ANALYSIS OF OPERATING CONDITIONS AND EMISSIONS OF THE SELECTED COMPONENTS OF EXHAUST GAS DURING SI ENGINE BRAKING PHASE

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Abstract

This paper presents analysis of conditions of CO_2, CO, HC and NO_x emissions during engine braking phase in vehicles with 1.6 SI engine, based on the results of investigations by Professor Romaniszyn. The analysis aimed to determine the effect of cooling of catalytic converter and engine chamber on emissions of toxins and fuel efficiency in next driving phase. Based on own investigations, the synthesis of fuel consumption under three non-driving conditions of engine operation (i.e. continuous drive, engine braking and drive in neutral) is also presented.

Current research centres often carry out extensive investigations of fuel efficiency and emissions of toxic compounds during real use of vehicles. Their results, due to previous assumptions or limitations in the scope of investigations, rarely provide an overall view of the problem. These attempts are typically made in scientific papers and dissertations [1-3]. Selective approach to the problem can be justified by the complexity and varied impact of each phase of engine's operation on fuel consumption under unsteady heat conditions. Fuel consumption map in speed-acceleration coordinates for vehicle and engine, characteristics of CH emissions, parameters of engine braking phase and temperature characteristics of exhaust gases before catalytic converter are presented in the paper.

Keywords: *toxic emissions, engine braking phase, catalytic converter, non-driving phases*

1. Introduction

Current research centres often carry out extensive investigations of fuel efficiency and emissions of toxic compounds during real use of vehicles. Their results, due to previous assumptions or limitations in the scope of investigations, rarely provide an overall view of the problem. These attempts are typically made in scientific papers and dissertations [1-3]. Selective approach to the problem can be justified by the complexity and varied impact of each phase of engine's operation on fuel consumption under unsteady heat conditions. Therefore this subject has been widely described in many scientific publications and dissertations [4-7]. There are a variety of papers on the effect of this condition of operation on fuel efficiency and emissions of toxins from exhaust gases released from engines [8-11].

There is also a multiplicity of publications on fuel efficiency and emission of toxins during each phase of engine operation in steady heat condition [12-14].

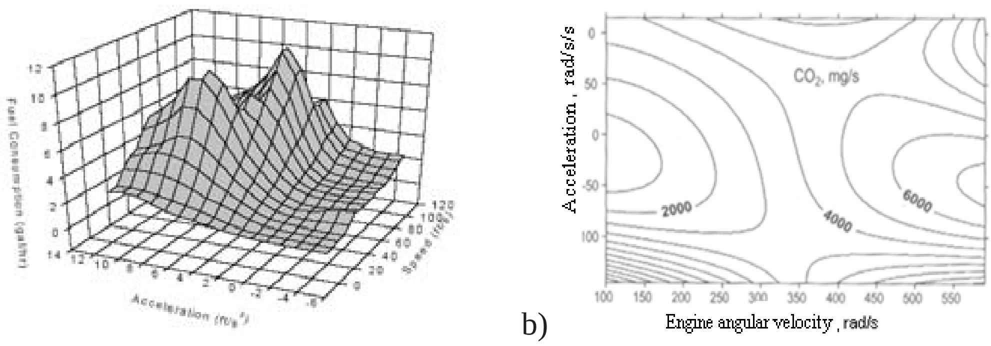
Relatively fewest scientific works focus on non-driving phases of engine operation [15, 16], usually considered in a simplified form or deliberately neglected [17, 18]. Non-driving phases of operation in contemporary SI and CI engines are much varied in terms of thermal conditions, fuel consumption and emissions of toxins. This mainly concerns the phases of engine braking. On the basis of the results of the investigations by Professor Romaniszyn [19], the complexity of operating conditions in SI engine was analysed in detail, based on fuel consumption (CO_2) values and emissions of selected components.

2. Theoretical assumptions

Internal combustion engine operating states during real operation can be divided into two groups: driving and non-driving ones. They can be assigned to each phase of speed profile in each condition of real operation of a vehicle. They depend on interrelations between the total of tractive resistance and the motive force acting on drive wheels of a vehicle.

Calculations of fuel efficiency in vehicles by means of the methods of total absorptiveness of energy and carbon balance, on the basis of emission maps for selected components, reveal discrepancies of the assumptions made for both methods [9, 10]. Furthermore, those discrepancies affect accuracy of calculations for fuel consumption and emissions of the selected compounds. In non-driving phases a considerable diversity of conditions of engine work occurs, which, in extreme cases, might impact on engine's operating conditions during driving phases.

Even bigger calculation errors for emissions of selected toxins are accepted during analyses conducted by means of vehicle speed/acceleration coordinates in real traffic conditions. This approach to investigations results in considerable scatter of working points in engine performance maps, assigned to a discrete range of calculations individually (Fig. 1a). The scatter of the results of measurements is caused by longitudinal road slope along the investigated route [20].



a) b)

Fig. 1. Fuel consumption map in speed-acceleration coordinates for vehicle (a) and engine (b) [24, 19]

During real operation of a vehicle, three basic types of the conditions of engine work in non-driving phases can be distinguished:

- continuous drive (particular case with load torque close to zero),
- drive in neutral,
- engine braking.

Each of these conditions requires separate analysis. It is unacceptable to assume, on the border with driving phases, a continuity of the processes of emissions of toxic compounds and fuel consumption (Fig. 1b). On the other hand, finding this border for driving under real conditions is very difficult due to variable angle of longitudinal road slope. Short synthesis of this problem for driving along a specified road distance is presented in Chapter 4, on the basis of previous results.

3. SI engine braking

Braking with SI engine with catalytic converter is, on the one hand, very beneficial due to the fact of zero fuel consumption. On the other hand, strong cool-down of the converter might occur due to the large amounts of cold air pumped by the engine with opened throttle. In the case of lack of protection the temperature in the converter can drop below 250°C and its warm-up will be necessary, which might result in considerable rise in fuel consumption and, in consequence, CO_2, CO and CH emissions from exhaust gases at the beginning of next driving phase.

For this reason the author suggests that the problem of calculations for emissions of selected compounds should be approached for each non-driving phase individually (under steady heat conditions).

The biggest problems arise for the abovementioned engine braking phase. After 2-3 seconds the fuel injection should be switched off, and, in order to reduce tractive resistance, the throttle is typically opened. Particularly high risk of excessive cool-down of the catalytic converter is from a new energy-effective driving style, very popular recent years. Its fundamental rule is to ensure engine operation at possibly lowest ranges of engine speed by means of optimal control of manual gearbox [21, 22]. At lower engine speeds, the temperature of exhaust gases before the converter is not much bigger than minimal temperature of its operation, which is presented in Fig. 3. Moreover, engine braking reduces vehicle's speed much more efficiently than in the case of driving in neutral and thus many drivers use both of these techniques of vehicle control interchangeably, as an alternative for continuous drive with small engine load, not exceeding 8-18%. Engine braking should also be used if vehicle speed reduction in necessary, which ensures saving of fuel and elements of braking system.

In consideration of engine braking phases, the question arises of where is a time limit over which a risk of excessive cool-down in catalytic converter occurs. The indirect answer to the question can be derived from the results of investigations by Professor Romaniszyn [19]. He presents the results of readings of emissions of four main components of exhaust gases from engines, i.e. CO_2, CH, CO and NO_x, in deliberately induced 6 phases of engine braking and driving in three highest gears.

Figure 2 presents an example of characteristics of emissions of hydrocarbons during NEDC cycle, elongated with additional phases. Starting point of each phase is marked by numbers from 1 to 6. In order to observe the decrease in efficiency of catalytic converter as a result of excessive cool-down and inertia of readings for exhaust gases parameters compared to speed profiles the particular focus should be on the following values, possible to be read from the characteristics:

- total duration of engine braking – t_c (Fig. 4a),
- delay of end of emissions release at the beginning of engine braking – t_e,
- delay of increase in emissions release after reverse phase is completed – t_{op},
- total time of registration of nearly-zero emissions of each compound – $t_{wył}$,
- range or speed in reverse phase in a given gearbox ratio – Δv_i,
- range of engine speeds during engine braking phase – Δn_i,
- mean value of delay of motion in reverse phase – $(dv/dt)_{śr}$,
- maximal emissions of each compound during driving phase after reverse phase – $E_{j,\ max}$,
- time of zero emissions / duration of reverse phase ratio – t_{Eo}/t_c.

The example of readings for each value is presented in Fig. 3a. The results of calculations are presented in Tab. 1-4.

3.1. Analysis of the parameters

On the basis of the shift of the characteristics of CO_2 emissions in relation to speed profile, one can observe that:

1. Average fuel injection switch-off time is 4 s shorter than duration of reverse phase resulting from speed profile; this time is 2 times longer than a theoretical fuel injection switch-off time after releasing of accelerator pedal.
2. Fuel injection delay time (CO_2 emissions) after release of accelerator pedal after run-up phase ($t_e \approx 8.0$ s) is comparatively steady. If 0.7 s is assumed for inertia of control system and vehicle response, balance of delay times is zeroed, i.e. $8 = (2.6 + 4 + 2 \times 0.7)$ s, where 2.6 s means fuel injection delay time t_{op}.

The fact of no response in control system to excessive cool-down in converter is proved by low emissions of each gaseous compound. On the other hand, time necessary for combustion chamber and catalyst carrier to reach working temperature can be proved by considerable increase in NO_x emissions after ca. 8 s (driving phase after reverse No. 2 in Tab. 4).

Due to the fact that measurements were taken from the vehicle in steady heat state, the values of CO_2, CO and CH emissions in driving phases, immediately after reverse phases which cools down the catalytic converter, are of essential value. Intensity of heat exchange in such thin-walled channels washed with the air and then exhaust gases with considerable turbulence (air and exhaust gases volume rates are given in Tab. 6) is very high. Cool-down and warm-up times for converter's channels, particularly with metal carrier, takes several seconds.

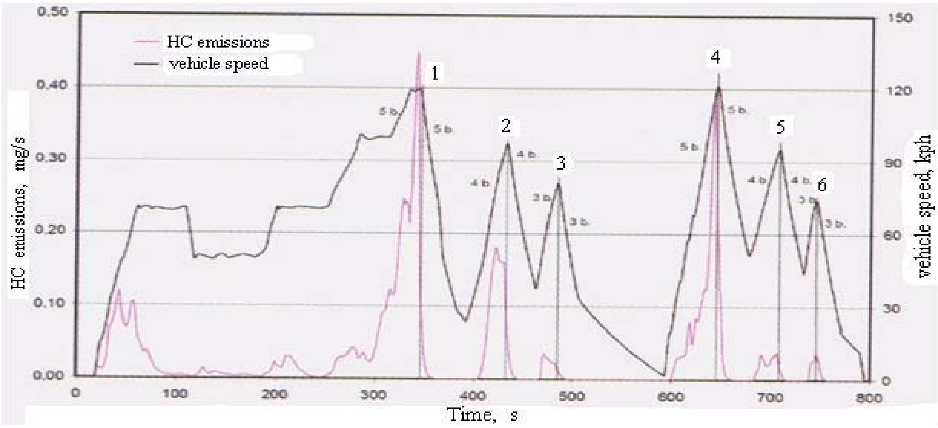


Fig. 2. Characteristics of CH emissions for 5 run-up phases in higher gears and engine braking after EUDC cycle, carried out on chassis dynamometer

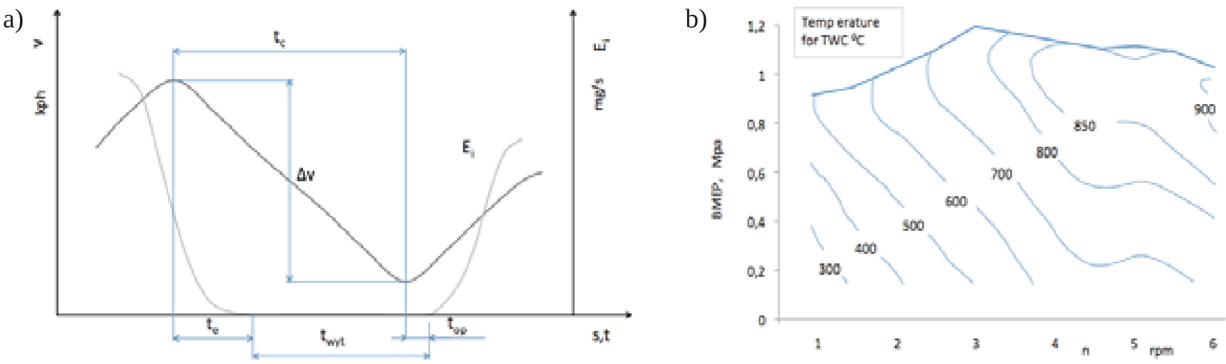


Fig. 3. Parameters of engine braking phase (a) and temperature characteristics of exhaust gases before catalytic converter (b)

Tab. 1. Characteristics of impact of engine braking phase on CO_2 emissions in C vehicle for each gearbox ratio (g/s)

Reverse No.	i_{rew} -	V_i kph	Δn rpm·100	$(dv/dt)_{av}$ - (m/s^2)	$t_c = f(v)$ s	t_e s	t_{op} s	$t_{wyl} = f(e_i)$ s	t_{wyl}/t_c -	Max E, g/s
1	2	3	4	5	6	7	8	9	10	11
1	5	120-27[1)]	40.4 – 9.1	0.660	38.3	7.7	6.1	35.9	0.94	8.0
2	4	97-38	39.7 – 15.5	0.565	29.5	7.5	–2.0	20.0	0.68	6.3
3	3	81-34	42.8 – 18.4	0.637	20.5	7.4	6.5	19.7	0.96	5.4
4	5	120-50	40.4 – 16.8	0.600	32.5	10.5	1.8	32.5	1.00	9.7
5	4	97-44	39.7 – 18.0	0.580	25.4	7.5	–1.5	15.9	0.63	5.8
6	3	75-18	40.6 – 9.7	0.604	26.2	7.5	4.8	23.8	0.91	5.2
Ave	-	-	-	0.607	28.7	8.0	2.6	24.6	0.85	-

[1)] – reverse phase after the phase of v ≈ const., [2)] – time of emissions resumption, difficult to be determined, ∞ – lack of possibility to determine the range due to poor emissions signal

4. Assess of fuel consumption (CO_2 emissions) in the area of zero motive force

Assess of fuel efficiency for three states of work engines, with the same initial and end value speed vehicle, during drive along the measurement distance 'up' and 'down' was carried out as in Fig. 4b, d. Boundary value for zero driving force are determined by the least value of unit power derived from additional tractive resistance (a*v). Remaining(a*v) values are used for optimization of the driving subphase which causes rise in kinetic energy during engine braking, as presented in Fig 4 a, c.

Tab. 2. Characteristics of impact of engine braking phase on CH and CO emissions in C vehicle for each gearbox ratio (g/s)

Rev. No.	t_c = f(v) s	HC					CO				
		t_e s	t_{op} s	t_{wyl}=f(e_i) s	t_{wyl}/t_c -	Max E, mg/s	t_e s	t_{op} s	t_{wyl}=f(e_i) s	t_{wyl}/t_c -	Max E, g/s
1	6	7	8	9	10	11	7	8	9	10	11
1[1)]	38.3	10.7	7.1+12.9[2)]	45.2	1.18	0.45	7.5	9+8.2[2)]	48.5	1.27	29.0
2	29.5	9.5	4.8	22.6	0.77	0.18	5.2	2-12[3)]	∞	-	2.2
3	20.5	7.1	∞	∞	-	0.034	6.5	∞	∞	-	0.5
4	32.5	11.1	4.4	26.7	0.82	0.38	9.8	12.7	36.3	1.12	12.7
5	25.4	6.7	4.4	23.9	0.94	0.04	5.4	3.0[3)]	22.5	0.89	3.6
6	26.2	7.8	∞	∞	-	0.04	3.0	∞	∞	-	0.15
Ave	28.7	8.8	4.6	-	0.93	-	6.2	-	-	-	-

1) – reverse phase after the phase of v ≈ const., 2) – time of emissions resumption, difficult to be determined, 3) – almost immediate, very slow rise in E_{CO}, ∞ – lack of possibility to determine the range due to poor emissions signal

Tab. 3. Characteristics of impact of engine braking phase on NO_x emissions in C vehicle for each gearbox ratio (g/s)

Reverse No.	i_{rew} -	V_i kph	Δn rpm·100	$(dv/dt)_{av}$ - (m/s²)	t_c =f(v) s	t_e s	t_{op} s	t_{wyl} =f(e_i) s	t_{wyl}/t_c -	Max E, g/s
1	2	3	4	5	6	7	8	9	10	11
1	5	120-27[1)]	40.4 – 9.1	0.66	38.3	4.8	8+4.5[2)]	48.5	1.27	0.7
2	4	97-38	39.7 – 15.5	0.565	29.5	4.4	1(8)[3)]	28.0	0.95	0.8
3	3	81-34	42.8 – 18.4	0.637	20.5	6.0	∞	∞	-	9.0
4	5	120-50	40.4 – 16.8	0.600	32.5	7.4	2.1	28.9	0.89	2.2
5	4	97-44	39.7 – 18.0	0.580	25.4	5.7	–1.5	18.5	0.73	22.5
6	3	75-18	40.6 – 9.7	0.604	26.2	17.8[4)]	∞	∞	-	1.2[5)]
Ave		-	-	0.608	28.7	5.7	2.6	-	-	-

1) – reverse phase after the phase of v ≈ const., 2) – this value relates to vehicle's acceleration phases, 3) – almost immediate, very slow rise in E_{NOx} for 8 s, then switching into sharp rise up to 9.0 mg/s, 4) – growing emissions during acceleration and reverse, 5) – max. emission in reverse phase, for 20s, ∞ – lack of possibility to determine the range due to poor emissions signal

Tab. 4. Comparison of basic time parameters which characterise emissions of CO_2, CO and CH for each engine braking phase

Nr	i_{rew} -	V_i×100 kph	t_c s	t_e s			t_{op} s			t_{wyl}/t_c -		
				CO_2	CO	HC	CO_2	CO	HC	CO_2	CO	HC
1	2	3	6	7	8	9	10	11	12	13	14	15
1	5	120-27[1)]	38.3	7.7	7.5	10.7	6.1	9+8.2[2)]	7.1+12.9[2)]	0.94	1.27	1.18
2	4	97-38	29.5	7.5	5.2	9.5	–2	2-12[3)]	4.8	0.68	-	0.77
3	3	81-34	20.5	7.4	6.5	7.1	6.5	∞	∞	0.96	-	-
4	5	120-50	32.5	10.5	9.8	11.1	1.8	12.7	4.4	1.0	1.12	0.82
5	4	97-44	25.4	7.5	5.4	6.7	–1.5	3.0[3)]	4.4	0.63	0.89	0.94
6	3	75-18	26.2	7.5	3.0	7.8	4.8	∞	∞	0.91	-	-
Ave	-	-	28.7	8.0	6.2	8.8	2.6	-	4.6	0.85	-	0.93

Particularly short time can be observed for cool-down, which, despite high initial temperature of the converter, occurs at the volume of the flowing air over twofold higher than exhaust gases warming it up during next driving phase (Tab. 6).

Tab. 5. Characteristics of media flowing through catalytic converters' core and immediately after engine braking phase, calculated from the moment of fuel injection switch-off.

Nr rew.	i_{rew} -	V_i kph	Δn rpm·100	$M_o/M_{o,max}$ [1)] -	t_{kat} [2)] °C	V_{air} [3)] dm^3/s	$M_o/M_{o,max}$ [4)] -	t_{sp} [5)] °C	V_{ss} [6)] dm^3/s
1	2	3	4	5	6	7	8	9	10
1	5	120-27[1)]	40.4 – 9.1	0.51	750	53.8	0.55	480	12.1
2	4	97-38	39.7 – 15.5	0.83	870	52.9	0.75	570	20.7
3	3	81-34	42.8 – 18.4	0.58	850	57.0	0.13	420	24.5
4	5	120-50	40.4 – 16.8	0.86	870	53.3	0.88	570	22.4
5	4	97-44	39.7 – 18.0	0.59	800	53.0	0.50	520	24.0
6	3	75-18	40.6 – 9.7	0.72	830	53.8	0.07	270	13.0
Ave		-	-	-	828	54.0	-	472	19.4

[1)] – relative value of engine torque immediately before the phase of engine braking and corresponding temperature of exhaust gases before catalytic converter, [2)] – (from Fig. 3), [3)] – volume of air pumped by the catalytic converter at first second of reverse phase (throttle opened), [4)] – relative load torque immediately after braking phase, [5)] – temperature of exhaust gases before catalytic converter, adequate to load torque, [6)] – intensity of flow of exhaust gases with a given temperature, resulting from engine displacement

During moving in both directions, driving phases (10-10) are a particular case of a driving subphase increasing kinetic energy during braking which takes so long that in order to obtain a speed profile identical to the phase of driving in neutral, the engine must work at zero load torque so that it does not cause vehicle stopping. In both cases, the process of continuous drive with zero load torque occurs for (a*v) ≈ –3.0 and –6.0 W/kg, respectively. „a*" equals a total of average acceleration of a vehicle and gravity, corrected respectively with coefficient of rotational mass and road slope p = sin α.

$$(a^*v) = (a\cdot\delta + g\cdot p)\cdot v, \tag{1}$$

where:

a - wehicle acceleration, m/s^2,
δ - mass ratio, -,
g - gravity constant, 9,81 m/s^2,
p - road slope, -,
v - speed of vehicle, kph, mps.

This simulation of calculations for fuel efficiency with consideration (dashed lines) and without consideration (continuous line) of the drop in engine's effective efficiency in non-stationary conditions of operation allows for optimization of dynamics of increase in kinetic energy of the vehicle in central subphase. Upper lines also concern (2x3) sec delay of fuel injection switch-off in two reverse phases. Rise in fuel efficiency by over 1 dm^3/100 km during reverse phase would be, for the distances (223 and 177 m, respectively) covered during these phases, two times shorter if the subphase were moved to the end of the braking phase.

Figure 4 presents comparison of fuel efficiency for three techniques of vehicle speed control. End values are reserved for the techniques that allow for obtaining of identical speed profiles in the calculated phase of vehicles motion: continuous drive with zero torque ($Q_{n.c.}$ ≈ 6.5 dm^3/100 km) and drive in neutral (Q_w ≈ 2.0 dm^3/100 km). In reverse motion, with subphase with moderate dynamics of kinetic energy recovery, fuel efficiency amounts to ca. 4.0 dm^3/100 km.

Therefore, in fuel consumption or emissions maps or maps for emissions in real conditions presented in many publications, these end values might vary within the range that depends on road slope and moving direction. For the road with insignificant slope (g·p = ±0.16 m/s^2) the end value of (a*v) = (a·δ + g·p) ·v ranges from –6.0 do –3.0 W/kg for upward movement.

The author does not determine the decrease in effective efficiency of the engine for negative values of (a*v) in his publications. According to the author, the drop in effective efficiency under these conditions is so low that, without erring, one can obtain this value on the basis of engine performance maps (quasi-stationary engine's operation conditions) [22].

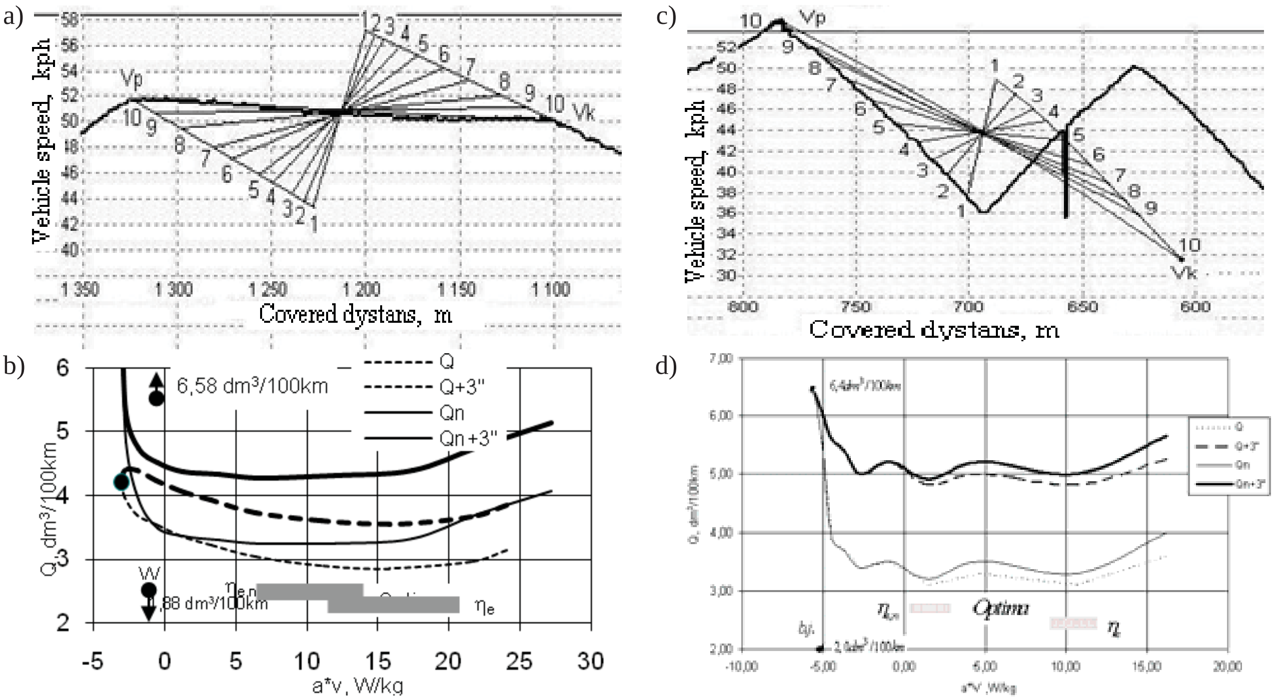


*Fig. 4. A varied scope (a*v) in driving subphases from (1-1) to (10-10) in the vehicle of B/K class during 'down' (a,b) and 'up' (c,d) motion*

5. Conclusions

On the basis of the conducted analysis of emissions of fundamental components of exhaust gases in the area of reverse phase, one can assume that:

1. Inertia of readings for exhaust gas parameters (2.6 s) is accompanied by 0.7 s time shift (delay and then acceleration) of emissions measurements response in relation to boundary values of vehicle velocity during engine braking.
2. Fuel injection (CO_2 emissions) switch-off time in the investigated C vehicle with 1.6 SI engine is on average by 3s shorter than the time of release of accelerator pedal.
3. Values of CO_2, CO and CH at the beginning of next (driving) phase, despite intensive cool-down of catalytic converter's core, do not indicate perturbation in mixture composition during its renewed warming-up up to working temperature.
4. Due to the limited area of cool-down in combustion chamber and the catalytic converter by means of the air pumped during the reverse phase, the time of reaching working temperature for both converter and engine does not take longer than 4-10 s, which is proved by intervals of fast increase in nitrogen oxides emissions.

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