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MODEL OF SURFACE VEHICLE FLEET ENERGY CONSUMPTION SUITABLE FOR CLIMATE-ENERGY POLICY ASSESSMENT

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Abstract

The first approximation of energy consumption for surface vehicles equipped with standard, hybridized or electric powertrains. Determination of a single averaged operation mode, defined by vehicle mass (including cargo and energy storage system), velocity and recuperative (harvestable) energy term. Energy transformation efficiency estimated from regression models of internal combustion engine, electric motor, generator and battery representations, fuel, fuel tank and accumulator data together with vehicle data chosen for different categories of surface transport vehicles. The available statistical data from transport and fuel business authorities used for model calibration. The results subjected to several cross-determination checks to increase the accuracy of prediction.

The outputs of the model suitable for assessment of alternative powertrain vehicle deployment in different future development scenarios, considering the current fulfillment and future development of vehicle regulations and standards together with climate-energy plans and policies.

1. INTRODUCTION

The increased demands on vehicle powertrain efficiency and the reduction of green-house gas (GHG) emissions call for setting strategies of future surface transport vehicle fleet development, supported by higher-level regulations. These strategies should be based on quantitative estimates of the potential for energy consumption and GHG emission reduction. Today, wishes and qualitative ideas of politicians and misinformed public substitute often this analysis. An example is the unambiguous

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support of e-mobility from the level of European Commission, which is not accepted in such a unique way in other parts of developed world (USA, Japan, etc.).

Moreover, many European regulations have not been harmonized yet. That is why, e.g., the regulations for future road vehicle parameters, applied at manufacturers, assume zero WTW emissions of e-mobiles, while the regulations for future renewable fuel share, as in [12], prefer biofuels of the second generation and suppress hydrogen usage in vehicle powertrains, not speaking about neglecting the significant meaning of nuclear energy for future sustainable electric energy demands of transport.

The paper deals with a computational tool for the estimate of energy and green-house gas emissions of the fleet of surface transport (road and rail) vehicles - [1], which is based on national statistical data and internal powertrain and vehicle databases of the authors' department together with data collected from vehicle inspection stations (e.g., operation distance read from odometers) by Center for Transport Research in Brno - [2]. The tool can be used for prediction of future fleet development scenarios, taking the fleet share of different vehicle types into account.

2. ENERGY CONSUMPTION BY A VEHICLE FLEET

The tool takes into account powertrain efficiency, vehicle traction resistance parameters, additional mass due to alternative powertrain components including energy storage device ("tank"), relative use of vehicle passenger or cargo capacity and emission factors depending on fuel composition and externalities of energy vector production (in TTW and WTT senses). The analytical models will be described now, followed by calibration methods from statistical data.

2.1 Basic Vehicle Energy Consumption

The well-known longitudinal dynamics of a vehicle yields the tractive force at engine/e-motor clutch in the simplest form for known total mass of a vehicle

$$F=\left(\frac{m_{tot}g\mu\cos\alpha+m_{tot}\left(g\sin\alpha+A\right)}{1000\eta_{trans}P_{ref}}+\frac{\rho S_x c_x}{2000\eta_{trans}P_{ref}}w^2\right)P_{ref}=\left(K'+K''w^2\right)1000P_{ref} \quad (1)$$

The rolling resistance component contains $\cos\alpha$, which is close to 1 and can be omitted. The Eq. (1) includes $m_{tot}\left(g\sin\alpha+A\right)$, i.e., the term for reduced acceleration and slope, which represents after the calibration of representative speed w the recuperation potential of a vehicle. The comments to this term are mentioned below. The Eq. (1) has been transformed to the form with coefficients K' *and* K'' and prepared for non-dimensional, i.e., normalized power P_{rel} relation. Then,

$$P=Fw=P_{rel}1000P_{nom}=\left(K'w+K''w^3\right)1000P_{ref} \quad (2)$$

$$P_{rel}=\frac{P}{1000P_{ref}}=\left(K'w+K''w^3\right)$$

Road energy consumption is

$$E\left[kWh/100km\right]=\frac{F\left[N\right]}{36\eta_{PM}}=F\left(1+L\right) \tag{3}$$

in which L means TTW relative losses of a prime mover, determined by regression formula - [7]

$$L=\begin{bmatrix} A_O+A_1\left(\dfrac{P_{rel}}{\omega_{rel}}\right)+A_2\left(\dfrac{P_{rel}}{\omega_{rel}}\right)^y+A_3\left(\omega_{rel}\right)+ \\ +A_4\left(\omega_{rel}\right)^x+A_5\left(P_{rel}\right)+A_6\left(P_{rel}\right)^z \end{bmatrix}\frac{\omega_{rel}^{x_g}}{P_{rel}} \tag{4}$$

whereas prime mover, i.e., engine or e-motor efficiency is

$$\eta_{PM}=\frac{1}{1+L} \tag{5}$$

and representative engine speed is determined (mostly reduced) from maximum torque speed for an ICE or nominal speed as $n_{M,ref}$ for electric machines

$$\omega_{rel}=K_w\frac{n_{M,\max}}{n_{M,ref}}=const. \tag{6}$$

This procedure yields the basic efficiency of a prime mover, which is valid for a single energy source (“fuel”) and a single prime mover. More complicated cases of dual-fuel or hybrid powertrains will be described below.

If E is known from statistical data, the set of equations (1) - (5) creates single equation for unknown representative vehicle speed. It can be solved by Newton-Raphson method, if vehicle speed derivative of E is used

$$w_{i+1}=w_i-\frac{E\left(w_i\right)-E_{cal}}{\dfrac{dE\left(w_i\right)}{dw}} \tag{7}$$

$$\frac{dE}{dw}=\frac{1}{36}\left(\left(1+L\right)\frac{dF}{dw}+F\frac{dL}{dP}\frac{dP}{dw}\right)$$

with

$$\frac{dP}{dw}=\left(K'+3K''w^2\right)1000P_{ref} \tag{8}$$

$$\frac{dF}{dw}=2000K''wP_{ref}$$

$$\frac{dL}{dP}=\frac{dL}{dP_{rel}}\frac{dP_{rel}}{dP}=\frac{1}{1000P_{ref}}\left\{\begin{matrix} \left[\left(\dfrac{A_1}{\omega_{rel}}\right)+A_5+A_2y\left(\dfrac{1}{\omega_{rel}}\right)^yP_{rel}^{y-1}+A_6z\left(P_{rel}\right)^{z-1}\right]\dfrac{\omega_{rel}^{x_g}}{P_{rel}}+ \\ -\begin{bmatrix} A_O+A_1\left(\dfrac{P_{rel}}{\omega_{rel}}\right)+A_2\left(\dfrac{P_{rel}}{\omega_{rel}}\right)^y+A_3\left(\omega_{rel}\right)+ \\ +A_4\left(\omega_{rel}\right)^x+A_5\left(P_{rel}\right)+A_6\left(P_{rel}\right)^z \end{bmatrix}\dfrac{\omega_{rel}^{x_g}}{P_{rel}^2} \end{matrix}\right\}$$

The dependence of E on vehicle speed features local minimum, i.e., the best compromise between too low engine power and efficiency, followed by low tractive resistance on one hand or on the other hand high engine power with high efficiency, but too high vehicle resistance at high vehicle speed – *Figure 1*.

The position of absolute energy consumption minimum can be found by setting the first derivative of E according to Eq. (7) to zero and by solving the resulting equation numerically, using Newton-Raphson method, again. This information is used for finding right-hand side velocity root for calibration energy consumption. The velocity root of Eq. (7) is sought for in interval between vehicle speed for minimum energy consumption and its maximum value, determined for power at prime mover pre-defined shaft speed (6) and maximum torque. Moreover, the information of optimum speed for any vehicle is worthwhile, since it shows the relevance of chosen powertrain for a vehicle of given size. The second derivative, needed for finding absolute minimum by Newton-Raphson method, is

$$\frac{d^2E}{dw^2}=\frac{1}{36}\left((1+L)\frac{d^2F}{dw^2}+2\frac{dL}{dP}\frac{dP}{dw}\frac{dF}{dw}+F\frac{d^2L}{dP^2}\left(\frac{dP}{dw}\right)^2+F\frac{dL}{dP}\frac{d^2P}{dw^2}\right) \tag{9}$$

$$\frac{d^2P}{dw^2}=6000K'''wP_{ref}$$

$$\frac{d^2F}{dw^2}=2000K''P_{ref}$$

$$\frac{d^2L}{dP^2}=\frac{d}{dP_{rel}}\left(\frac{dL}{dP_{rel}}\right)\frac{dP_{rel}}{dP}=\left(\frac{1}{1000P_{nom}}\right)^2\left\{\begin{array}{l}\left[A_2y(y-1)\left(\frac{1}{\omega_{rel}}\right)^y P_{rel}^{y-2}+A_6z(z-1)(P_{rel})^{z-2}\right]\frac{\omega_{rel}^{x_g}}{P_{rel}}+\\ -2\left[\left(\frac{A_1}{\omega_{rel}}\right)+A_5+A_2y\left(\frac{1}{\omega_{rel}}\right)^y P_{rel}^{y-1}+A_6z(P_{rel})^{z-1}\right]\frac{\omega_{rel}^{x_g}}{P_{rel}^2}\\ +2\left[\begin{array}{l}A_0+A_1\left(\frac{P_{rel}}{\omega_{rel}}\right)+A_2\left(\frac{P_{rel}}{\omega_{rel}}\right)^y+A_3(\omega_{rel})+\\ +A_4(\omega_{rel})^x+A_5(P_{rel})+A_6(P_{rel})^z\end{array}\right]\frac{\omega_{rel}^{x_g}}{P_{rel}^3}\end{array}\right\}$$

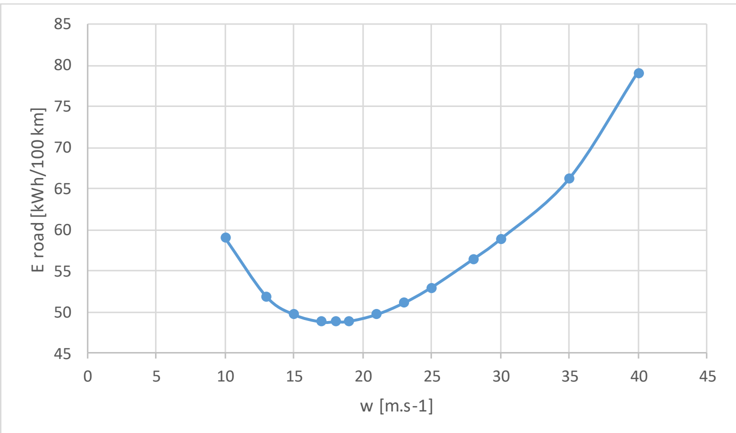

***Figure 1**: Energy consumption for a small class car with a gasoline, spark ignition engine in dependence of vehicle speed*

Absolute minima of vehicle energy consumption may be used as not yet known calibration data, using efficiency increasing multiplier from experience, frequently close to 1.3.

Let's assume given total mass of a vehicle. There are still two additional unknowns in relation between vehicle speed and given energy consumption: the slope and reduced acceleration term in Eq. (1) and transmission ratio coefficient in Eq. (6). The latter can be estimated as stated above and checked by achieved primary mover efficiency in comparison to its total optimum. The former term influences representative vehicle speed and could be determined, if the information on operation time of a vehicle is collected from vehicle internal records. It is not the current case, although it would be worthwhile to determine the averaged operational speed.

Currently, the value of slope and inertial term can be estimated comparing the representative speed to class average from experience. If the term is chosen inside a realistic range (total virtual slope value inside 0.5-2% with *A=0* according to the use of vehicle – higher for city operation and light vehicles, lower for long-distance operation), it may change the representative speed by 10-15 km/h, which is not critical for energy consumption prediction except for hybrid vehicles. In this case, the term represents all accelerations (increasing kinetic energy) and slopes (increasing potential energy) with the possibility of recuperation to energy storage device, being available after natural replacing part of tractive energy by direct recuperation at wheels (coasting down, etc.). The direct wheel power coverage by coasting-down is consumed in internal power loop for any vehicle powertrain. The additional slope and acceleration term in the resistance force relation thus shows the unused potential and kinetic energies, which can be recuperated or (in standard powertrains) dissipated via forced braking.

2.2 Dual Fuel and Hybrid Vehicle Energy Consumption

The treatment of more complicated powertrain cases increases the number of free calibration parameters and internal dependences among model parameters, which are not constant more.

Potential and kinetic energies available for recuperation can be found from the value of slope and acceleration term, mentioned above. The traction resistance (*R*) and kinetic+potential energy components of energy consumption are

$$E=\frac{m_{tot}\left(g\sin\alpha+A\right)+\left(m_{tot}g\mu+\frac{\rho S_x c_x}{2}w^2\right)}{36\,\eta_{PM}\eta_{trans}}=\frac{F_{kin+pot}+F_R}{36\,\eta_{PM}\eta_{trans}}=\frac{E_{kin+pot}}{\eta_{PM}\eta_{trans}}+E_R \qquad (10)$$

If transformed into relative values

$$E_{kin+pot,rel}=\frac{E_{kin+pot}}{E}=\frac{\left(E-E_R\right)\eta_{PM}\eta_T}{E}=\frac{m_{tot}\left(g\sin\alpha+A\right)}{m_{tot}g\mu+m_{tot}\left(g\sin\alpha+A\right)+\frac{\rho S_x c_x}{2}w^2}\eta_{PM}\eta_{trans} \qquad (11)$$

If recuperated into accumulator, the generator (*eM*) and charging (*CH*) efficiencies have to be respected. Moreover, assuming the same transmission efficiencies for active driving and recuperation (suitable for the first approximation), it yields

$$E_{rec,rel} = E_{kin+pot,rel}\eta_{trans}\eta_{eM}\eta_{CH} \approx \frac{m_{tot}\left(g\sin\alpha + A\right)}{m_{tot}g\mu + m_{tot}\left(g\sin\alpha + A\right) + \frac{\rho S_x c_x}{2}w^2}\eta_{PM}\eta_{trans}^2\eta_{eM}\eta_{CH} \quad (12)$$

The numerical results for specific vehicles are realistic in comparison to detailed simulations [8], reaching 10-15% at cars, 20-25% for city buses and more than 30% for rail vehicles. It indirectly reflects realistic calibration coefficients, as well.

Primary mover PM efficiency is linked to the primary energy source:

- ICE efficiency, if an engine has been used in full hybrids for battery charging,
- e-motor efficiency (including power control devices), if direct grid connection is available (e.g., tram),
- e-motor and discharging efficiencies, if battery is used.
- moreover, the externally charged energy to a battery from a grid has to be reduced by charging efficiency (unlike re-fueling without losses), which keeps TTW data at more realistic level.

Generator efficiency has to be considered in any case of recuperative charging. Charging efficiency is up to 100% if recuperated energy is being returned directly to a grid, otherwise battery charging efficiency is respected. The negative recuperated energy value is added to the total energy consumption, as applied in Eq. (13) below.

The code developed enables to assess dual-fuel operation of a single engine/e-motor powertrain (the latter case can be e-motor with electric energy supply directly from grid – a trolley-bus – or from batteries). In the case of hybrid vehicles, there are two powertrain movers and two sources of energy (ICE fuel and electric one, if charged to a battery from grid, typically with RE HEV or PHJEV). The relative use of primary source *x* depends on the share of external delivery of energy. In the case of ICE fuel, used as the only source, and recuperative charging of battery *x=1*. In the cases of twin sources, the share of both of them is defined according to experience. The resulting averaged energy consumption including contribution of recuperation for any electric vehicle is

$$E = \left(xE_1 + \left(1-x\right)E_2\right)\left(1 - E_{rec,rel}\right) = \frac{E_1 s_1 + E_2 s_2}{s_1 + s_2} \quad (13)$$

Since the vehicle speed is determined separately for the both shares of different energy sources, the resulting speeds are weighted by time operated with a certain source of energy, using expansion of the second relation in Eq. (13).

$$E\left(w_1 t_1 + w_2 t_2\right) = E_1 w_1 t_1 + E_2 w_2 t_2 \quad (14)$$

which yields

$$\bar{w} = \frac{s}{t} = \frac{w_1 t_1 + w_2 t_2}{t_1 + t_2} = \frac{w_1 \frac{t_1}{t_2} + w_2}{\frac{t_1}{t_2} + 1} = \frac{w_1 \frac{E_2 - E}{E - E_1} + w_2}{\frac{E_2 - E}{E - E_1} + 1} \quad (15)$$

Up to now, the pre-determined total vehicle mass has been assumed as constant. It is not right more for alternative powertrains with higher mass (starting with diesel engine replacing a gasoline one and continuing to hybrid powertrains with electric motor added to a standard car powertrain) and – more important – with heavier storage facilities. Typical mass/power or mass/stored energy ratios are used to assess the added mass. In the case of storage facilities, the operation range of a vehicle is set as an additional input, and the energy consumption from Eqs. (13) and (3)-(6) is applied. The iterative procedure is required to find the result, since the mass of vehicle induces motion resistance.

In the case of commercial vehicles, the regression assignment of cargo load to different curb or total weights of vans and trucks has been determined - *Figure 2*. The number of passengers to different public transport devices was assigned to classes of them, as well. Moreover, the factors of the use of cargo capacity and maximum number of passengers helped in the calibration, creating another degree of freedom for those vehicles. The use of possible cargo load is close to 50%, because the load for going back from the mission is not too frequently available. The suburban buses are often not used more than to 25% of their capacity, too.

Similar procedures have been applied for rail vehicles.

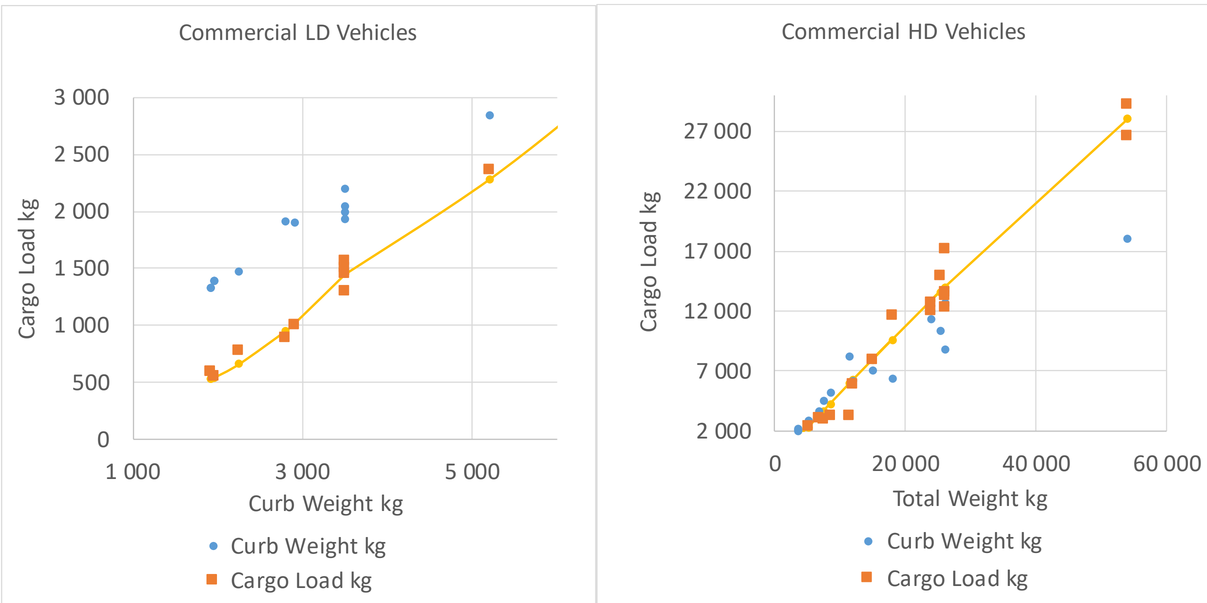

Figure 2: *Cargo load representation for LD and HD vans and trucks*

The energy consumption assessment is completed by additional factors, respecting efficiency deterioration due to

- transient modes of operation (especially for PMs and storage devices),

- compromise matching to more fuels in the case of bi-fuel or dual-fuel operation,
- shifting with clutch or torque converter and possibility of keeping a primary mover close to optimum efficiency (in dependence of number of gears up to smooth torque/speed control in electric transmission),
- PM and storage facility cooling (including HVAC heat pump cooling of batteries during fast charging or due to solar radiation overheating)
- additional energy consumptions by HVAC, electronic control units, lighting, power-steering or braking, infotainment, etc.
- additional influence of alternative powertrains with auxiliaries (e.g., heat exchangers) or exhaust gas aftertreatment on vehicle mass or drag – typical for more complicated hybrid vehicle lay-outs, organic Rankine cycle uses, etc.

These corrections can create a part of already mentioned PM and transmission efficiencies, but it is more transparent to define them explicitly.

The information on the yearly operated distance of sub-fleets of different size and of different design types of vehicles together with information on fleet fuel consumption - [2] - is used for the calibration of mean speed of a vehicle class representative - [3], done for standard produced vehicles in past and based on technical inspection stations data. Vehicle classes create sub-fleets. Moreover, energy recuperation potential of a class representative vehicle type is determined, which is important for vehicles with energy accumulation facilities, especially for not yet inspected vehicles. The results, which moreover yield the mean powertrain efficiency, are cross-checked, using several indirect methods, comparing:

- the predicted maximum speed of a vehicle class representative to the averaged statistical data of the class,
- integrated predicted fuel consumption to the statistics of fuel consumption (distinguished by fuel type - [4]),
- predicted public passenger transport capacity and freight capacity to statistical data,
- powertrain efficiency achieved with representative transmission ratio between vehicle and engine/e-motor speed,
- the both speeds achievable with different powertrains or fuels in the case of dual-fuel, bi-fuel or hybrid vehicles.

Calibrated data create a database for assessing different scenarios of fleet development in future. In such a way, regulatory activities at national level might be optimized and the discussions at EU level may be based on quantitative knowledge.

3. EXAMPLES OF RESULTS

The calibration of operation representative values was done for complete data of Czech registered vehicles from the year 2016. Electric vehicle features with insufficient available data were added from numerous optimizations, done in past for this type of vehicles - [8], [9], [10] or [11] – and based on real vehicle parameters.

The procedure described above has been processed for different current and future passenger cars (PC), commercial light-duty (LD) vans and heavy-duty (HD) trucks for both city and long-haul freight operation, for city buses including electric buses and trolley-buses and long-distance coaches and for examples of rail vehicles (passenger and express or goods locomotive trains, trainsets for suburban regional or fast intercity service and shunting locomotives). Different realistic possibilities of powertrains and energy sources were taken into account.

Some examples of PC energy consumption and green-house gas emissions per distance are presented in *Figure 3* and *Figure 4*. The energy sources are assigned for better orientation to the groups of vehicles with increasing mass.

The differences in energy consumption depend mainly on combustion system. Gasoline SI engines are not yet turbocharged for mini, small and lower medium classes, unlike all diesel engines. SICE for both gasoline and gas fuels are therefore less economic than diesels. Dual-fuel operation with CNG or even hydrogen can be found there together with simple compromised bi-fuel layouts. Electric BEV or REHEV and PHEV are optically energy saving, which is caused by TTW data of energy consumption and possibilities of energy recuperation. PEMFC powertrains are comparable to diesel ones, if realistic total efficiency of a PEMFC stack with accessories is used.

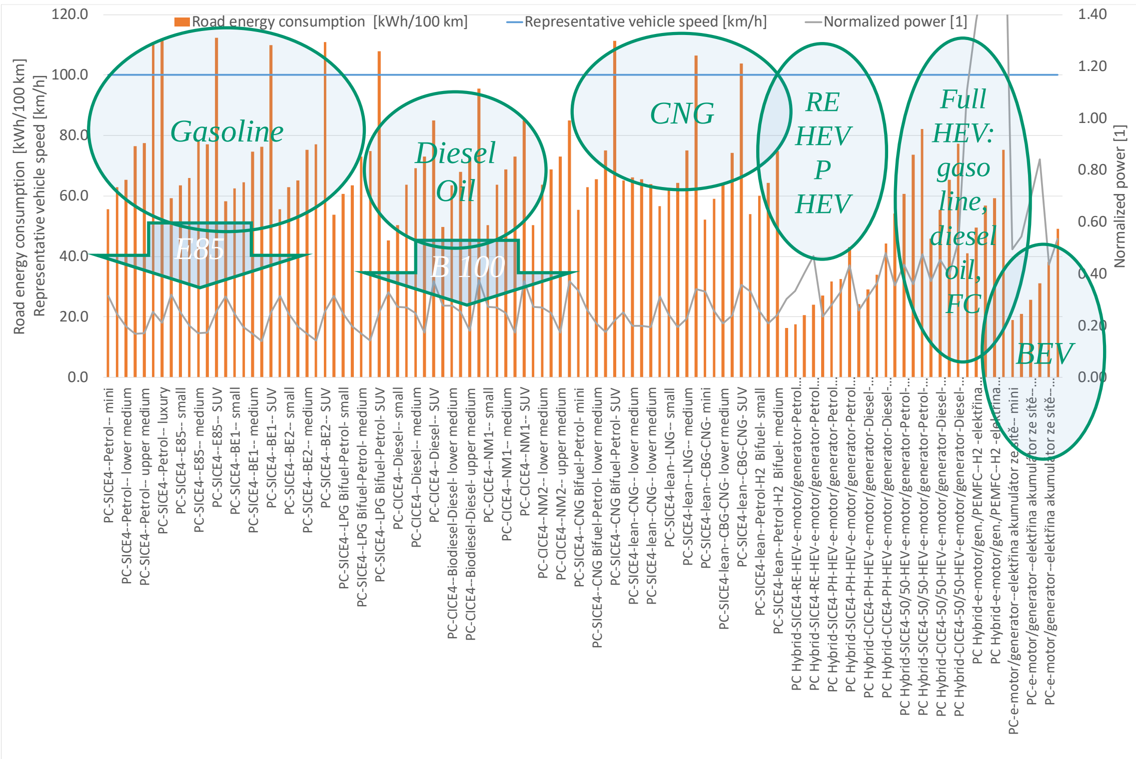

***Figure 3**: Energy consumption for different lay-outs of passenger cars with groups for different fuels and sub-groups of different powertrain features (system of combustion), arranged according to the size of a vehicle*

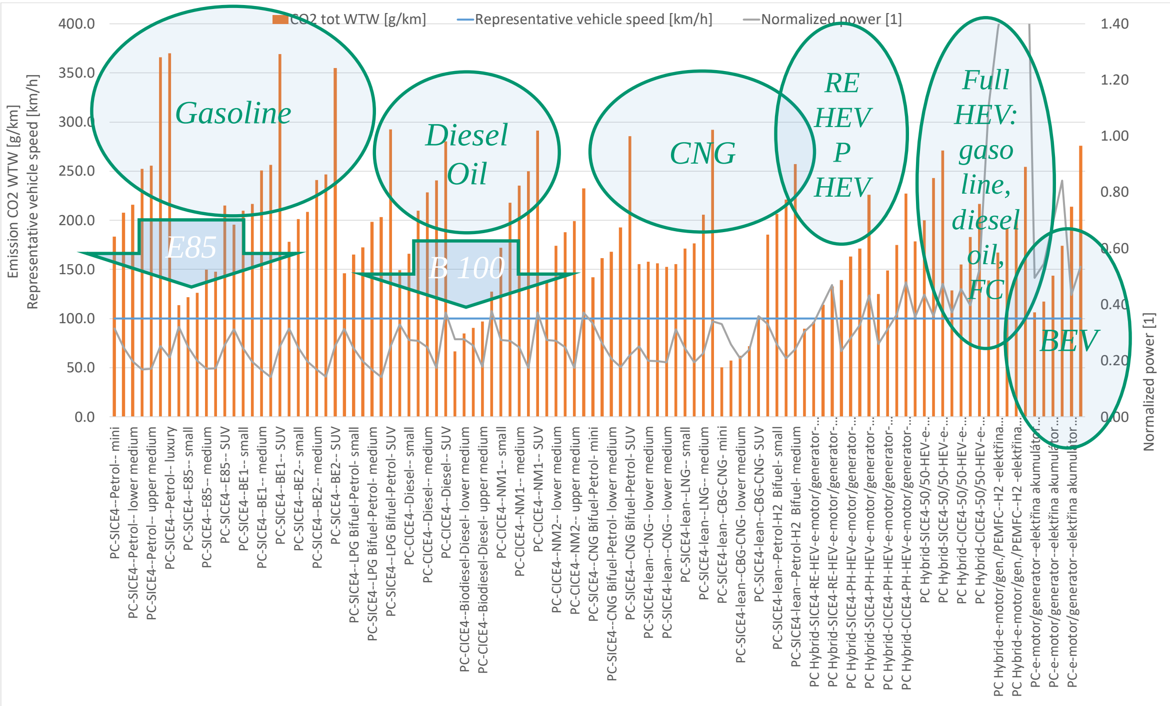

Figure 4: *Green-house gas emissions for different lay-outs of passenger cars with groups from Figure 3*

Figure 5*: Specific energy consumption for different lay-outs of heavy duty commercial city vehicles with groups for different fuels and sub-groups of different powertrain features (system of combustion), arranged according to the size of a vehicle*

Figure 6: *Specific green-house gas emissions for different lay-outs of city heavy duty commercial vehicles with groups from Figure 5*

Different picture occurs if green-house WTW emissions are taken into account, using current Czech or German energy mix (approx. 500 g CO_2/kWh). Electric vehicles are still more efficient in green-house gas emissions, but it is valid for low class mass and low range only. The data from European regulation on renewable fuels for transport RED II - [12] – were used for described assessment. Hydrogen is not very efficient using the current mix of fossil fuel and electricity mix for its production, but its energy accumulation potential has to be taken into account for future.

The examples for HD city vehicles can be found in *Figure 5* and *Figure 6*. Gasoline is not attractive at all in this domain, but except for diesel engines CNG ones can bring a solution. In those cases, lean mixture diesel-like combustion was assumed with appropriate impact on robust engine design and high compression ratio, which increases the efficiency of CNG SICE close to diesel engines. Short trips for city deliveries make BEV or RE/PHEV quite competitive. The impact on energy consumption is expressed by specific energy consumption, which does not handicap larger vehicles. The same is valid for specific green-house emissions, whereas all comments to passenger cars are valid. As expected, larger vehicles are more efficient, if loaded up to the same relative level of cargo possible limit. All the other examples of long-haul HD and buses have similar results, but the presentation would go over the size of the current paper.

4. CONCLUSION

The computational code has been developed, which enables the calibrated prediction of energy consumption and green-house gas emissions for different numbers, operation distances and layouts of road or rail vehicles.

The historical calibration has been done combining different public or sectorial data sources for distance operated by vehicles of a specific class and fuel/energy consumption compared to integral data of fuel consumption at a national level.

In results, the code links

- vehicle parameters assigned to different mass and size classes (the authors' database),
- powertrain powers and vehicle sizes (the authors' database),
- powertrain efficiencies (the authors' database) including energy recuperation, if available,
- emission factors, dependent on fuel properties or electricity production energy mix (RED II or internal documents from [1]),
- time of vehicle presence at road, assessing the traffic intensity,
- capacity of different modes of transport, enabling optimization of transport mode range whereas keeping the same transported capacity.

The code is being used for governmental decisions on transport control and fiscal/funding support of it together with the elaboration and realization of climatic-energy plans of the Czech Republic.

LIST OF ABBREVIATIONS AND ACRONYMS

BEV	battery electric vehicle
CICE	compression-ignition internal combustion engine
CNG	compressed natural gas
HD	heavy-duty commercial truck
H2	hydrogen
ICE	internal combustion engine
LD	light-duty commercial vehicle (a delivery van up to 3.5 t)
LNG	liquefied natural gas
LPG	liquefied petroleum gas
PC	passenger car
PEMFC	proton-exchange membrane fuel cell
PHEV	plug-in hybrid electric vehicle
REHEV	range-extender electric vehicle
SICE	spark-ignition internal combustion engine
TTW	tank (vehicle storage device inlet)-to-wheel
WTW	well-to-wheel
A	reduced acceleration; regression coefficient
E	road specific energy consumption [kWh/100 km]
F	tractive force [N]
g	gravity acceleration [$m.s^{-2}$]

K'	rolling and slope/acceleration factor for vehicle normalized resistance power
K''	air drag factor for vehicle normalized resistance power
L	relative loss power of a primary mover
m	vehicle mass [kg]
n	primary mover speed [min^{-1}]
P	power [kW]
s	path, distance [m]
$S_x c_x$	drag coefficient and drag area of a vehicle
t	time
w	vehicle speed [$m.s^{-1}$]
X	relative use of energy source (fuel) 1
x	regression exponent
x_g	regression exponent
y	regression exponent
z	regression exponent
α	slope of a road [rad]
μ	rolling resistance coefficient
ρ	air density
ω	primary mover angular speed [$rad.s^{-1}$]

Subscripts

cal	calibration value
CH	charging
DCH	discharging
i	iteration step ***i***
kin	kinetic
M,max	maximum WOT torque of a primary mover
M,ref	torque at reference power
PM	prime mover of powertrain (ICE, e-motor or both of them)
pot	potential
R	traction resistance
rec	recuperated
ref	reference (nominal)
rel	relative (normalized to reference value)
tot	total (curb+cargo in the case of vehicle mass)
trans	transmission efficiency powertrain clutch-wheels
WOT	wide-open throttle
1	energy source 1
2	energy source 2

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