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VEHICLE COAST-DOWN METHOD AS A TOOL FOR CALCULATING TOTAL RESISTANCE FOR THE PURPOSES OF TYPE-APPROVAL FUEL CONSUMPTION

Summary. A coast-down test is carried out in cases when there is a need for the exact expression of the forces acting on a road vehicle during its coast-down. These forces act mainly against the vehicle's movement due to air and tyre rolling resistance. Knowledge of the course of these forces throughout the vehicle's movement range is also a requirement when measuring fuel consumption with a roller performance dynamometer. The reason is that this device has to load the

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rollers by force or performance corresponding to the given vehicle, while testing it during various driving cycles. For approval purposes, the requirements for this type of test are described in the applicable regulations, i.e., UNECE Regulations No. 83 and No. 101, or the newly developed Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Slovak Technical Standard STN 30 0556 also contains detailed procedures for carrying out the test. The authors of this paper have taken into account both types of technical regulations in order to conduct coast-down tests on chosen vehicles. The results are usable in terms of measuring fuel consumption on a roller dynamometer. Furthermore, the vehicle's economic performance in normal operation mode can be also assumed with these results.

Keywords: coast-down method, vehicle resistance, aerodynamic drag, tyre rolling resistance, fuel consumption

1. INTRODUCTION

A coast-down test is applied to determine resistance under real conditions. This is the test in which a vehicle running by its inertia is slowed down due to driving resistances from the moment of shifting the neutral position of the transmission until reaching zero speed. The test is carried out on a test track. The driving resistances represent forces that act in opposition to the movement of the vehicle running on a horizontal track. These include air resistance and mechanical resistance. Air resistance is caused by the effect of air flow as the vehicle passes through the air. Mechanical resistance represents tyre rolling resistance and resistances in bearings and parts of the transmission device [5 10,11,15,20].

2. MEASUREMENT METHODOLOGY

The vehicle is driven on a straight test track at constant speed under windless conditions; and, after shifting into neutral, it moves further forward by inertia. The vehicle is thus gradually slowed down due to rolling resistance, aerodynamic drag and friction resistance in the transmission device until it completely stops. Changes in the vehicle speed are continuously recorded. The vehicle movement is straight and unevenly slowed during the coast-down. Driving resistances are calculated based on the ascertained course of vehicle deceleration during the coast-down, as well as geometric parameters of the test track and the known vehicle's inertia parameters. The coast-down characteristic of the vehicle is ascertained by coast-down tests. Based on this characteristic, it is possible to assess the mechanical condition of the vehicle, the chassis settings, the influence of used tyres and the aerodynamic properties of the vehicle body [14,19].

Several requirements relating to a vehicle, test track, test speed, atmospheric conditions and measuring equipment must be met when carrying out coast-down tests. These requirements differ depending on the type of regulation used. The requirements of the individual regulations regarding a vehicle, test track, atmospheric conditions and accuracy of the used measuring and recording equipment are listed in Table 1. The most detailed description of such requirements is provided in the WLTP. The results obtained in accordance with the WLTP are used for transferring the load of a road vehicle in normal operation mode onto the rollers of a roller performance dynamometer in order to determine the type-approval fuel consumption [25,30].

The methodology recommended by the WLTP involves performing each coast-down measurement without interruption. However, the division of the section is permitted if the data cannot be collected in a continuous manner across the full speed range. When dividing the measurement process, it is necessary to ensure that vehicle conditions remain as stable as possible at each point of division [29].

Tab. 1

Different requirements for carrying out the coast-down test [23,27,28,29]

Measurement requirements		Available methodologies for the coast-down			
		UNECE No. 101	UNECE No. 83	WLTP	STN 30 0556
Test track parameters	Longitudinal slope	±2%	±1.5%	±1%	±1%
	Local inclination	±0.5%	-	±0.5%	-
	Cross-sectional slope	Max. 1.5%	-	Max. 1.5%	Max. 1.5%
Atmospheric conditions	Wind speed (average)	Max. 3 $m \cdot s^{-1}$	Max. 3 $m \cdot s^{-1}$	Max. 7 $m \cdot s^{-1}$	Max. 1.5 $m \cdot s^{-1}$
	Wind speed (gusts)	Max. 5 $m \cdot s^{-1}$	Max. 5 $m \cdot s^{-1}$	Max. 10 $m \cdot s^{-1}$	-
	Wind cross vector component	Max. 2 $m \cdot s^{-1}$	Max. 2 $m \cdot s^{-1}$	Max. 4 $m \cdot s^{-1}$	-
	Area of measurement above the surface	0.7 m	0.7 m	-	-
	Air temperature	5- 35°C	-	5-40°C	5-25°C
	Air pressure	91-104 kPa	-	-	97.33-101.25 kPa
	Relative humidity	Max. 95%	-	-	-
Vehicle	Vehicle run-in	Min. 300 km	Min. 3,000 km	Min. 3,000 km	-
	Tyre run-in	Min. 300 km	-	Min. 200 km	Min. 1,000 km
	Tread depth	50-90%	50-90%	80-100%	67%
	Time recording (frequency)	-	-	5 Hz	-
Measuring equipment (accuracy)	Time recording (accuracy)	±0.1 s	±0.1 s	±0.01 s	-
	Speed record (accuracy)	±0.5 $km \cdot h^{-1}$	±2%	±0.5 $km \cdot h^{-1}$	-
	Wind speed	-	-	±0.3 $m \cdot s^{-1}$	-
	Wind direction	-	-	±3°	-
	Air temperature	-	-	±1 K	-
	Air pressure	-	-	±0.3 kPa	-
	Vehicle mass	-	-	±10 kg	-
	Tyre pressure	-	-	±5 kPa	-

The measurements of coast-down are carried out in both directions repeatedly until at least three consecutive measurement pairs meet the requirements for statistical accuracy p in percentage terms as shown below (1).

$$p = \frac{h}{\sqrt{n}} \cdot \frac{\sigma}{\Delta t_j} \cdot 100 \tag{1}$$

where $\frac{h}{\sqrt{n}}$ represents the coefficient, which is determined by the WLTP depending on the number of performed pairs of coast-down measurements. For example, the coefficient 2.48 is used for n=3 and the coefficient 1.6 is applied for n=4. The standard deviation expressed in seconds is denoted as σ, while Δt_j is the average time of the coast-down at the reference speed in seconds.

The standard deviation is calculated according to the following formula:

$$\sigma = \sqrt{\frac{1}{n-1} \cdot \sum_{n=1}^{n} (\Delta t_{ji} - \Delta t_j)^2} \tag{2}$$

where Δt_{ji} represents the harmonized average time of the coast-down of the i-th pair of measurements and is calculated according to the following formula:

$$\Delta t_{ji} = \frac{1}{\frac{1}{\Delta t_{jai}} + \frac{1}{\Delta t_{jbi}}} \tag{3}$$

where Δt_{jai} and Δt_{jbi} represent the time of the coast-down for the i-th measurement in each direction, respectively.

The calculated statistical accuracy of at least three consecutive coast-down tests in each direction (three pairs of measurements) should not exceed 3%, according to the WLTP [29].

After meeting the accuracy of the performed coast-down tests, coast-down curves are created based on the recorded data (Figure 1), while vehicle resistances are determined in newtons for the whole range of examined speed. To calculate these resistances, it is necessary to divide the coast-down curve into individual vehicle speed intervals. The WLTP recommends an interval width of 20 $km \cdot hod^{-1}$ for the coast-down from the speed higher, rather than 60 $km \cdot hod^{-1}$. The durations are assigned to the respective intervals of speed decreases, and thus the vehicle resistances are determined or the dependence of vehicle resistance on speed is ascertained.

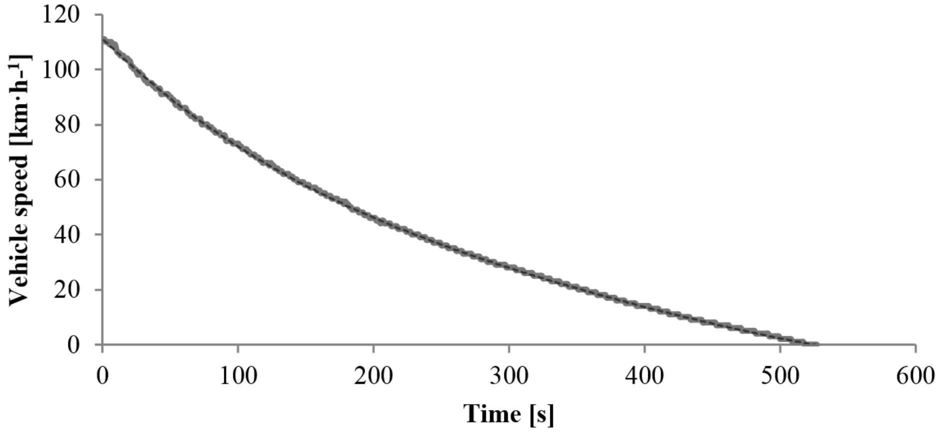

Fig. 1. Coast-down curve

The resistance force for individual speed intervals is calculated according to the formula shown below (4). In this formula, m_{av} represents the vehicle mass while tested. This is the average vehicle mass before and after carrying out the coast-down, while considering the consumed fuel. Further, m_r is the equivalent effective mass of all the wheels and vehicle components rotating with the wheels during the coast-down on the road. It should be measured or calculated by an appropriate technique. Alternatively, m_r may be estimated to be equal to 3% of the unladen vehicle mass when increased by 25 kg.

$$F_j = (m_{av} + m_r) \cdot \frac{\Delta v}{3.6 \cdot \Delta t_j} \tag{4}$$

If necessary, it is also possible to determine resistance forces for individual directions of the vehicle coast-down. This requires calculating the average times of the intervals for the relevant direction; however, the formula is the same as the previous one.

$$F_{j(a/b)} = (m_{av} + m_r) \cdot \frac{\Delta v}{3.6 \cdot \Delta t_{j(a/b)}} \tag{5}$$

3. MEASUREMENT RESULTS

Three vehicles were used for practical tests on the coast-down (Figure 2). The first tested vehicle was that used in the laboratory of the Department of Road and Urban Transport, namely, a Kia Ceed 1.6 CVVT, which is a vehicle with a spark-ignition engine. The vehicle kerb weight is 1,163 kg, the air resistance coefficient is 0.33 and the vehicle frontal area is 2.25 m^2. The second tested vehicle was a Ford Galaxy 2.0 Ghia, which has a diesel engine. The vehicle kerb weight is 1,799 kg, the air resistance coefficient is 0.314 and the vehicle frontal area is 2.78 m^2. The third tested vehicle was a Hyundai i30 Wagon with a 1.6 CRDi diesel engine. The vehicle kerb weight is 1,413 kg, the air resistance coefficient is 0.3 and the vehicle frontal area is 2.136 m^2. Before carrying out the coast-down tests, the vehicles were subjected to tyre pressure control and the tyres were inflated as required by the WLTP.

Fig. 2. Tested vehicles (Kia Ceed, Ford Galaxy, Hyundai i30)

The coast-down tests were carried out on the road connecting Water Dam Žilina with the village of Mojš. The test track was 1.25 km long. The rest of the road section was used for vehicle acceleration and turning the vehicle in opposite direction. The road had an asphalted surface of sufficient quality. At the beginning of the section, it was necessary to achieve the required vehicle speed. The initial vehicle speed was 115 km·h^{-1} and the coast-down was recorded from the speed of 110 km·h^{-1}. As the test track was not sufficiently long enough to carry out the whole coast-down, the test was divided into two measurement parts (from 110 km·h^{-1} to 60 km·h^{-1}, and from 65 km·h^{-1} to 0 km·h^{-1}). The test track is graphically illustrated in Figure 3.

Fig. 3. Test track [Google Maps]

During the coast-down measurements, atmospheric conditions were controlled and recorded by using a weather station with a thermometer, a moisture meter and an anemometer. All atmospheric conditions complied with the required level for the measurements. The wind speed was at the average level of 1.1 m·s^{-1} and air temperature was 14°C.

The universal OBD2 diagnostics device, which was compatible with the diagnostic interface equipped with the ELM327 chip and TouchScan software, was used to record vehicle speed over time. This device allows for recording data at a frequency of approximately 3 Hz. Before using the diagnostics device, it is advisable to calibrate a speed indicator, e.g., by using a roller performance dynamometer, which is also among the equipment available from the laboratory of Department of Road and Urban Transport [3,9,17,19]. The record of vehicle speed over time is saved in .txt format, meaning that it is possible to work with it in Microsoft Excel.

After processing the results of the coast-down for tested vehicles, the calculation of accuracy was made according to the formulas mentioned previously in the paper (see Chapter 2). In total, three coast-down tests in each direction of the measuring section for each tested vehicle were carried out. Each measured coast-down was divided into two measurement parts (from 110 $km \cdot h^{-1}$ to 60 $km \cdot h^{-1}$, and from 65 $km \cdot h^{-1}$ to 0 $km \cdot h^{-1}$) due to the insufficient length of the test track. Based on Table 2 and Figure 4, it can be concluded that the duration of the coast-down in Direction 1 was significantly shorter than the coast-down in Direction 2. This is caused by the longitudinal slope of the measuring section. The value of this slope was 1.1%, which slightly exceeds the required value according to the WLTP. Therefore, the harmonized average time of the coast-downs was applied to the calculations. In the case of first two vehicles, the required statistical accuracy of not exceeding 3% was met. However, the Ford Galaxy slightly exceeded this requirement. In the case of using this information for determining the type-approval fuel consumption or the official measurement of fuel consumption, it would have been necessary to repeat the measurements with this vehicle until the statistical accuracy was achieved at the required level.

Tab. 2

Calculation of statistical accuracy of the coast-down for the tested vehicles

Vehicle	Coast-down Direction 1 [s]	Coast-down Direction 2 [s]	Coast-down Direction 1 [s]	Coast-down Direction 2 [s]	Coast-down Direction 1 [s]	Coast-down Direction 2 [s]	Harmonized average time Δt_{ji} [s]			Average time of the coast-down Δt_j [s]	STD σ [s]	Statistical accuracy p [%]
Kia Ceed	145.80	186.28	145.85	196.02	145.00	190.30	163.57	167.25	164.59	165.14	1.90	2.85
Hyundai i30	143.94	191.25	149.69	184.75	147.74	184.36	164.26	165.38	164.03	164.56	0.72	1.09
Ford Galaxy	149.90	205.77	150.80	209.70	153.33	213.89	173.45	175.44	178.62	175.83	2.61	3.68

It is possible to express the resistance force of the vehicle for each direction separately. Mainly in the case of roads with a longitudinal slope near to the tolerance limit, or in the case of wind direction in the longitudinal direction of the measuring section, differences may occur in the values for individual directions. For this reason, the harmonized average time (Δt_j) of the alternating measurements of the coast-down must also be determined, so that the average total vehicle resistance (F_j) can be calculated. The processed results of the coast-down test for the Hyundai i30 are presented in detail in Table 3.

The outcome of this type of test is the determination of the total driving resistance of the vehicle while driving at constant speed on a horizontal road. If necessary, it is also possible to calculate the required performance (power) to overcome this resistance. The resultant resistance force expressed in newtons is multiplied by the actual vehicle speed in $m \cdot s^{-1}$, such that the calculated performance required to overcome the resistance is expressed in watts. Using these types of calculation, it is also possible to determine the performance needed to overcome any speed or the maximum speed of the vehicle [7,8,10,11,14,32].

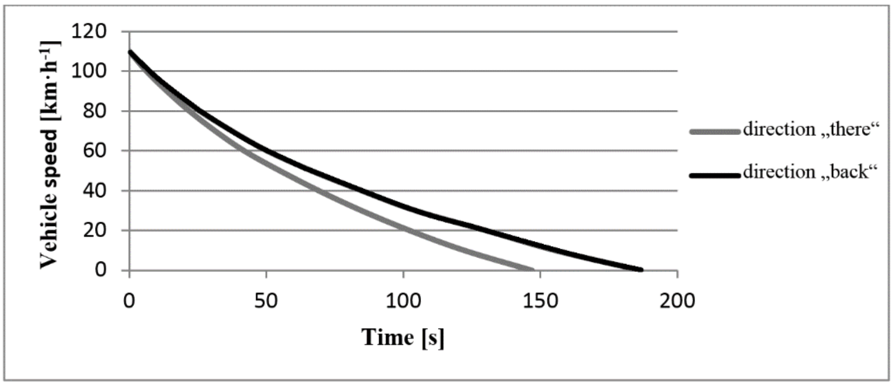

Fig. 4. Average times of the coast-down in the “there” and “back” directions for the Hyundai i30

Tab. 3

Processed results of the coast-down for the Hyundai i30

Vehicle speed and speed intervals [km·h^{-1}]		Time of the coast-down for respective intervals for Direction 1 [s]			Δt_{ja}	Time of the coast-down for respective intervals for Direction 2 [s]			Δt_{jb}	F_{ja}	F_{jb}	Δt_j	F_j
105	<110;100)	6.17	6.50	6.14	6.27	6.69	7.78	7.24	7.24	758.52	657.20	6.72	707.86
95	<100;90)	6.62	7.99	7.79	7.47	9.01	8.77	8.31	8.70	636.96	546.87	8.03	591.91
85	<90;80)	8.24	7.87	8.58	8.23	9.40	10.10	10.12	9.87	577.88	481.70	8.98	529.79
75	<80;70)	8.50	9.84	9.95	9.43	11.31	11.92	11.79	11.67	504.34	407.42	10.43	455.88
65	<70;60)	10.80	11.11	9.96	10.62	12.94	12.92	12.82	12.89	447.69	368.87	11.65	408.28
55	<60;50)	12.45	13.54	13.20	13.06	16.14	16.18	16.33	16.22	364.07	293.28	14.47	328.67
45	<50;40)	13.46	14.50	14.66	14.21	18.60	18.14	18.29	18.34	334.77	259.27	16.01	297.02
35	<40;30)	15.00	16.10	15.81	15.64	19.47	19.85	19.65	19.66	304.15	241.95	17.42	273.05
25	<30;20)	17.45	17.35	18.02	17.61	25.76	25.76	25.76	25.76	270.12	184.63	20.92	227.37
15	<20;10)	20.03	19.59	20.39	20.00	29.18	22.72	23.96	25.29	237.76	188.08	22.34	212.92
5	<10;0>	25.22	25.30	23.24	24.59	32.75	30.61	30.09	31.15	193.44	152.68	27.48	173.06
∑		143.94	149.69	147.74	147.12	191.25	184.75	184.36	186.79	-	-	-	-

For type-approval fuel consumption purposes, the final result of this kind of test is the function of driving resistance curves. These curves are expressed as a quadratic function of velocity. Individual parameters then become the basis for transferring the load of a particular vehicle to the rollers of a roller performance dynamometer. Subsequently, this device is able to simulate respective driving resistances in relation to the actual speed of a vehicle moving on the rollers.

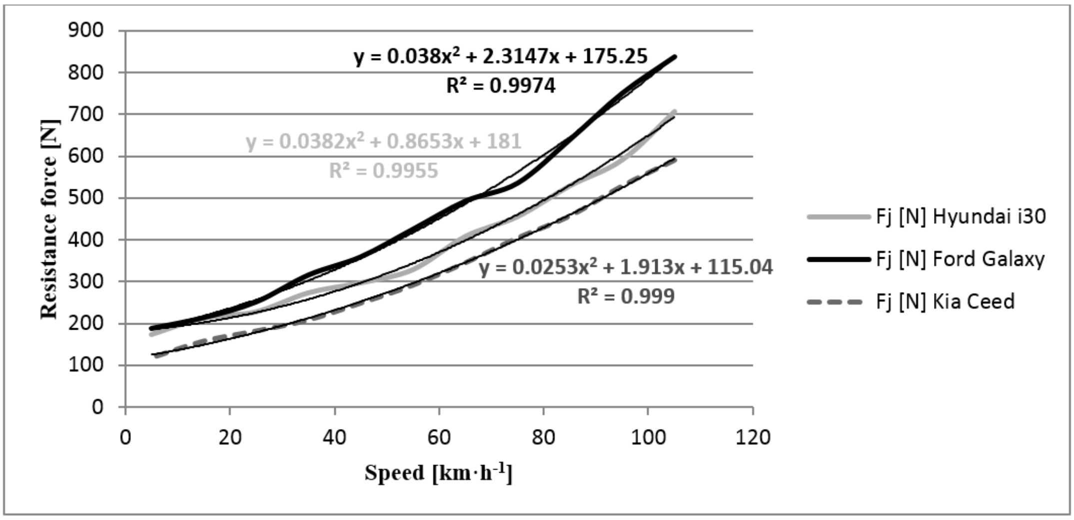

Fig. 5. Comparison of the average driving resistance of the tested vehicles

3. CONCLUSION

The issue of measuring vehicle resistance is addressed by several methodologies. For the type-approval fuel consumption purposes in 2018, it will be necessary to follow the methodology presented in the WLTP [20,29], which insists on significant requirements to be met relating not only to measuring equipment but also to the test track, atmospheric conditions and the vehicle itself. This paper has analysed the existing regulations for carrying out the coast-down test, as well as addressed the difficulty in quantifying driving resistances by using practical measurement examples involving three vehicles. The difficulty of the test lies primarily in processing the results with statistical tools in such a way that the resultant vehicle resistance corresponds to normal operation mode as realistically as possible.

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