UDC 629.3: 629.47.083: 629.047.25
DOI: 10.33868/0365-8392-2024-1-278-18-27

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CARS EFFICIENCY DURING WORLDWIDE HARMONIZED LIGHT-DUTY VEHICLES TEST CYCLES

Abstract. *Automobiles have attained a prominent position in the modern world, exerting a significant influence on various aspects of our lives. However, they also bring about negative effects, particularly in terms of ecology and safety. The ecological impact of automobiles stems from the energy sources they rely on and the pollution generated during their production. In this paper, our focus is on examining the efficiency of different energy sources used in automobiles, particularly how they have evolved over the past 10-15 years.*

During this time frame, there has been a notable shift in the energy sources employed by automobiles, with a departure from fossil fuels in favor of greener alternatives like electrical batteries. This transition not only addresses environmental concerns but has also prompted changes in car design, resulting in enhanced overall efficiency.

To assess the efficiency of modern cars, we base our study on the Worldwide Harmonized Light-Duty Vehicles Test Cycles (WLTC), like most modern cycle. The WLTC is a standardized testing procedure that measures various parameters related to vehicle performance and energy consumption. By applying the energy-work theorem, our research aims to compare the efficiency of cars equipped with internal combustion engines, plug-in hybrids, and fully electric systems. Which gives all basics requested data to analyze different types of cars.

Our analysis specifically focuses on the top 10 cars in the Ukrainian market for the year 2021. By examining their efficiency, we can gain valuable insights into the current state of automobile technology and evaluate how different energy sources perform in terms of energy consumption and overall vehicle efficiency

Keywords: *WLTP, energy consumption, vehicle energy losses, vehicle efficiency, energy per WLTC, car fuel efficiency, car battery usage efficiency.*

Introduction

In recent years, the automotive industry has made significant advancements in improving the efficiency of modern cars. With the increasing concern for environmental sustainability and the rising cost of fuel, car manufacturers have been compelled to develop innovative technologies and design strategies to enhance fuel efficiency and reduce carbon emissions. This article aims to explore the various factors that contribute to the improved efficiency of modern cars, including advancements in engine technology, lightweight materials, aerodynamics, hybridization, and electrification. By understanding these factors, consumers can make more informed decisions when purchasing their next vehicle, taking into account both their personal preferences and the environmental impact of their choice.

The coefficient of efficiency refers to the measure of how efficiently a power plant and drive train converts input energy into useful output energy. Here is some information about the coefficient of efficiency for modern battery electric, hybrid, classical spark ignition, and diesel cars [1-5]:

Modern Battery Electric Cars:

1. All-electric vehicles (EVs) run on electricity only and are propelled by an electric motor powered by rechargeable battery packs. The efficiency of battery electric vehicle powertrains can vary, but they generally have higher efficiency compared to traditional gasoline-powered vehicles. The drivetrain efficiency of electric vehicles is typically around 80%, meaning that 80% of the energy from the battery is converted into useful work.

2. Hybrid cars combine an internal combustion engine with an electric motor and battery. The efficiency of hybrid powertrains depends on the specific design and configuration

of the hybrid system. In general, hybrid powertrains can offer improved fuel economy compared to conventional gasoline-powered cars. The fuel economy of hybrid cars can vary, but it is often better than that of traditional spark ignition vehicles.

3. Classical spark ignition cars refer to traditional gasoline-powered vehicles. The efficiency of spark ignition engines can vary depending on factors such as engine design, technology, and driving conditions. On average, spark ignition engines in cars have an efficiency of around 20-35%, meaning that only a portion of the energy from the fuel is converted into useful work.

4. Diesel cars use compression ignition engines that are known for their high efficiency. Diesel engines can achieve higher thermal efficiency compared to spark ignition engines. The efficiency of diesel engines can range from around 30% to 50%, depending on various factors such as engine design and operating conditions.

There is no straight way to prescience calculate efficiency of a car, because a wide range conditions change it significantly like operational mode, temperature, speed, acceleration etc. which vary a lot due using conditions. Generally speaking, only continuously controlling fuel/energy consumption give us full information about real efficiency. More difficulties connected to enclosing different drivetrain used in different cars even with the same engine. Complete data about cars' powertrain not easy to get.

Calculating the efficiency of a car is not a straightforward task, as it is influenced by various factors such as operational mode, temperature, speed, acceleration, and other conditions that can vary significantly. Therefore, accurately predicting the efficiency of a car becomes challenging. To obtain comprehensive information about real efficiency, it is crucial to continuously monitor and control fuel or energy consumption.

Furthermore, the task becomes more complex due to the diversity of drivetrain systems used in different cars, even if they have the same engine. Each drivetrain configuration, such as battery electric (BEV), hybrid, or internal combustion engine, has its own unique characteristics that affect overall efficiency. Obtaining complete and standardized data about powertrain efficiency across different car models can be a challenging endeavor. For example, even the same BEV with different batteries will have different efficiency.

More detailed analysis should answer the question where the energy of fuel goes? There are a lot of different parameters, energy use and losses, which vary a lot. Collect them by drive cycle for gasoline vehicles based on analysis over 100 vehicles by Oak Ridge National Laboratory using EPA Test Car List Data files table 1 [8-13].

Table 1

Main Energy Loses Vehicles with internal combustion engine

Loses origin		Combined	City	Highway
Engine loses	total	68-72%	71-75%	64-69%
thermal (radiator, exhaust heat etc)		58-62 %	60-64%	56-60%
combustion		3%	3%	3%
pumping		4%	5%	3%
friction		3%	3%	3%
Auxiliary electric loses (e.g. climate control fans, steering wheel warmer, headlight, etc.)	Total	0-2%	0-2%	0-2%
Parasitic loses (e.g. water, fuel and oil pumps, ignition systems, engine control systems, etc.)	total	4-6%	5-7%	3-4%
Energy to wheels	total	16-25%	12-20%	20-30%
wind resistance		8-12%	3-5%	12-19%
rolling resistance		4-7%	3-5%	5-9%
braking		4-7%	6-10%	2-3%
Drivetrain loses	total	3-5%	4-5%	3-5%
Idle losses (they are including as part of engine and parasite losses)	total	3%	6%	0%

In conclusion, the calculation of a car's efficiency is not a simple task due to the multitude of variables involved, and obtaining comprehensive data about powertrain efficiency across different vehicles can be difficult.

Methods

Generally, approach to estimate efficiency of a vehicle by analyzing structural members of all components like engine, drivetrain etc. But it is a complex task, because parameters change due motion characteristics and mostly cannot be collected or simplified within enough accuracy.

Let's look outside vehicle, which moving on horizontal plane with speed $\vec{V}$, main forces shown at fig. 1, F- total moving force (force on wheels from engine, including all powertrain losses), F_r – total resistance force (including wind resistance, rolling resistance, electric losses etc.).

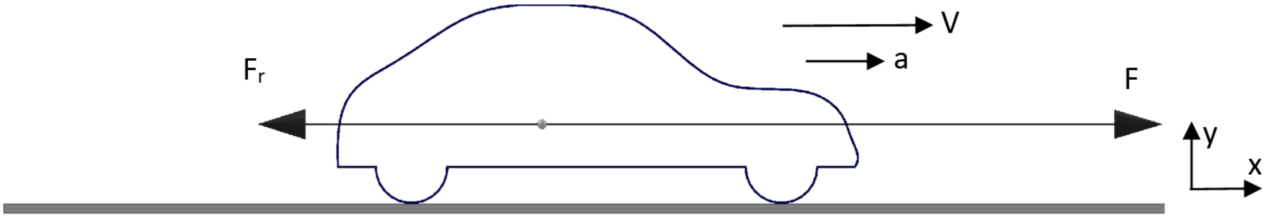

Fig. 1. Moving Vehicle

According the work-energy theorem

$$W = \int_{x_1}^{x_2} F(x)dx = F \cdot d = \frac{mV_2^2}{2} - \frac{mV_1^2}{2} = m \cdot a \cdot d \qquad (1)$$

According to (1) total work of a vehicle can be calculated, without knowing all complex parameters of the powertrain. But (1) can be used only during acceleration/deceleration of vehicle, because if speed is constant ($\vec{V}$ =const) the work of moving forces and resistance forces equilibrium and total work equal to zero. In this case, to know the work/energy we spend moving we should estimate all parameters of the powertrain, which is hard to achieve.

In real conditions to compare different vehicle characteristics we use different driving cycles. They are an essential element for the measurement of fuel consumption and emissions. Currently, each region uses its own driving cycle, varying from a stylized, less dynamic driving pattern – e. g., the NEDC in Europe – to a more dynamic driving pattern such as the US06 cycle used in the United States. The characteristics of a driving pattern, such as average speed, dynamic behavior, and length and number of stops, all have an effect on the resulting emissions and fuel consumption. Therefore, the best guarantee of realistic measurement results is to use a driving cycle that represents real life driving conditions as well as possible. A more realistic driving cycle also helps ensure that improvements in fuel efficiency and emissions indicated by the certification test are representative of improvements under real-life driving conditions.

Since the WLTP was intended to harmonize test procedures worldwide, the GRPE's task scope included development of a new cycle representing typical driving characteristics around the world. This is referred to as the World Harmonized Light-duty Vehicle Test Cycle, or WLTC. The real-world driving data used as input for this development came from five different regions: the European Union plus Switzerland, the United States, India, Korea, and Japan. This led to a database with more than 765,000 kilometers of driving data, covering a wide range of vehicle categories (vehicle segments, various engine capacities, power-to-mass ratios, manufacturers, etc.), road types (urban, rural, motorway) and driving conditions (peak, off-peak, weekend). Weighting factors were applied to adjust the collected data to the respective vehicle fleet mileages in each region. Next, the values of key vehicle emission characteristics were determined for the weighted database. In a complex automated process, combinations of “short-trips'' from this database were evaluated against these key characteristics values. The best matching combination became the new driving cycle, consisting of four phases with different speed distributions (low, medium, high and extra-high). Three different driving cycles were developed representing three different vehicle classes, based upon a vehicle’s power-to-mass ratio and its maximum speed. The figure 2 below shows the speed pattern for a Class 3 vehicle, which is the highest power and speed class. This class is likely to cover the largest share of the world light-duty vehicle market. The length of the cycle was fixed at 1800 seconds (compared with 1180 seconds for NEDC, 1205 seconds for the JC08 cycle, and 1372 seconds for the FTP cycle). Two cycles for lower power/speed vehicles were also developed that eliminate the 4th hill (Class 1 and Class 2) and the 3rd hill (Class 1), as well as reduce the maximum acceleration rates and top speeds of the other hills.

The developed test cycle and the gearshift procedure were evaluated in several laboratories all over the world. The general conclusion was that the dynamics of the WLTC reflect the average real-world driving behavior of light-duty vehicles quite well. In addition, a good balance between representativeness of in-use driving data and drivability on the chassis dynamometer was found. However, the increase in fuel consumption compared to the NEDC was lower than expected. One explanation, among others, is the additional cold-start fuel consumption is being averaged over a larger distance and thus has a lower impact per km, due to the influence of the cycle length (WLTC: 1800 seconds, NEDC: 1180 seconds, JC08: 1205 seconds) [7, 15].

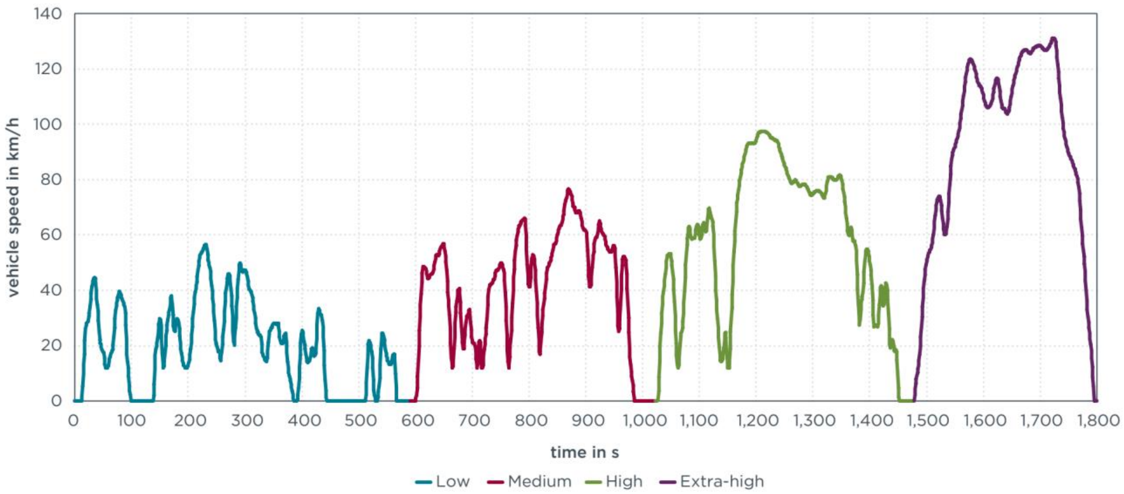

Fig. 2. Speed pattern for Class 3 vehicles (power-to-mass >34 kW/ton, and top speed >120 km/h). The individual cycle phases (low, medium, high and extra-high) are colored respectively blue, red, green and purple [15]

According to WLTC we know speed, acceleration, time with period 1Hz. Based on WLTC and (1) we can calculate used net power of vehicle:

$$P_i = \frac{m\cdot a_i\cdot d_i}{t_i} = m\cdot a_i\cdot V_i. \qquad (2)$$

Total energy consumed during the cycle is:

$$E = \sum_{i=1}^{i=1800}(P_i\cdot t_i) = E = \sum_{i=1}^{i=1800}(m\cdot a_i\cdot V_i\cdot t_i). \qquad (3)$$

The equation (3) shows energy balance of WLTC, but it will be zero, because all energy of engine was transfer to kinetic energy of vehicle and due braking transferred to heat in result finish speed is zero and no energy left. But we can take positive power/energy calculated by (2) and dismiss negative braking power/energy such as it gives no positive effect, except safety reasons etc. Some cars can recuperate braking energy and store it for future accelerations, which make them even more efficient. To be sure that everything is correct total energy should be summed E_p positive energy of acceleration and E_b energy of braking due brakes and/or resistance:

$$E = E_p +\cdot E_b = 0 \qquad (4)$$

Analyzing the amount of positive energy E_p shows real work of forces to move a vehicle (pure acceleration without all losses), and E_b shows real work of braking systems (losses like rolling and wind resistance has positive effect here). So, this gives us the possibility to compare the efficiency of different vehicles, if we know the amount of energy consumed during the WLTC test (E_{WLTC}). Then efficiency of vehicle can be calculated:

$$\eta = \frac{E_p}{E_{WLTC}} \cdot 100\% \qquad (5)$$

For BEV cars energy consumed during WLTC test is measured in KWh and can be accessed, for internal combustion engine (ICE) based powertrain vehicles or hybrids we need to calculate E_{WLTC} from fuel consumption. General fuel properties to make this calculation collected in table 2.

Table 2

Fuel properties comparison [16-20]

	Energy content (LHV) [MJ/Kg]	Energy content (LHV) [MJ/L]	Density [kg/m^3]	Octane [RON]	Flame velocity [m/s]	Flammability limits [vol/%]	Minimum Ignition Energy [mJ]
Compressed Hydrogen (gaseous)	120	2.46 *(300 bar, 5°)*	20.54	>130	3.25	4.7-75	~0.016
Diesel n-dodecane)	44.11	32.89 *(1 atm, 25°)*	745.7	<20	~0.80	0.43-0.6	~0.23
Gasoline (iso-octane)	44.34	*(n-octane)*	*(n-octane)*	100	0.41	0.95-6	1.35
		30.93 *(1 atm,25°)*	697.6		~0.58 *(RON 90-98)*	0.6-8 *(RON 90-98)*	~0.14 *(RON 90-98)*
Methanol	19.90	15.65 *(1 atm,25°)*	786.3	108.7	0.56	6.7-36	~0.14
Ethanol	26.84	21.07 *(1 atm,25°)*	785.1	108.6	0.58	3.3-19	0.65
Cooled Ammonia (Liquefied)	18.6	12.69 *(1 atm, -33°)*	682	>130	0.067	15-28	680

Results and Discussion

Calculation needs an advanced mathematical platform, so authors chose “Jupyter notebook” based on python 3.11, this package is powerful enough for this purpose.

Generally, total specific (per 1 kg of vehicle weight) energy of WLTC shows at fig. 3. It was calculated by (2).

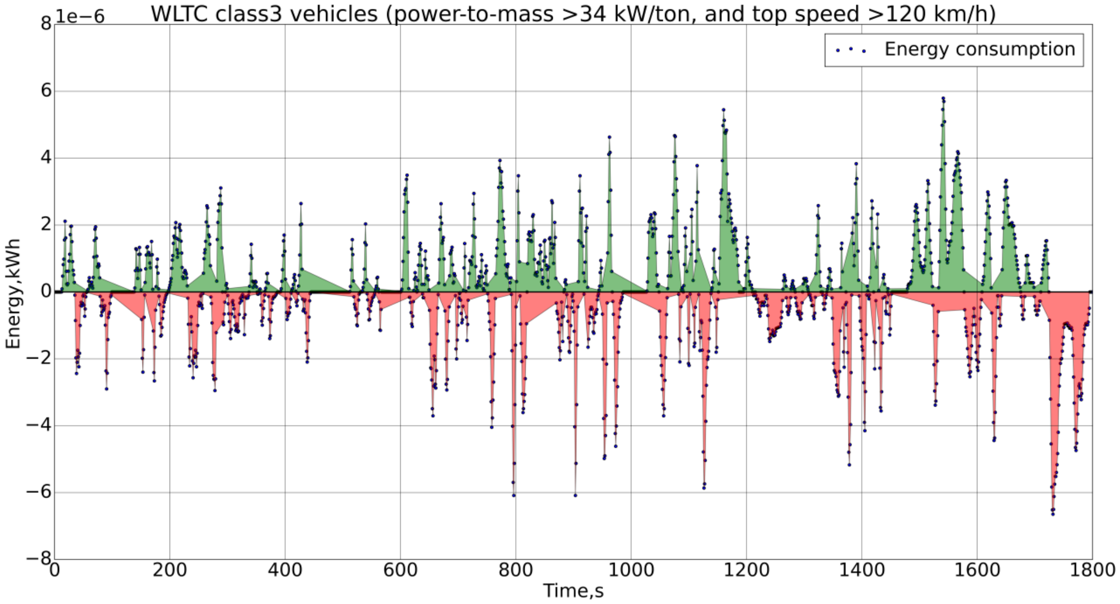

Fig. 3. Total specific (per 1 kg of vehicle weight) energy of WLTC class 3

At the figure 3 E_p positive energy shown by green area and E_b energy of braking due brakes and/or resistance by red area. Total energy should be summed E_p positive energy of acceleration and E_b energy of braking due brakes and/or resistance, according (4) and data fig.4 will have:

$$E = E_p +\cdot E_b = 6.9 \cdot 10^{-20} \approx 0\ kWh/kg \qquad (6)$$

This amount (6) is neglected and most probably is the result of rounding during calculation and measuring. To have possibility compare different vehicle, specific summed positive energy of acceleration $E_p=0.991 \cdot 10^{-3} kWh/kg$. This number gives us the possibility to calculate the average efficiency of vehicles class 3 during the WLTC test. Using the same methodology calculate similar specific energy for vehicles class 2 and class 1, results put to table 3 and figure 4-5.

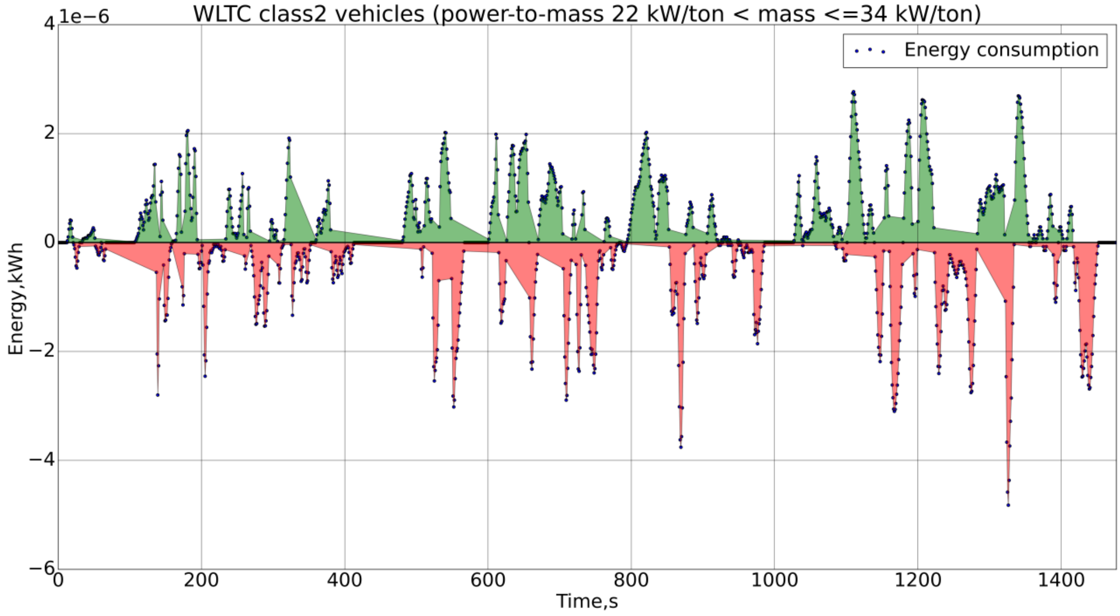

Fig. 4. Total specific (per 1 kg of vehicle weight) energy of WLTC class 2

Fig. 5. Total specific (per 1 kg of vehicle weight) energy of WLTC class 1

Let's find some efficiencies of the vehicle based on WLTC test procedure data and calculate Specific summed positive energy of acceleration for the cycle. For example of vehicles, took top 10 best sellers of Ukrainian market at 2021 (VAZ excluded from the list):

1. Kia Sportage;
2. Toyota Rav4
3. Skoda Kodiak
4. Nissan leaf
5. Volkswagen ID4
6. Tesla model3
7. Renault ZOE
8. BMW I3.

These lists consist of BEV, classic and hybrid vehicles, so make the range of efficiencies much wider.

Table 3

Summed E_p positive energy of acceleration

WLTC class of vehicle	Specific summed positive energy of acceleration, E_p [kWh/Kg]	Total energy error, [kWh/Kg]
Class 1 (power to 22≤masskW/ton, duration 1022 s)	$0.184\cdot10^{-3}$kWh/kg	0
Class 2 (power to 22> mass ≤34 kW/ton, duration 1477 s)	$0.5199\cdot10^{-3}$kWh/kg	$-4.4 \cdot 10^{-20}$
Class 3 (power to mass >34 kW/ton, duration 1800 s)	$0.991\cdot10^{-3}$kWh/kg	$6.9 \cdot 10^{-20}$

Collect all necessary data about models to table 4, and use general types of powertrains.

Table 4

Cars data [21-27]

Vehicle	Type	Drivetrain	Mass, kg	Type of engine	Battery, kWh	WLTC energy consumption by manufacturer
Kia Sportage	Hybrid	FWD, Automatic 6 speed	2245	169 kW petrol (1.6 l T-GDI) 44.2 kW electric	1.49	6.4 l/100 km
	PHEV	FWD, Automatic 6 speed	2415	195 kW petrol (1.6 l T-GDI) 44.2 kW electric	13.8	1.1 l/100 km
	normal	Manual 6 speed	2140	100 kW1.6 CRDI	-	5.4 l/100 km
Toyota Rav4	Hybrid	FWD	2135	2.5l Hybrid A25A-FXS	n/a	4.74-4.82 l/100 km (design)
	Hybrid	AWD-i	2225	2.5l Hybrid A25A-FXS		4.83-4.91 l/100km
Skoda Kodiak	SE L Executive	FWD DSG ACT	2275	1.5 TSI 150PS		7.2-7.4 l/100 km
	Sportline	DSG 4x4 SCR	2534	2.0 TDI 200PS		6.6-6.8 l/100 km
Nissan leaf	Acenta	2WD	1995	110 kW	39	WLTP combined range 168 miles
Volkswagen ID4 pro			2212	210 kW	82	18.4-15.9 kWh/100km
Tesla model3		RWD	1752	239 kW	62	97-198 Wh/km
Renault ZOE	R110	2WD	1988	Synchronous with wound rotor 80 kW	52 (Z.E. 50)	WLTP combined range 385 km
BMW I3		2WD	1365	170 h.p.		13.1 kWh/62 miles

According data of tables 2 and 3 we can get energy consuming of WLTC these cars by formula for internal combustion version (all cars are class3 WLTS length of cycle 23262m):

$$E_{WLTC} = L_{100km} \cdot E_{LVH} \cdot 0.278 \cdot 0.23 \ \left[\frac{kWh}{WLTC}\right] \qquad (7)$$

Where E_{WLTC} – consuming energy by car during WLTC, L_{100km} – car's fuel consumption, [l/100km] E_{LVH} – energy fuel content (LHV) [MJ/L] (table 2), 0.278 – coefficient correction [MJ/L] to [kWh], 0.23 – correction for WLTC length 23.262 km.

Results of calculation by (7) collect to table 5, with mean data of electric cars also.

Table 5

Summed E_p positive energy of acceleration

Vehicle	Type	Positive energy of acceleration, E_p for vehicle mass, [kWh]	E_{WLTP} consuming energy by car for WLTC (7)	Efficiency of vehicle by (5) [%]
Kia Sportage	Hybrid	2.22	14.29	15.56
	PHEV	2.39	16.00	14.95
	Diesel	2.12	11.49	18.45
Toyota RAV4	FWD	2.12	9.56	22.12
	AWD	2.20	9.74	22.63
Skoda Kodiak	Executive	2.25	14.6	15.43
	Diesel	2.50	14.25	17.61
Nissan leaf	Electric	1.98	3.36	58.89
Volkswagen ID4 pro	Electric	2.19	3.99	54.9
Tesla model 3	Electric	1.73	2.25	57.29
Renault ZOE	Electric	1.97	3.14	62.7
BMW I3	Electric	1.35	3.05	44.27

Some manufacturers give the range of consuming energy by WLTC, so to get data table 5 we use mean values.

Discussion

EVs motors are much more efficient then internal combustion motors (at least more than 90%), but we didn’t consider efficiency of electricity generation, delivery network and charging/discharging energy losses in this research. These electric motors, generally speaking, are around 2 times more efficient, but according to table 5 all electric vehicles are more than 2 times more efficient. This happened because all full EVs have a recuperation energy system, which returns energy from braking to battery. Positive energy E_p (4) totally neglects this, assuming then energy E_b fully lost in the braking system.

Mathematical model (3) has also some miss corrections, like during WLTC are moments then V_i vehicle speed is constant or close to that, it means that acceleration a_i is close to 0 and kinetic energy of motor/engine equalized by resistance of movements (air, rolling friction etc) or by braking. We don’t know exactly what is happening, so some energy from these moments is wasted. This happening, for example, at seconds of WLTC [56, 196, 197, 291, 296, 337, 351, 562, 628, 819, 883, 967, 1048, 1090, 1151, 1187, 1188, 1189, 1190, 1191, 1192, 1193, 1194, 1210, 1211, 1214, 1215, 1284, 1297, 1307, 1329, 1330, 1331, 1339, 1372, 1420, 1444, 1577, 1608, 1675, 1710, 1724] (class 3 WLTC), but total specific (per 1 kg of vehicle weight) energy for these period is small ($1\cdot10^{-5}$ kWh), so we totally neglect it, similar to braking or resistance energy losses.

Authors would like to find some mathematical model for assuming cars/engines efficiencies and are welcome to join us to continue discussion about.

Conclusions

Proposed total energy consumed model during the WLTC. Compare WLTC fuel/energy consuming data from different manufacturing and calculate efficiencies.

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