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COMPARATIVE ANALYSIS OF THE INSTANTANEOUS FUEL CONSUMPTION OF A CAR WITH DIFFERENT TYPE OF POWER TRAIN SYSTEM UNDER TRANSIENT CONDITIONS

Wawrzyniec Gołębiewski, Konrad Prajwowski

West Pomeranian University of Technology, Szczecin
Department of Automotive Vehicles Operation
Piastów Av. 19, 70-310 Szczecin, Poland
tel.: +48 91 449 40 45
e-mail: wawrzyniec.golebiewski@zut.edu.pl, konrad.prajwowski@zut.edu.pl

Abstract

The aim of this study was to compare instantaneous fuel consumption of a FIAT Panda car with three types of propulsion system applied: engine positioned front-lengthwise to the direction of travel and rear-wheel drive, engine positioned front-transversely to the direction of travel and front - wheel drive and all-wheel drive. The vehicle was equipped with a 1.3 JTD MultiJet compression-ignition engine being used for conducting experimental tests. This part was based on making the load characteristics (relationship between specific fuel consumption and engine torque) using engine dynamometer. This was made for given parameters corresponding to specific traffic conditions. They were determined in a simulation and were represented by rolling resistance and air resistance. Their value was affected by vehicle technical and operating characteristics and its design features, such as maximum weight, transmission system ratios, dynamic wheel radius, drag coefficient, width and height, and efficiency of propulsion system. The efficiency of power train system was adopted from a simulation conducted for different types of propulsion system. Apart from basic resistance, additional drag (inertia resistance) was the most important in vehicle energy balance. It played an important role in determining the value of instantaneous fuel consumption for variable velocity and constant acceleration values used in the UDC test (Urban Driving Cycle – subtest of the EUDC cycle). The lowest fuel consumption for a given car velocity was for front-wheel drive transmission system, whereas the highest for all-wheel drive system (4x4).

Keywords: *instantaneous fuel consumption, UDC cycle, passenger car, propulsion system, variable velocity*

1. Introduction

The efficiency of vehicle propulsion system is an important parameter associated with its fuel consumption. High-energy efficiency of a car depends on the design of propulsion system applied. Extension of this system with further modules can improve vehicle performance characteristics but worsen at the same time its traction properties and increases its fuel consumption. Therefore, fuel consumption assumes different values depending on the design of a particular car but also on its technical condition and a number of other factors (e.g. weather conditions – pressure, temperature and humidity, driver's style of driving, resistance to motion, or physicochemical fuel properties [7]). The real-world conditions of driving are thus variable and therefore they define a variable value of fuel consumption.

In order to map real life motion conditions, detailed driving cycles were created, simulating the profiles of changes in vehicle velocity and acceleration. Among European car manufacturers, the NEDC cycle (New European Driving Cycle), conducted under laboratory conditions using a chassis dynamometer, has found a common application. It is a part of the UNECE regulation and is composed of two subcycles: UDC (Urban Driving Cycle) and EUDC (Extra Urban Driving Cycle; 1990). In the United States of America, the EPA Federal Test (SFTP US06/SC03; 2008) is an equivalent of this test, while the JC08 test (2008) in Japan [9, 11]. Certain alternatives for the above-mentioned cycles have been also developed, e.g. ADAC EcoTest [1] or CUEDC-P [2].

The ADAC EcoTest NEDC cold was implemented under laboratory conditions using a chassis dynamometer and allowed obtaining the CO_2 emission in 2010 being by 1% higher than that furnished by a car manufacturer, while by 20% lower in relation to the data provided by car users [1, 9].

The CUEDC-P cycle (Composite Urban Emission Driving Cycle for Petrol Vehicles) was performed under the real-world car driving conditions. It lasted thirty minutes and was composed of four subcycles: Residential, Arterial, Freeway and Congested. The mathematical model adopted by the authors assumed determination of instantaneous fuel consumption on the basis of theoretical formulas, as well as on the basis of the above-mentioned driving cycle. A very high level of reliability for estimation of instantaneous fuel consumption was demonstrated, being slightly different from the values measured during the real-world CUEDC-P cycle [2].

Owing to the fact that the NEDC cycle is being used, the authors decided to take up the problem of instantaneous fuel consumption in the standard subcycle Urban Driving Cycle and to perform a comparative analysis of this parameter for three different types of propulsion system: classical drive, block front-wheel drive and four-wheel drive (4x4).

2. Research objective and experimental methods

The aim of this study was to analyse fuel consumption of a vehicle equipped with one of three types of propulsion system, i.e. classical drive, block front-wheel drive and four-wheel drive (4x4). The comparison of simulation instantaneous fuel consumption was made for a FIAT Panda vehicle equipped with a MultiJet 1.3 JTD engine. Prediction of this parameter was based on the urban cycle test (UDC). The acceleration values being used in this test corresponded to specific engine torque values determined based on tests performed on engine test bench. The characteristics of specific fuel consumption in relation to engine load, expressed as its torque, were important for the analysis. Experiments were conducted in accordance with the methods provided in the standard [10] and performed according to the requirements specified in it. The comparison of instantaneous fuel consumption was performed for variable traffic conditions.

3. Course of testing

Experimental testing consisted in making, based on measurements, the characteristics of specific fuel consumption in relation to engine torque for particular speeds of power unit (i.e. for vehicle velocities 15, 32, 35 and 50 km/h being used in the UDC cycle). In order to determine these velocities, the relationships presented in the paper entitled "Comparison of the instantaneous fuel consumption of vehicles with a different type of propulsion system at constant velocity." Next, the characteristics of engine load, presented in Fig. 1, were made.

The value of engine torque was defined by engine load moment. The latter, however, was transmitted throughout the propulsion system from wheels onto engine crankshaft and depended on vehicle motion conditions. It was represented by vehicle velocities (corresponding to engine speeds) and resistance to motion (engine load moment). The basic resistance to motion included rolling resistance and air resistance being determined from the relationship presented in the paper entitled "Comparison of the instantaneous fuel consumption of vehicles with a different type of propulsion system at constant velocity."

Apart from the above-mentioned rolling resistance and air resistance during driving with variable velocities during starting off and accelerating, inertia resistance occurred, and its contribution was the most important in fuel consumption. Additional resistance to motion were defined by the following function [3, 11]:

$$F_B = m_C \cdot a \cdot \delta = m_c \cdot a \cdot (1.04 + 0.03 \cdot i_b^2), \qquad (1)$$

where:
F_B – inertia resistance [N],
m_C – maximum gross vehicle weight [kg],
a – vehicle acceleration [m/s^2],
δ – allowance for rotating parts,
i_b – gearbox ratio.

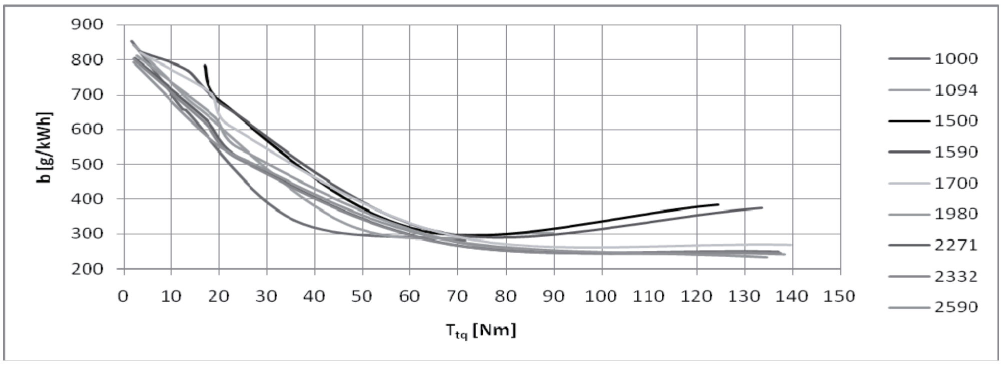

Fig. 1. The load characteristics of FIAT 1.3 JTD engine: b – specific fuel consumption, T_{tq} – engine torque; Legend – rotational speeds of engine crankshaft

Determination of the total resistance to motion and, as a consequence, the value of engine torque needed to overcome it, required to use vehicle technical and operating characteristics and to determine specific motion conditions. Vehicle data and motion conditions were determined in the paper entitled "Comparison of the instantaneous fuel consumption of vehicles with a different type of propulsion system at constant velocity." They were of crucial importance in the analysis of simulation fuel consumption for different types of propulsion systems.

4. Simulation instantaneous fuel consumption

The profile of changes in vehicle velocity and acceleration defines the energy intensity of vehicle motion, which is associated with particular fuel consumption. The sum of instantaneous fuel consumption is composed of three factors and was determined on the basis of the following relationship:

$$f_c = \alpha + \beta_1 + \beta_2, \tag{2}$$

where:
α –instantaneous fuel consumption at neutral gear [mdm^3/s],
β_1 –instantaneous fuel consumption at constant velocity [mdm^3/s],
β_2 –instantaneous fuel consumption at variable velocity [mdm^3/s].

The vehicle being permanently in traffic waits for opportunity to drive on traffic lights. It constitutes a quite big part of the whole driving time (although it is a standstill), particularly in-congested urban agglomerations. At that time, the engine operates without load at neutral gear and its instantaneous fuel consumption α is represented by the following formula [2]:

$$\alpha = B_v = \frac{B_m}{\rho_P}, \tag{3}$$

Where:
B_v –volumetric fuel consumption [dm^3/s],
B_m –mass fuel consumption [g/s],
ρ_P –fuel density [g/dm^3].

In Tab. 1 below, fuel consumption at neutral gear is determined on the basis of testing FIAT MultiJet 1.3 engine performed on engine test bench.

Tab. 1. Fuel consumption at neutral gear

Parameter	n_{bj}	B_m	ρ_P	B_v	$\alpha = B_v$
Unit	[min^{-1}]	[g/s]	[g/dm^3]	[dm^3/s]	[mdm^3/s]
Value	800	0.06	820.1	0.00007	0.0731

where: n_{bj} – engine speed at neutral gear.

Instantaneous fuel consumption for constant velocities was determined on the basis of the relationship from the paper entitled "Comparison of the instantaneous fuel consumption of vehicles with a different type of propulsion system at constant velocity," and it is presented for different types of propulsion systems in Tab. 2.

Tab. 2. Instantaneous fuel consumption at constant velocity – classical drive, block drive and 4x4 drive

Parameter	*Gear*	*v*	*v*	*n*	β_1 – classical drive	β_1 – block drive	β_1 – 4x4 drive
Unit		[km/h]	[m/s]	[min^{-1}]	[mdm^3/s]	[mdm^3/s]	[mdm^3/s]
Value	I	15	4.2	1980	0.218	0.216	0.235
	II	32	8.9	2332	0.482	0.478	0.517
	II	35	9.7	2590	0.531	0.526	0.569
	III	35	9.7	1590	0.561	0.557	0.597
	III	50	13.9	2271	0.826	0.820	0.876
Parameter	η_{UN}				0.91	0.92	0.84

5. Simulation instantaneous fuel consumption at variable velocities

Instantaneous fuel consumption at variable velocities and constant acceleration values is the most difficult to be determined in the total balance of instantaneous fuel consumption. The engine operates then at transient conditions, whereas the vehicle accelerates within a range of certain velocities. For comparative purposes, the authors of this paper decided to use the load characteristics (Fig. 1) and calculate numerically the instantaneous fuel consumption using the following relationship:

$$\beta_2 = \frac{b \cdot (F_T + F_P + F_B)}{3600 \cdot 10^3 \rho_P \cdot \eta_{UN}} \cdot dv\,, \tag{4}$$

where:

β_2 – instantaneous fuel consumption at variable velocity [mdm^3/s],
b – specific fuel consumption [g/kWh],
F_T – rolling resistance [N],
F_P – air resistance [N],
F_B – inertia resistance [N],
v – vehicle velocity [m/s],
ρ_P – fuel density [kg/dm^3],
η_{UN} – efficiency of propulsion system.

In order to use relationship (4) for determining instantaneous fuel consumption when using one gear, the integral calculus needed to be used according to the following formula:

$$\beta_2 = \int_{v1}^{v2} \frac{b \cdot (F_T + F_P + F_B)}{3600 \cdot 10^3 \cdot \rho_P \cdot \eta_{UN}} \cdot dv\,. \tag{5}$$

The motion conditions being defined by vehicle velocity and resistance to motion determined the values of engine speeds and engine load moment. Equalising engine torque was determined from the relations presented below:

$$T_{tqK} = (F_T + F_P + F_B) \cdot r_d \,, \tag{6}$$

$$T_{tq} \cdot \eta_{UN} \cdot i_{UN} = (F_T + F_P + F_B) \cdot r_d \rightarrow T_{tq} = \frac{(F_T + F_P + F_B) \cdot r_d}{\eta_{UN} \cdot i_{UN}} \,. \tag{7}$$

The above relationships allowed reading the specific fuel consumption for engine load moment and particular vehicle velocities (corresponding to engine crankshaft speeds) and making the characteristics of specific fuel consumption and total resistance to motion in relation to vehicle velocity during acceleration. Sample diagrams of that type for block front-wheel drive are presented in Fig. 2 and Fig. 3.

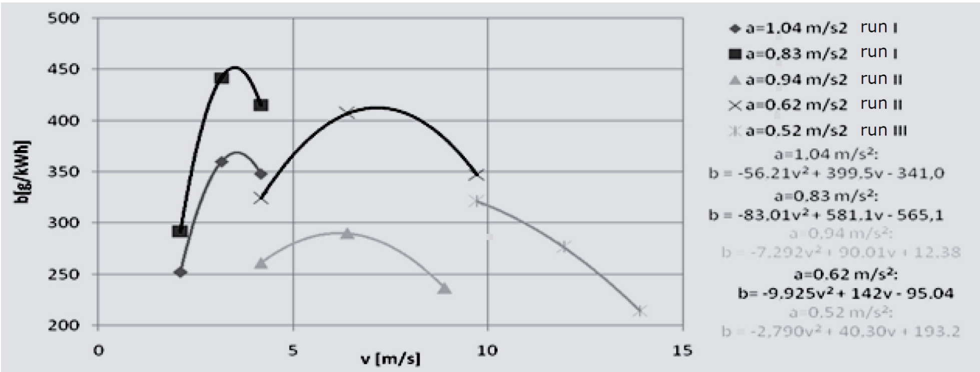

Fig. 2. The characteristics of specific fuel consumption b in relation to vehicle velocity v: a – vehicle acceleration; Legend – trend curve equations

To determine instantaneous fuel consumption during acceleration, relation (5) needed to be applied and integration by parts to be made:

$$\beta_2 = \frac{\int_{v1}^{v2} b \cdot (F_T + F_P + F_B) dv}{3600 \cdot 10^3 \cdot \rho_P \cdot \eta_{UN}} = \frac{1}{3600 \cdot 10^3 \cdot \rho_P \cdot \eta_{UN}} \left[\int_{v1}^{v2} b dv \cdot (F_T + F_P + F_B) \Big|_{v1}^{v2} - \int_{v1}^{v2} c \cdot (F_T + F_P + F_B)' \Big|_{v1}^{v2} \right], \tag{8}$$

where: c = $\int_{v1}^{v2} b dv$.

Using the equations of chosen trend lines representing specific fuel consumption and resistance to motion (based on Fig. 2 and Fig. 3), the value of instantaneous fuel consumption was determined after their integration.

Tab. 3. Instantaneous fuel consumption at variable velocities

Gear	v_1	v_1	v_2	v_2	a	β_2		
						classical drive	*block drive*	*4x4 drive*
	[km/h]	[m/s]	[km/h]	[m/s]	[m/s^2]	[mdm^3/s]	[mdm^3/s]	[mdm^3/s]
I	*7.60	2.11	15.00	4.17	1.04	0.628	0.628	0.630
I	*7.60	2.11	15.00	4.17	0.83	0.619	0.619	0.624
II	15	4.17	32	8.89	0.94	0.866	0.865	0.876
II	15	4.17	35	9.73	0.62	0.998	0.996	1.099
III	35	9.73	50	13.89	0.52	0.485	0.485	0.484
η_{UN}						0.91	0,92	0.84

where: v_1 – initial velocity, v_2 – final velocity, a – vehicle acceleration, β_2 – instantaneous fuel consumption at variable velocity.

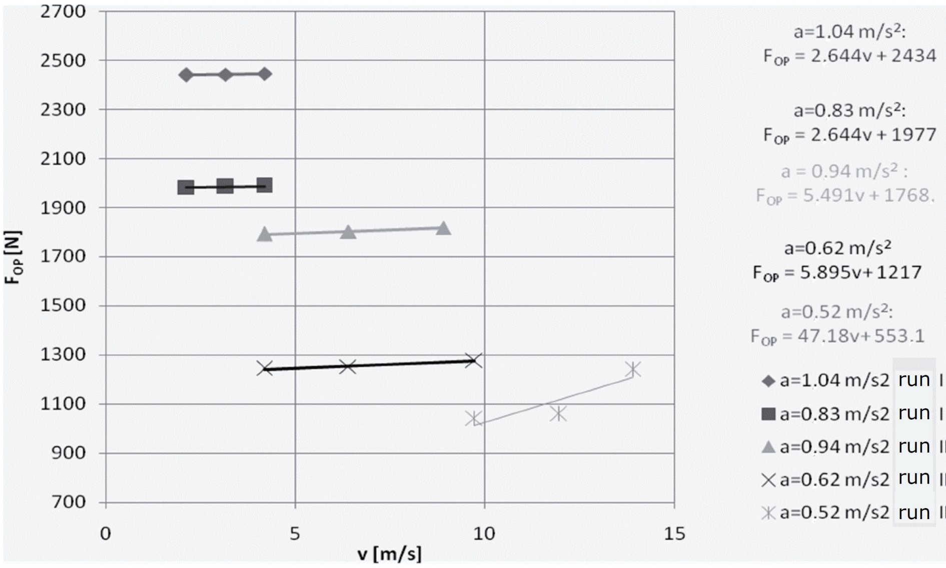

Fig. 3. The characteristics of total resistance to motion F_{OP} in relation to vehicle velocity v: a – vehicle acceleration; Legend – trend curve equations

* – according to the UDC cycle the vehicle accelerates from velocity 0 km/h to 15 km/h; however, the vehicle equipped with a friction clutch and multi-speed gearbox cannot start with velocity from 0 km/h due to clutch slip and specific value of first gear ratio.

The determined values of instantaneous fuel consumption were incorporated in the sum of total instantaneous fuel consumption converted into its mileage value in next section.

6. Simulation instantaneous fuel consumption according to the UDC cycle

The sum of instantaneous fuel consumption for the represented profile of vehicle velocity and acceleration, in accordance with Tab. 4, defined the value of mileage fuel consumption for classical propulsion system (Tab. 5). For other propulsion systems, it was calculated in a similar way.

7. Conclusions

Comparison of instantaneous fuel consumption allowed drawing the following conclusions:

a) block front-wheel drive is characterised by the lowest fuel consumption, whereas vehicle's all-wheel driven system represents the highest fuel consumption;
b) the method included computations of fuel consumption for maximum gross vehicle weight but this weight could be lower in chassis dynamometer tests, therefore the value of mileage fuel consumption provided by manufacturer was lower;
c) real-world mileage fuel consumption is affected by a lot of factors not taken into account in this paper or simplified ones (e.g. variable fuel density, driving conditions – outdoor pressure and temperature, rolling resistance coefficient, tyre pressure, elevations, level of engine warming-up, efficiency of propulsion system resulting from gear lubricant viscosity, etc.);
d) UDC is not the best cycle which maps the simulation mileage fuel consumption in urban driving cycle for passenger cars equipped with Common Rail fuel system;
e) the set out direction of experimental and simulation research allows modification and construction of a more complex mathematical model being based on a larger number of variable parameters and a driving cycle taking into consideration the above remarks (e.g. application of the WLTC test); this will allow mapping the real-world instantaneous fuel consumption in the best possible way and, as a consequence, its mileage value, too.

Tab. 4. Instantaneous fuel consumption according to the UDC cycle for classical drive system

Phase No.	Action	v_1	v_2	t	t_{sum}	a	f_c	f_c*t
		[km/h]	[km/h]	[s]	[s]	[m/s^2]	[mdm^3/s]	[mdm^3]
1	neutral gear			11	11		0.073	0.804
2	acceleration	0	15	4	15	1.04	0.628	2.512
3	constant velocity	15	15	9	23		0.218	1.962
4	braking	15	10	2	25	-0.69	0.000	0.000
5	braking, clutch disengaged	10	0	3	28	-0.92	0.073	0.219
6	neutral gear			21	49		0.073	1.535
7	acceleration	0	15	5	54	0.83	0.619	3.095
8	gear change			2	56		0.073	0.146
9	acceleration	15	32	5	61	0.94	0.866	4.330
10	constant velocity	32	32	24	85		0.482	11.568
11	braking	32	10	8	93	-0.75	0.000	0.000
12	braking, clutch disengaged	10	0	3	96	-0.92	0.073	0.219
13	neutral gear			21	117		0.073	1.535
14	acceleration	0	15	5	122	0.83	0.619	3.095
15	gear change			2	124		0.073	0.146
16	acceleration	15	35	9	133	0.62	0.998	8.982
17	gear change			2	135		0.073	0.146
18	acceleration	35	50	8	143	0.52	0.485	3.880
19	constant velocity	50	50	12	155		0.826	9.912
20	braking	50	35	8	163	-0.52	0.000	0.000
21	constant velocity	35	35	13	176		0.561	7.293
22	gear change			2	178		0.073	0.146
23	braking	32	10	7	185	-0.86	0.000	0.000
24	braking, clutch disengaged	10	0	3	188	-0.92	0.073	0.219
25	neutral gear			7	195		0.073	0.512
							Total	62.258

where: v_1 – initial velocity, v_2 – final velocity, t – phase length, t_{sum} – total time of respective phases, a – vehicle acceleration, f_c – instantaneous fuel consumption.

Tab. 5. Mileage fuel consumption for different types of propulsion system of a FIAT Panda vehicle

Mileage fuel consumption [dm^3/100 km]			
Classical drive system	Block front-wheel drive	4x4 drive	Manufacturer
6.12	6.10	6.42	5.4

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