

THE ENERGY-EFFICIENT TWO-PHASE DRIVING CYCLE ($\eta_n > 1$) CAN EFFICIENCY η_n IN VEHICLES BE HIGHER THAN 1.0?

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Abstract

The study presents an important part of fourth chapter of the monograph 'Energy Consumption in Relation to Fuel Efficiency Under Complex Driving Conditions' (2003) concerning opportunities to improve vehicle drive efficiency through application, during one phase of driving in neutral in two-phase driving cycle. Theoretical simulation of total energy consumption in vehicles with SI engine provided explanation of a relatively low fuel efficiency observed under real driving conditions in serial cars [1].

The study cites the original method of calculations developed by the author in order to calculate the efficiency of vehicle power unit in two-phase driving cycle assuming that one of the phases might be non-driving. The calculations were made for complex driving conditions, i.e. simulated changes with predefined steps for road slope (-3.5° to 3.5°), acceleration (-0.36 – 0.36 m/s²) and average speed (60–140 kmph) for a distance of 2x500 m. The results of calculation variants for each type of a drive system of a car proved that there are significant limitations of optimising the fuel consumption of cars. The first one is conditioned by the fact that the engine works at full dynamic load and the second one by the fact that idle running is against the 'Highway Code'.

Keywords: efficiency, driving cycle, overall engine efficiency

1. Introduction

Efficiency η_n is one of the most difficult and important issues to be solved in theoretical considerations of energy consumption in vehicles [1-4]. During driving phase, it is not difficult to calculate it since it has already been published in a number of studies [5-9] as a product of two efficiencies: engine efficiency and power transmission system efficiency: $\eta_n = \eta_o \cdot \eta_p$. None of them have demonstrated efficiency over the value 1.0. However, reaching unbelievably small fuel consumption in vehicles on complex routes has been reported to be possible.

Driving at record-breaking low fuel consumption is usually impossible. The records are set by dedicated vehicles from serial production, driven by persons demonstrating improved skills in terms of energy-saving driving cars. Twenty years ago, record-beating performance was fuel consumption of 1.7 dm³/100 km in Audi with CI TDI R5 engine and 2.38 dm³/100 km in three-litre VW Lupo engine [10, 11]. Krupcała reported the consumption of 1.7 dm³/100 km reached in Fiat 126 p (SI 0.65 dm³) driven in fourth gear by means of impulse-neutral technique [12]. It seems to be improper to mention records beaten on the route of over 1000 km covered using one litre of fuel, since they were achieved in ultra-light vehicles [13]. The question arises: is it possible (and under which conditions) to reach efficiency over 1.0?

2. Efficiency During Driving Phase

Obtaining of this high efficiency in vehicles powered by whether SI or CI engine is impossible due to limitation of the values of each of the listed efficiencies. Tab. 1 presents possible scopes of engine efficiency and power transmission system efficiency. The former, under steady working

conditions, is the highest within the range of the engine working rarely whereas unsteady working conditions typically limit it to several percent (depending on the gear) [14, 15]. The latter of the efficiencies depend on gear ratio, load and share of energy loss used to compensate for rotational speed of clutch shaft and output shaft in gearbox. It should be emphasized that higher fluctuations during one driving phase are observed for overall engine efficiency (from 0 to maximal value) [14, 15]. Furthermore, in order to simplify calculation, efficiency in power transmission system η_p is frequently adopted as 1.0 [17].

Tab. 1. Data for efficiency in vehicles

Engine/Characteristics	BSFC _{min} g/(kW·h)	BSFC _{NEDC} g/(kW·h)	$\eta_{e,max}$	$\eta_{e,NEDC}$	η_p
SI	230–270	330–415	0.31–0.38	0.20–0.25	(0.10) ¹⁾ 0.90–0.95
SI GDI	230–245	260–290	0.34–0.365	0.29–0.32	(0.10) 0.90–0.95
CI DI	195–210	240–260	0.40–0.43	0.32–0.35	(0.10) 0.90–0.95

¹⁾ – in driving phases of engine work during vehicle manoeuvring with very small speed ('half-clutch') [u]

3. Efficiency in Variable Two-Phase Driving Cycle

Since it is hard to find any combination of both efficiencies within one phase which might give in result the efficiency higher than 1.0, a driving cycle should be designed for the route with variable road slope and two phases, of which one is a driving (motive) phase and the other is non-driving (neutral) phase [15, 17]. A computer simulation for calculations of energy consumption of the movement was carried out with the following assumptions for Fig. 1 for the vehicle powered by SI 1.4 engine:

- average vehicle speed in the considered driving cycle is constant within the range of 60 to 140 kph,
- during simulation a varied road slope was assumed with the step of 0.46° within the range of $-3.5^\circ \geq p \geq 3.5^\circ$ and vehicle acceleration during motive phase of $-0.24 \geq a \geq 0.24 \text{ m/s}^2$ with calculation step of 0.04 m/s^2 ,
- calculations were made for the drive in the highest possible gear (fifth or fourth) for SI engine with varied dynamics of engine torque ($M_m = 75, 90, 110, 135 \text{ Nm/Mg}$).

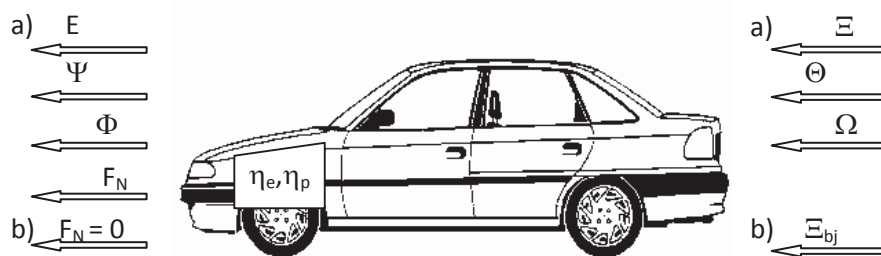


Fig. 1. The energy-related model of the car in the driving (a) and non-driving (b) phases

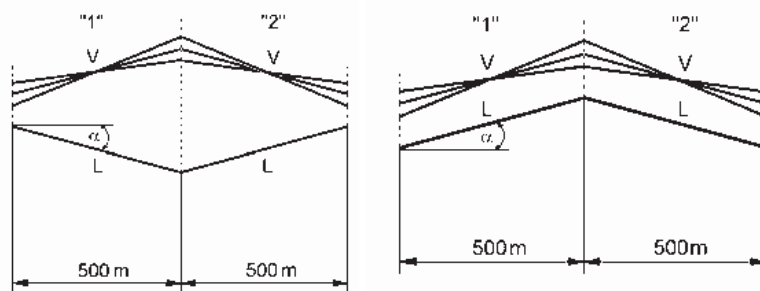


Fig. 2. The model of singular phase with the changeable road profile and with the fixed energy-consumption of traffic

Since driving was considered for constant average speed with the step of 10 kmph within the range of 60 to 140 kmph in driving phase in the highest gear, drop in overall efficiency under unsteady engine work conditions was neglected since it is close to zero [15].

3.1. Definition of Efficiency in Two-Phase Driving Cycle ($L = 2 \times 500$ m)

Left side of the model of a vehicle in Fig. 1 shows symbols for motion energy-consumption $E = F_n \cdot L$ (Nm), energy consumption per metre Ψ (Nm/m) and unit energy consumption Φ (Nm/m·kg), whereas left side contains the same units after taking efficiency ($\eta_e \cdot \eta_p$) into consideration. This means, as defined by the author, an overall motion energy consumption Ξ (Nm), etc. (Θ , Ω). Energy, which should be supplied in the fuel.

The problem of changes in efficiency in the discussed two-phase cycle model while driving in neutral in one of the phases. According to the definition, efficiency is a quotient of motion energy consumption (at the output) and actual energy consumption i.e. the one which was supplied to the vehicle in order for this motion to be carried out (input energy consumption). Therefore, after dividing the numerator and denominator by the distance covered in the cycle and vehicle weight, it can be given by (numbering in equations adopted from the monograph) [21, 24]:

$$\eta_n = \frac{E}{\Xi} = \frac{\Psi}{\Theta} = \frac{\Phi}{\Omega}, \quad (4.46)$$

After expansion of Φ and Ω in two-phase cycle:

$$\Phi = \frac{(F_1 + F_2) L / 2}{m L}, \quad (4.47)$$

$$\Omega = \frac{(\Xi_1 + \Xi_2) L / 2}{m L} = \frac{(F_1 / \eta_{n1} + F_2 / \eta_{n2}) L / 2}{m L}, \quad (4.48)$$

and, after substitution and transformation, the formula for efficiency for a driving cycle with both drives phases:

$$\eta_n = \frac{\eta_{n1} \eta_{n2} (F_1 + F_2)}{F_1 \eta_{n2} + F_2 \eta_{n1}}, \quad (4.49)$$

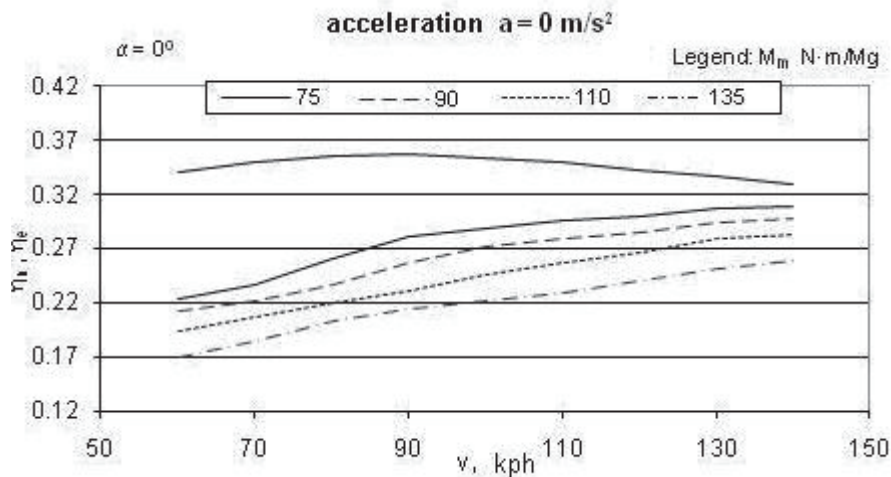


Fig. 3. The average efficiency of the passenger cars drive with the SI engines as a function of rational speed and dynamics of the drive in the phase with two drive phases

which, for the adopted model with two driving phases corresponds to the obtained results? If one of the phases is a driving phase and if due to insignificant torque (energy consumption) drive can be replaced by driving in neutral, say phase 2 ($p < 0$), phase 1 is characterized in both cases by high driving torque ($p > 0$) and high efficiency (the highest, close to maximal overall engine efficiency if working point in the highest gear is located in the 'eye' of engine performance map). Thus, if we assume that $F_2 = 0$, equation (4.49) can be transformed into:

$$\eta_n = \frac{\eta_{n1} \eta_{n2} F_1}{\eta_{n2} F_1} = \eta_{n1}, \quad (4.50)$$

and power transmission is, under certain conditions, close to maximal overall engine efficiency, particularly for maximal speed and low M_m index (131 Nm/Mg) (Fig. 3).

This happens if for both, driving phases, one of them is so low energy-saving that it can be replaced by driving in neutral and if average speed and selected velocity-distance profile are chosen in relation to the dynamics of vehicle drive and power transmission system so that working point in phase 1 is located in the minimum BSFC (maximal engine efficiency), which in the selected characteristic can be adopted as $BSFC \leq 240$ g/kW·h ($\eta_e = 0.37$).

An interesting point is interpretation of the effect of the equation (4.49) on efficiency. For the given constant average speed, total of driving forces in both phases is constant, and the only variable parameter, depending on the given velocity-distance profile, is proportions between each other. Inversely proportional values are observed for efficiency alternately corresponding to those forces (driving torque) in equation denominator. In Fig. 4, for average speed of 140 kmph for vehicles with drive dynamics of 110 and 135 Nm/Mg (Tab. 2), course of the value of the product of efficiency of both phases and the total of products in denominator in the equation (4.49) as a function of road slope α .

The product of efficiencies in the numerator being a characteristic as a function of climbing angle shows an analogous parabolic course for each constant value of acceleration, with a tendency toward shift of the peak (maximum) from over 0° for $a = 0$ m/s² to -1° for $a = 0.18$ m/s². Because average efficiency for the discussed cycle with constant a and M_m changes within an insignificant range, it seems easy to draw a conclusion that analogous changes in terms of the product ($\eta_{n1}\eta_{n2}$) are observed for denominator, being a total of products of alternated driving forces and efficiencies of both phases in the cycle.

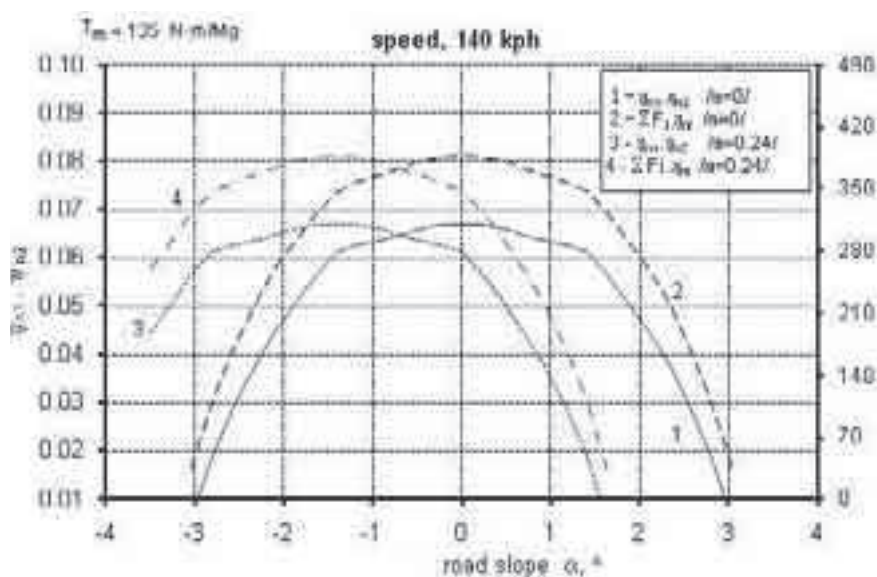


Fig. 4. The course of the $(F_1\eta_1 + F_2\eta_1)$ expression and the $(\eta_1 \eta_2)$ product for the car on the road with the variable profile and speed at fixed, average speed 140 kmph

Tab. 1. Test drive a two-phase variation of the efficiency of car driving cycle of $Mn = 135$ and 110 [Nm/Mg] [2]

Kąt [°]	a [m/s ²]	F _{N1} [N]	F _{N2} [N]	F _{N1} +F _{N2} [N]	T _m =135 [Nm/Mg]			T _m =110 [Nm/Mg]			F _{N1} η _{n2} [N]	F _{N2} η _{n1} [N]	(12)+(13) [N]	(8)/(14) *10 ⁻⁴ [N]	F _{N1} η _{n4} [N]	F _{N2} η _{n3} [N]	(16)+(17) [N]	(11)/(18) *10 ⁻⁴ [N]
					η _{n1}	η _{n2}	2	η _{n3}	η _{n4}	η _{n3} η _{n4}								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
-3.037	0.00	22	1477	1498	0.02	0.32	0.01	0.02	0.33	0.01	7	28	35	1.715	7	36	43	1.851
	0.08	134	1365	1498	0.09	0.31	0.03	0.11	0.32	0.04	42	128	170	1.720	43	153	196	1.854
	0.16	246	1253	1498	0.15	0.31	0.04	0.17	0.32	0.06	75	184	259	1.730	78	219	297	1.868
	0.24	358	1141	1498	0.19	0.30	0.06	0.21	0.31	0.07	107	216	323	1.752	112	241	353	1.872
-2.103	0.00	245	1253	1498	0.15	0.31	0.04	0.17	0.32	0.06	75	184	259	1.730	78	219	296	1.868
	0.08	357	1141	1498	0.19	0.30	0.06	0.21	0.31	0.07	107	216	323	1.752	112	241	353	1.872
	0.16	469	1029	1498	0.21	0.29	0.06	0.23	0.31	0.07	137	221	358	1.751	144	237	381	1.856
	0.24	581	917	1498	0.23	0.28	0.06	0.26	0.30	0.08	165	209	374	1.729	174	235	409	1.873
-1.164	0.00	469	1029	1498	0.21	0.29	0.06	0.23	0.31	0.07	137	221	358	1.751	144	237	381	1.857
	0.08	581	917	1498	0.23	0.28	0.06	0.26	0.30	0.08	165	209	374	1.729	174	235	409	1.873
	0.16	693	805	1498	0.25	0.27	0.07	0.28	0.29	0.08	186	200	386	1.728	201	224	425	1.897
	0.24	805	693	1498	0.27	0.25	0.07	0.29	0.28	0.08	200	186	386	1.728	224	201	425	1.897
0	0.00	749	749	1498	0.26	0.26	0.07	0.28	0.28	0.08	194	194	388	1.728	213	213	425	1.894
	0.08	861	637	1498	0.28	0.24	0.07	0.29	0.27	0.08	204	177	382	1.730	232	188	419	1.890
	0.16	973	525	1498	0.29	0.22	0.06	0.30	0.24	0.07	215	151	366	1.734	236	159	396	1.863
	0.24	1085	413	1498	0.30	0.21	0.06	0.31	0.22	0.07	225	122	347	1.766	239	128	367	1.861
1.164	0.00	1029	469	1498	0.29	0.21	0.06	0.31	0.23	0.07	221	137	358	1.751	237	144	381	1.857
	0.08	1141	357	1498	0.30	0.19	0.06	0.31	0.21	0.07	216	107	323	1.752	241	112	353	1.872
	0.16	1253	245	1498	0.31	0.15	0.04	0.32	0.17	0.06	184	75	259	1.730	219	78	296	1.868
	0.24	1365	133	1498	0.31	0.09	0.03	0.32	0.11	0.04	129	41	170	1.720	153	43	196	1.854
2.103	0.00	1253	245	1498	0.31	0.15	0.04	0.32	0.17	0.06	184	75	259	1.730	219	78	296	1.868
	0.08	1365	134	1498	0.31	0.09	0.03	0.32	0.11	0.04	129	41	170	1.720	153	43	196	1.854
	0.16	1477	22	1498	0.32	0.02	0.01	0.33	0.02	0.01	28	7	35	1.718	36	7	43	1.854
	0.24	1589	-90	1498	0.32	-	-	0.31	-	-	-	-29	-	-	-	-28	-	-
3.037	0.00	1477	22	1498	0.32	0.02	0.01	0.33	0.02	0.01	28	7	35	1.715	36	7	43	1.851
	0.08	1589	-90	1498	0.32	-	-	0.31	-	-	-	-29	-	-	-	-28	-	-
	0.16	1701	-202	1498	0.32	-	-	0.30	-	-	-	-65	-	-	-	-61	-	-

What will happen, if, in one of the phases, more energy will be supplied than it is required by the energy consumption of the considered velocity-distance profile, i.e. when in order for required velocity to be maintained, energy should be dissipated through braking in one of the phases?

$$F_1 - F = \Delta F \text{ and } E_1 - E = \Delta E, \quad (4.51)$$

where:

F – minimal driving force for a cycle (total of forces in both driving phases, with $F_2 = 0$),

E – level of minimal energy consumption in the cycle,

ΔF – driving force increment in phase 1 over the required value,

ΔE – energy consumption increment over the minimal value,

F_1 – driving force in driving phase in the cycle.

After substitution of the equation (4.51) in (4.50) and consideration of the rise in kinetic energy obtained with average efficiency, it can be obtained, from the definition of η_n for two-phase cycle:

$$\eta_n = \frac{(F + \Delta F)L / 2}{\frac{(F + \Delta F)L}{2\eta_{n1}} - \Delta E_k} = \frac{E + \Delta E}{\frac{E}{\eta_{n1}} + \frac{\Delta E}{\eta_{n1}} + \frac{\Delta E_k}{\eta_{nsr}}}, \quad (4.52)$$

where ΔE_k - kinetic energy increment given by:

$$\Delta E_k = \frac{m}{2} (v_p^2 - v_w^2), \quad (4.36)$$

$$\Delta E_{sr} = \frac{m}{2\eta_{nsr}} (v_p^2 - v_w^2), \quad (4.36b)$$

where:

v_w – velocity at the end of neutral phase, m/s,

v_p – velocity assumed in the velocity profile at the end of driving phase, m/s,

η_{nf} – efficiency for driving phase in the cycle,

η_{nsr} – average efficiency in the cycle with both driving phases.

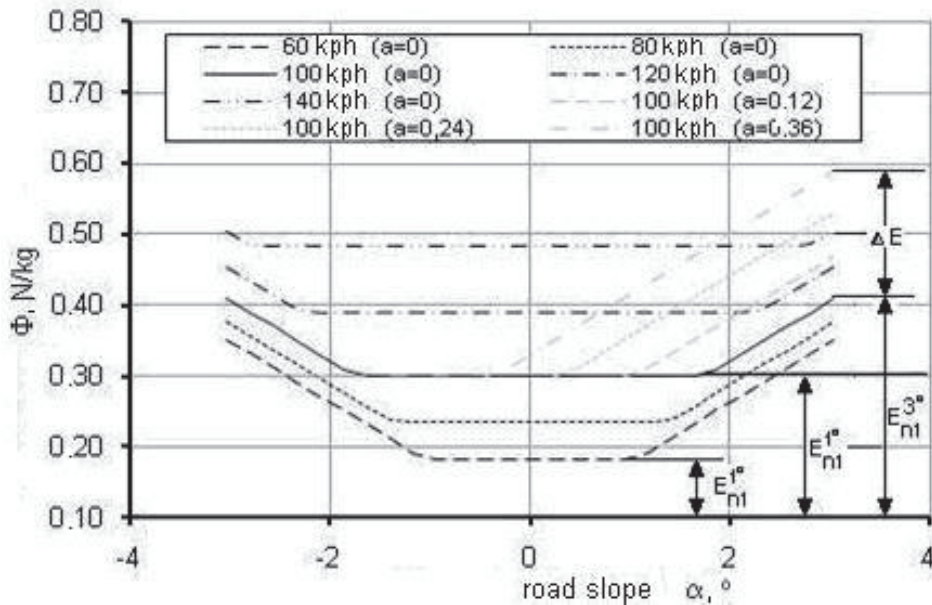


Fig. 5. The course of the unitary demand of the car energy-consumption at different constant speed and for instance for 100 kmph with different acceleration increasing ΔE

If average efficiency is substituted in these equations with η_{n1} and we assume that surplus energy was replaced by kinetic energy with certain efficiency ($\Delta E = \Delta E_k$), the equation (4.52) is given by:

$$\eta_n = \frac{\eta_{n1} (E + \Delta E)}{E}, \quad (4.53)$$

which clearly shows that increase in the energy ΔE transformed into kinetic energy increases efficiency to (as confirmed with calculations, see Fig. 6) the values, which considerably exceed maximal engine efficiency and even up to 1.0. This constitutes another benefit of using impulse-neutral driving under predefined conditions. First of them in the presented model allows for increasing, from average value of efficiency (from 0.04 to 0.12) to the value close to maximal engine efficiency and then, using surplus energy consumption ΔE , one can improve the efficiency up to the value considerably exceeding η_e (even 1.0). However, improving efficiency using this method is sometimes irrational, since, as a consequence of enhanced kinetic energy of the vehicle (velocity), a necessity occurs to decelerate e.g. during braking process. Therefore, rise in ΔE in this case also cannot be translated into the drop in fuel efficiency.

The conclusion can be drawn that braking process is in disagreement with high efficiency and energy-saving control of vehicle speed.

Figure 5 presents how unit energy consumption increment changes in relation to longitudinal climbing angle for selected constant driving speeds (for velocity profile $a = 0 \text{ m/s}^2$). For the angle $\alpha = 1.8^\circ$ varied increments of unit energy consumption in relation to average velocity and, with the example of a profile for 100 kmph (continuous line), also for acceleration ($a = 0.12; 0.24; 0.36 \text{ m/s}^2$ – i.e. velocity profile) can be observed. In extreme cases for $v_{sr} = 100 \text{ kmph}$ $[(E + \Delta E)/E] = 2$.

As results from calculations for the assumed model for simulation of driving on a motorway under mountain conditions, it is possible to reduce actual energy consumption for the car and thus fuel consumption within the range of 10 - 20% for the adopted average driving speed. This is obtained with zero expenditures, through rational driving technique in consideration of varied (in terms of longitudinal road slope) driving conditions.

3.2. Average Efficiency in Two-Phase Driving Cycle

It is possible for each phase in the adopted model of driving cycle to calculate efficiency as a product engine efficiency η_e found in engine performance map and power transmission system efficiency η_p adopted for each gear.

Knowing efficiency for both driving phases of a driving cycle and the values of the corresponding driving forces from the equation (4.49) one can calculate average efficiency for driving cycle with both driving phases. Since unit energy consumption is constant in both driving phases of the adopted driving cycle, and unit overall energy consumption changes within an insignificant range for all engine versions of the power unit, the quotient of both indexes will be constant, changing only in relation to the speed and dynamics of the vehicle. In Fig. 3, for each of the dynamics of the drive, average vehicle efficiency was determined (for $M_m = 75 \text{ Nm/Mg}$) in the adopted cycle.

Figure 5 shows that rise in velocity and decline in dynamics results in the increase in efficiency to the value close to maximal engine efficiency, obviously without exceeding this value. If one of the phases, with motion resistance of $F_{op} \leq 0$, is realized with the neutral, another phase will require driving force higher than the total of driving forces if both phases showed a positive motion resistance force. Cycle efficiency is then calculated according to the formula (4.53), where, with constant denominator, numerator increases with the rise in driving force and energy consumption ΔE . Particularly high-rise in ΔE , reaching 150%, is observed for lower driving speeds and e.g. 3° road slope, which is illustrated by Fig. 5 by means of unit motion energy consumption index Φ .

Figure 6 presents average efficiency in a vehicle with SI engine in the considered driving cycle for all driving speeds and a few dynamics of power unit and constant velocity profile corresponding to the acceleration of $a = 0.24 \text{ m/s}^2$.

As can be observed, efficiency does not exceed 1.0, which is a result of increase in nominator in equation (4.53). Rise in efficiency is also reflected by the drop in total unit energy consumption and fuel efficiency, and in the adopted calculation model this means the effect of consideration of changes in kinetic energy of a vehicle corrected with the efficiency of its acquisition by the power unit, which can be observed in the last term in the nominator of the equation (4.49) and Fig. 4.

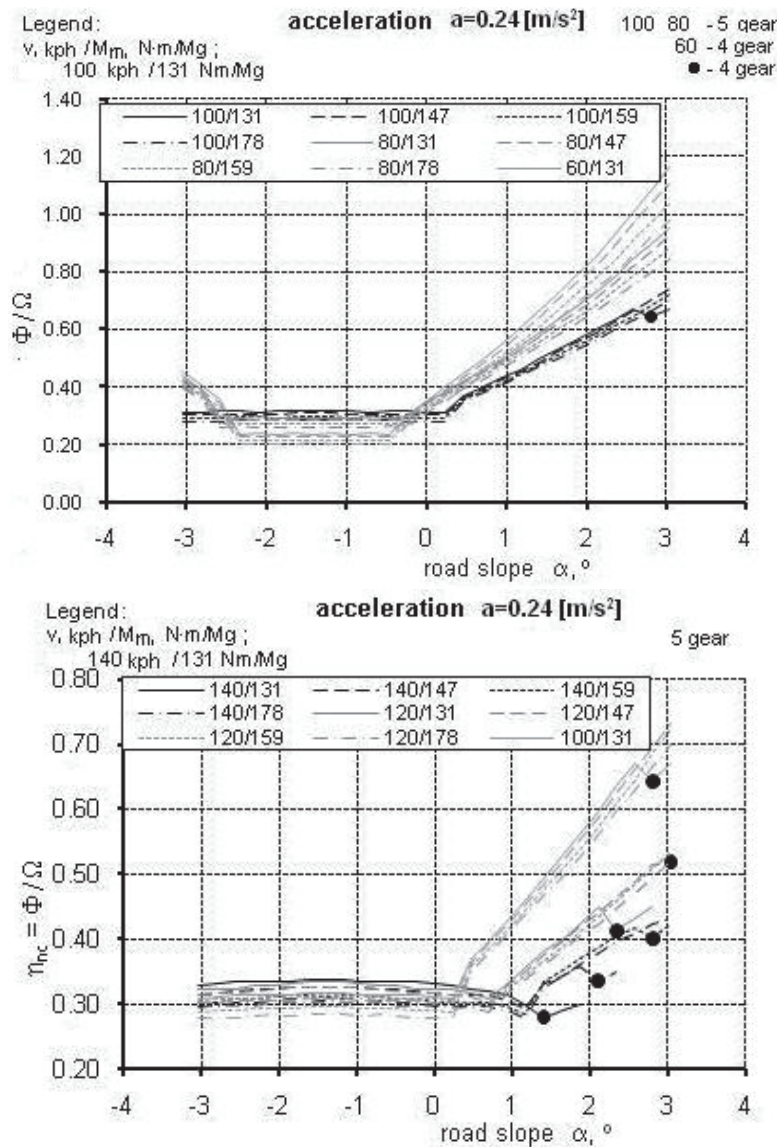


Fig. 6. The average efficiency vs. speed, dynamics and road profile with constant $a = 0.24 \text{ m/s}^2$ speed profile

Optimization of energy consumption can be carried out for both driving phases of a driving cycle only for maximal driving speed in vehicles with SI engines with dynamics, which allow for using working field in the transitional zone at the economical line E. It occurs when transition of working point of one of the phases over the economical line in the characteristic results in disturbance to the balance of total energy consumption in both phases, since, instead of the expected rise in total energy consumption in one phase and drop in the other, a rise is observed in both of them. This phenomenon can be demonstrated through investigation of the function (4.49) which defines average efficiency for both driving phases of the adopted driving cycle for maximal vehicle speed with engine of a suitable drive dynamics ($v = 140 \text{ kmph}$, $M_m = 131 \text{ Nm/Mg}$ – Fig. 4).

Table 2 shows that the total of driving forces in both phases, which exists in numerator of the equation (4.49), is constant, thus the average value of efficiency of the adopted driving cycle is determined by the product of efficiency for both phases and the total of alternated products of efficiency and driving force. Course of both terms, which affect the final value, is presented in Tab. 2, Fig. 4.

Efficiency for the car with the selected dynamics is invariable within a wide range of simulated conditions of vehicle driving, with the exception of some characteristic phases, of which one shows a disturbed monotonic profile of overall efficiency. For lower driving speeds, this considerable differences are not observed, since engine-working points do not cross beyond the economic working line E in engine performance map (monotonicity undisturbed).

4. Conclusions

As results from the presented material, the goals set in the title are possible to be reached, which is also confirmed by the practice:

1. Considerable reduction in unit motion energy consumption can be achieved through application of non-driving neutral phases instead of driving phases, which are characterized by low load to the engine (low overall efficiency η_0).
2. In order to reach high efficiency η_0 , it is helpful, apart from driving in neutral, to achieve low unit engine torque index (M_m) and the route, which covers roads with considerably variable longitudinal slope p which allows for alternate use of driving and non-driving phases using maximal overall efficiency and drive uncoupling.
3. Through use of **higher** energy consumption in driving phases in the route with positive road slope p , over minimal E_1 by the value of ΔE with road slope of $p \geq 2.5^\circ$ in driving phase 1, engine torque index $M_m = 131 \text{ Nm/Mg}$ and average speed of 60 kmph in 6th gear, it is possible to reach efficiency higher than 1.0. The higher the quotient $(E+\Delta E/E)$, the higher efficiency (for acceleration in phase 1, $a = 0.24 \text{ m/s}^2$), under the condition of use of surplus energy and not its dissipation during the process of braking in order to maintain the assumed average speed in two-phase cycle.
4. A considerably high M_m index is necessary for ensuring a required engine load at the highest adopted gear ratio within the adopted range of velocities (**60–140 kmph**), of which the lowest one allows for the most energy-saving driving, which is confirmed in practice [10, 17].

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