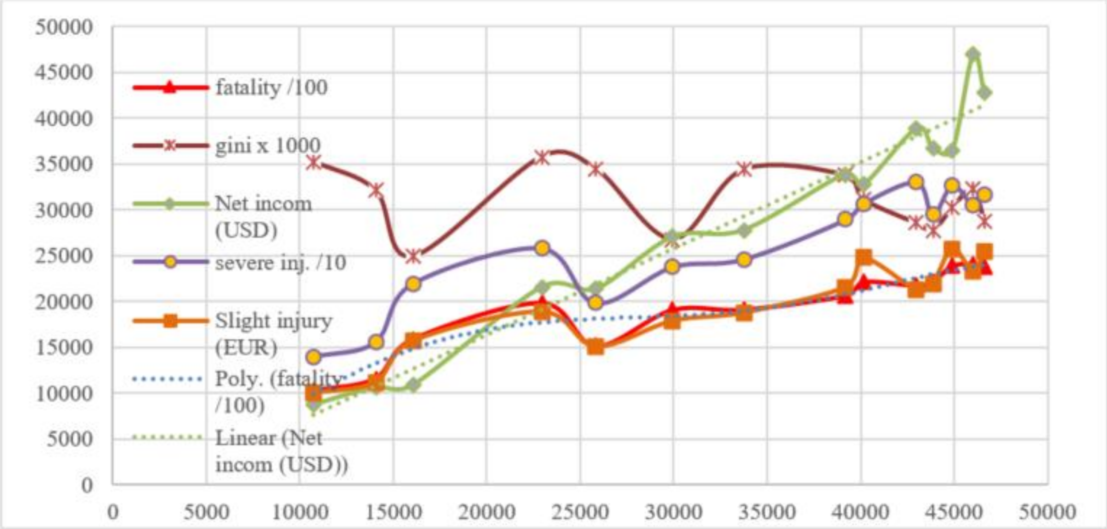

Figure 7 - Some economic factors and cost of accident casualties as a function of GDP

In any case, the fatality costs estimated for different countries are correlated with the GDP [33].

This study used the adapted costs that were determined from Table 2. The values were increased proportionally with GDP growth and corrected by the dynamics of changes in net incomes using the model from.

The developed methodology is adapted to calculate the TIPI safety impact of accidents as external costs, calculating at first, the accident risk using 2006-2015 data (of derailments of a train, level crossing accidents, accidents to person by rolling stock in motion, collisions excluding at level-crossing accidents, fires). Secondly, dependent on the number of persons involved classifying between injuries and fatal accidents (Fig. 8) The cost conversion was estimated from the willingness to pay for a country.

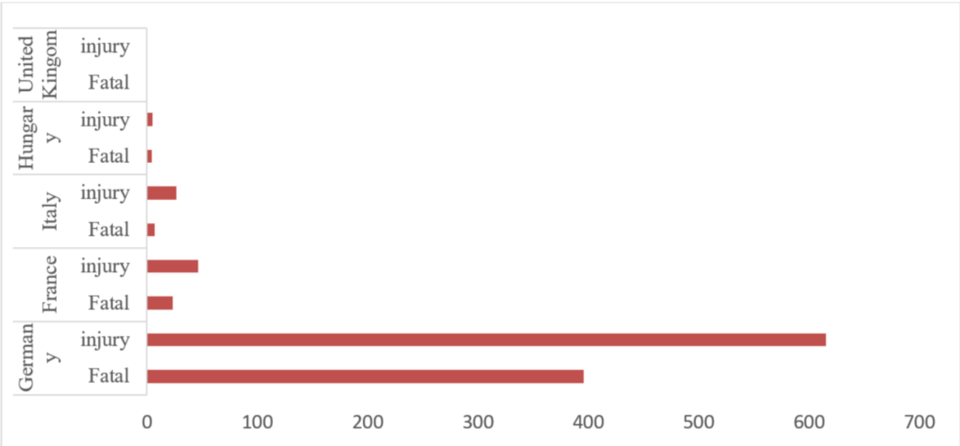

Figure 8 - TIPI for safety aspect (rail accidents) for selected regions

Another example investigated is the congestion cost. This cost is calculated as a cost related to the unit of vehicle km (Fig. 9). The cost intensively depends on the regions, urban road and population density, vehicle types, capacities of the road systems. The applied methodologies are based on the capacity ratio (number of vehicles at the given time related to the road's maximum capacity) and time value. The models might be used for calculating the cost of people traveling by car. This method seems too complex.

The congestion cost depends on the type of roads, traffic intensity, weather conditions, and the calculation required for detailed modelling. This study has applied a more straightforward method, calculating the yearly delay in traveling because of the congestions. There were an estimated increase in travel times for each day of traveling and the number of appearing congestion because of the overcapacity traffic. The value of congestion was determined by using time estimated for congestions multiplied by the number of travellers in the vehicle and the value of time and divided by the annual vehicle running distance.

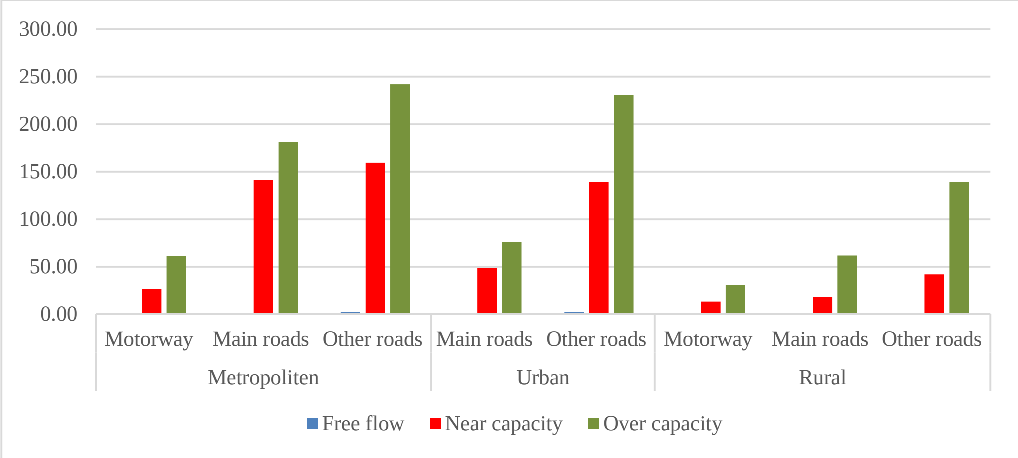

Figure 9 - Congestion cost (EUR ct/vkm)

There were identified two incompletions during developing the methodology described here: the congestion on the accident risks [46] and delay in travel because of the accidents or congestions initiated by accidents. Of course, the effect on the accident risk might be taken into account in generally applied risks. The delays due to the accidents are recommended to include in the accident consequences. It might be calculated as the number of people and cars affected by the traffic flow reduction and delays multiple by increased travel time and people value of time and cars' operating costs (separately). The calculation must be adapted to the investigations' objectives and the possible way of selecting or determining the required inputs. For instance, the Hungary accident statistics for 2014 (Table 3) demonstrate that road transport is a leading contributor to transport external safety costs. However, in rail accidents, 135 cases were caused by collisions with persons.

Table 3. Accident data for Hungary in 2014 [47]

Transport means	Road	Rail	Water	Air
number of accidents with human injures	15847	180	3	30
number of persons injured in accident	20124	94	0	27
number of persons killed in accidents	626	108	3	4

According to the Hungarian statistics [47], the accident ratio with damage only (without people injury) about 8 % for rail, around 14 % for water, and reaches 40 – 45 % for road passenger car transport.

Some interesting results are shown in Figs. 10 and 11.

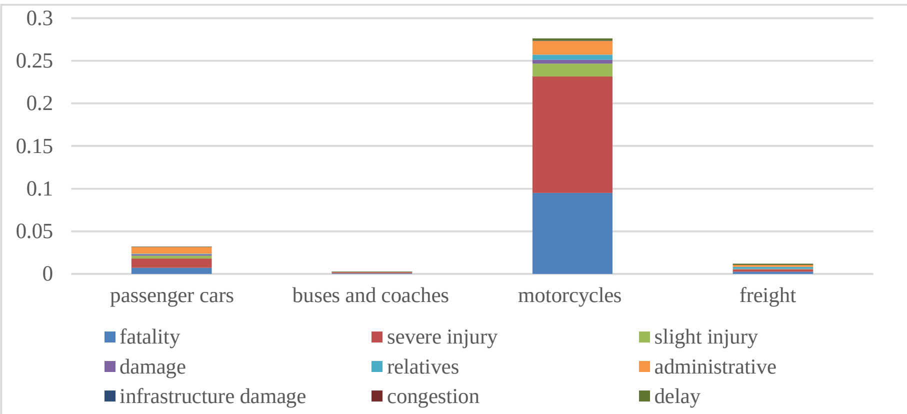

Figure 10 - Safety total impact performance index calculated for average European road transport in 2014 (in EUR /pkm and EUR/ 1tkm for freight transport)

Figure 10 shows that motorcycle vehicles have the most significant external costs induced by the safety factors because of the considerable risk for fatal accidents and severe injury. Another exciting fact is that the congestion, which the researchers include in the safety area, generates the determining parts of external costs. (Actually, the high value of congestion calculated for freight transport is "great" because it is related to the 1 tkm that equals about 10 pkm). Notably, the authors' position is that the congestion must be considered in sub-system transport support because it depends on flow management rather than safety factors. Of course, the increases in accident risk because the congestion must be calculated as part of accident risks.

Figure 11 demonstrates how the developing method can be applied in comparison to the regional transportation systems. The relatively significant difference in Hungarian and European safety TIPI can be explained by (i) higher accident risks in Hungary depending on the GDP (when GDP is smaller, the risk is more significant [45], (ii) lower social cost of fatalities and severe injury) (iii) lower value of time (about 2.5 times less), (iv) less congestion marginal external costs, (v) less time and cost of administrative works induced by accidents and (vi) relatively older fleets of vehicles in Hungary.

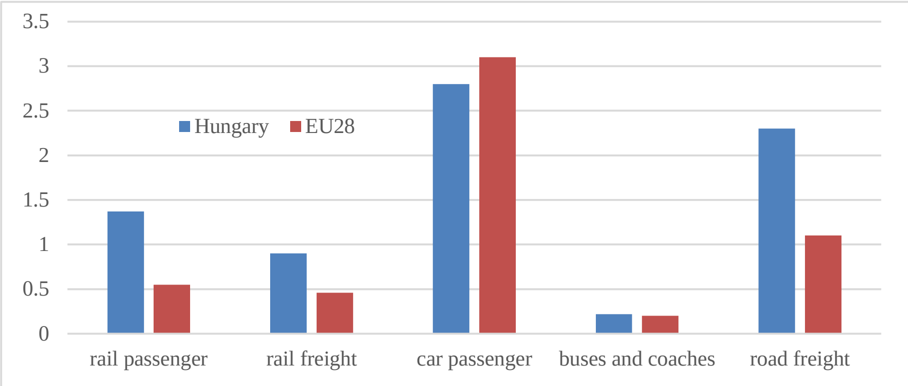

Figure 11 - Safety total impacts performance index: external costs generated by the safety impacts in 2014 (the costs induced by congestions are excluded) (EUR ct/pkm and EUR ct/0.1tkm)

The figures show the results for 2014, which can be realized on a broader form, calculating for pasts years then for a predicted time (when the inputs must be selected from the technology foresight and transport forecasts). Finally, the index must be calculated as a weighted average for the transport depending on the vehicle type and age composition.

3.4 Comparison of Total Lifecycle Emission of Aircraft with Different Propulsion Systems

The typical aviation fuel applied to the piston engine is the AVGAS 100, the heating value of which equals 43.5 MJ. It is equivalent to 12.08 kWh. The aircraft piston engine has an energy efficiency coefficient of about 30 % [48], and the propeller system efficiency is around 85 % [49]. So the energy total energy efficiency of an aircraft with a piston engine propeller system is 25.65 %. At the same time, the energy efficiency of the electric power system nearly 100 %, but considering the losses in the energy supply chain, this energy efficiency might be defined as 95 % in total. So, burning the 1 liter aviation fuel equals to using the 0.2565 x 12.083 / 0.95 = 3.26 kWh. (or burning 1 kg fuel equals 2.6 kWh.) That means the GHG, namely CO_2e emission of aircraft with a piston engine and an electric propulsion system equal to 2 [50] and 1,467 kg for a 1-liter fuel equivalent.

Another intriguing effect is caused by accumulator banks having considerable weights compared to the vehicle dry weight. The battery banks' performance is increasing very rapidly. In 2009 the energy density was about 120 Wh/kg [51], for 2015 had reached the level 260 Wh/kg [52]. The existing cars still use a battery of about 180 – 200 Wh/h energy density. At the same time, the electric cars are completed by a battery of 80 – 100 kWh instead of 24 – 36 kWh used in early electric cars. This energy is already enough for 600 – 700 km driving.

The vehicle weight breakdown shows that the engine weight reduces by 60 – 75 % by replacing it with electromotors. However, the mass of battery banks increases aircraft weight by 100 – 400 % depending on the acceptance of the considerable reduction in range.

For example, by replacing the piston engine with an electric motor in a moderate size 4 seater aircraft analogic to the Cessna 172N, the mass breakdown may change, as shown in Figure 12. As it can be seen, the take-off mass increases by 70 %, which increased the airframe mass to nearly 40 %. The initial empty mass increases from 510 kg up to 1360 kg because the battery bank has about 800 kg, while the electric motor has about 120 kg – less mass. If it still seems acceptable, the aircraft performance must be checked, too. The initial piston engine has 120 kW power, and the aircraft may use more than 200 l of fuel during flying to 1290 km. Instead of this, the 800 kg battery mass may store only 200 kWh energy, allowing flying for 360 km distance, only, at the same cruise speed.

These preliminary calculations demonstrate that the technology does not allow to make acceptable and affordable electric aircraft. Therefore, hybrid aircraft development should be in focus [53], [54].

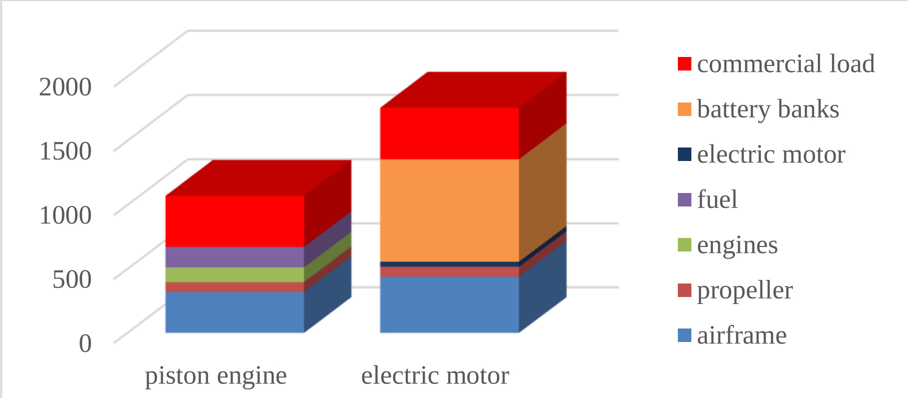

Figure 12 - Take-off mass breakdown of the aircraft with conventional and with the full electric propulsion system.

There are two significant differences in the calculation of the total impact performance index of the aircraft with conventional (piston engine), hybrid and electric propulsion systems, namely impact of used electric energy instead of the fuel that is caused by electric energy generation and impact-induced by total using (production, operation, recycling) the electric accumulators. These impacts are considered depending on the mix in an electric generation. According to the available information [22], [23], [24], an average of 586 MJ energy is required for producing each KWh accumulator capacity. Using this and data on CO2e emission of electric energy generation, Figure 13 shows significant differences in emission of accumulator production depending on the regions. In recycling the batteries, the CO2e emissions are only 1 – 2 kg /kWh depending on the applied technologies.

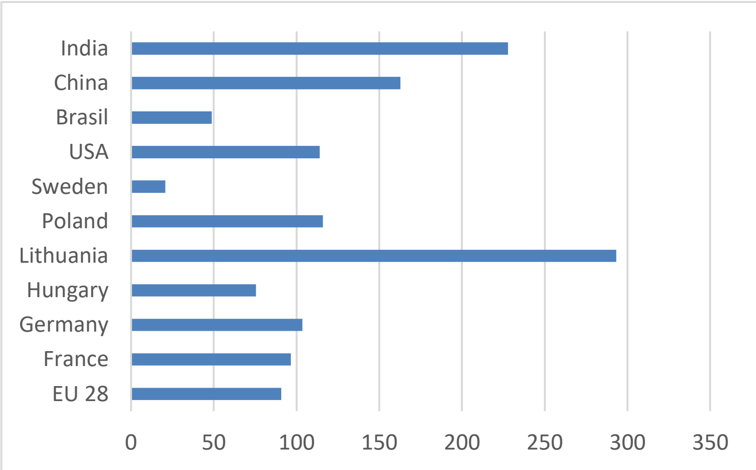

Figure 13 - Battery production emission (CO_2 - kg/kWh)

In further investigation, the average European mix in electric energy generation is used.

Nowadays, greenhouse gas emissions might be accounted as one of the essential emission factors; therefore, it is used to compare aircraft with a different propulsion system. There were defined five different 4 – seater aircraft. The first one is the conventional small aircraft with a piston engine. Two aircraft are equipped with hybrid propulsion systems, and the electric sub-systems allow flying for 15 and 45 minutes in full electric modes. Another two are full electric aircraft having accumulator banks of 200 and 400 kWh.

Figure 14 contains the mass breakdown of the investigated aircraft that had been determined from the initial aircraft analogical to the well-used Cessna 172N. The hybrid aircraft have the same flight performance as the initial aircraft. Because of the battery, their take-off weights increased by 13.5 and 28.5 %. The battery masses were calculated from power density equals 250 Wh/kg. The masses of sub-systems were determined from the weight balance of the developed aircraft. For example, the airframe mass is increasing with increasing the mass of power plants. The full-electric aircraft cannot have flight performance analogic to the initial aircraft. The take-off masses were increased by 61.5 and 142.5 % in using 200 and 400 kWh capacities, respectively, and the range was reduced by 72.3 and 60 %, respectively.

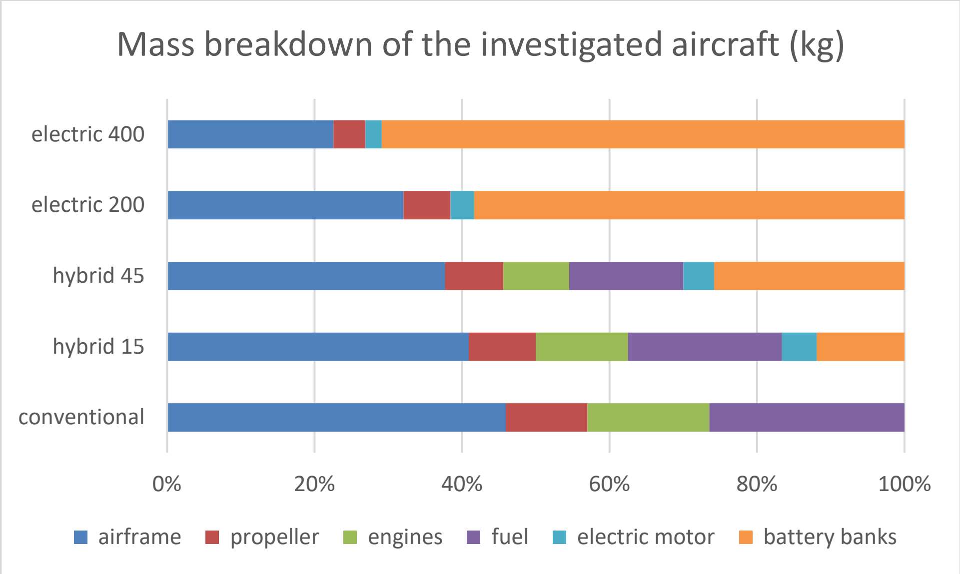

Figure 14 - Mass breakdown of the investigated aircraft (kg)

So, as seen, the full electric aircraft cannot be realized while the power density will not be a minimum of four times greater. Even in such cases, the range will considerably reduce.

The total life cycle CO_2 emission of the investigated aircraft is shown in Fig. 15.

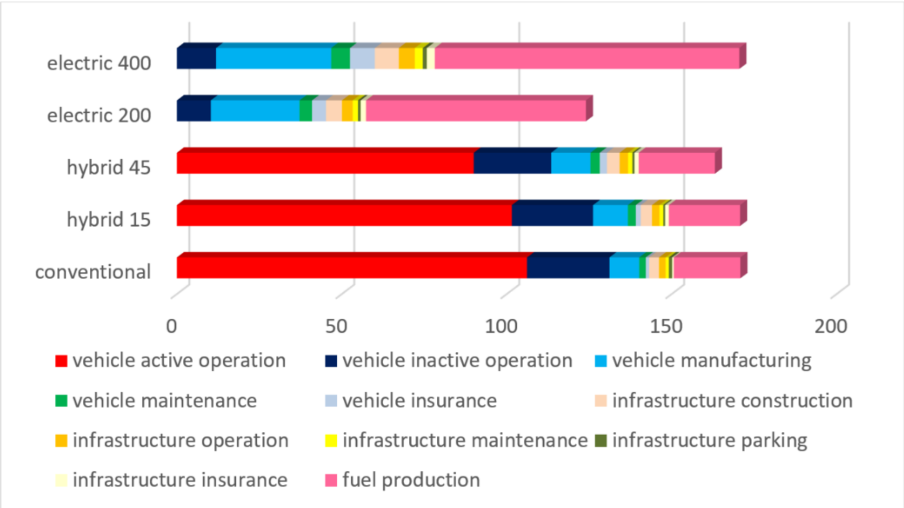

Figure 15 - The greenhouse emissions of the investigated aircraft (g/pkm)

Figure 15 demonstrates that greenhouse emissions might be considerably reduced if radically cutting the range (electric aircraft 200). Hybrid aircraft have a small reduction in greenhouse emissions, but it may reduce the environmental impact in airport regions.

4. Conclusion

Nowadays, in the era of climate change, sustainability is a significant objective of future vehicles and transportation systems' development methods. Many international and national projects estimate the impact of various transportation means, different elements of the transport systems on the environment, economy, and societies. This paper takes a further step and recommends using a total impact performance index as the total life-cycle external costs related to the vehicles' unit of transportation work. This way, it combines the total life-cycle emission evaluation methods and transport costing methods. This study also defines the methodology to calculate the suggested new total performance index. This method can perform comparative studies of transportation means, different transportation networks, emerging new solutions, and new technologies (such as electric vehicles). The developing methodology is tested for concept validation calculations in the safety aspect of road and rail transport. The methodology is applied to the five different small aircraft: one conventional, two aircraft with hybrid propulsion systems, and two aircraft with full-electric power systems. The analysis has resulted in conclusions: (i) full electric aircraft might be developed with radical decreasing in range of aircraft, while (ii) the hybrid aircraft may have minor environmental impact generally, and (iii) their most significant advance is the radical catting the environmental impacts (emission) in airport regions. The further works may include creating a series of models, significantly cost models for the different impacts. The available models today have many uncertainties and even unclear dependence on economic and societal factors.

7. Copyright Statement

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