Acta
Technica
Jaurinensis

Vol. 14, No. 4, pp. 477-487, 2021
DOI: 10.14513/actatechjaur.00593

Methods and simulation to reduce fuel consumption in driving cycles for category N1 motor vehicles

A.A. Kolin*, S.E. Silantyev, P.S.Rogov, M.E. Gnenik

Nizhny Novgorod State Technical University n.a. R.E. Alexeev,
Nizhny Novgorod, 24 Minin street, 603950, Russia.
***e-mail: kolinaa@nntu.ru**

Submitted: 27/01/2021; Accepted: 14/04/2021; Published online: 19/05/2021

Abstract: The paper presents the results of using the simulation model estimating the fuel consumption of a light commercial vehicle in road traffic cycles; virtual tests are performed. The impact analysis of the motor vehicle design parameters on fuel consumption in NEDC and WLTC cycles is conducted. Numerical values of average fuel consumption are obtained for variation of the main parameters of the structure in NEDC and WLTC cycles. Energy distribution is shown during the motion of category N1 light commercial vehicle.

Keywords: fuel consumption in cycles; simulation model; light commercial vehicle

1. Introduction

Fuel consumption is an important criterion that determines the attractiveness of a car for a costumer. All of the world's leading automakers are committed to reduce fuel consumption [1]. The continuous rise in fuel prices and deterioration of the environment associated with higher intensity traffic lead to creation and implementation of single-approach methods that are used to determine and estimate fuel consumption, economic and environmental properties based on standard driving cycles.

The most common driving cycles include the New European Driving Cycle (NEDC) [2], the American Driving Cycle (FTP-75) and the Japanese Driving Cycle (JC-08).

Additionally, the World Harmonized Driving Cycle (WLTC) [3] was introduced in 2017. It is based on the world statistical study of driving modes and features high accelerations and lack of steady-motion intervals.

The purpose of the study is to build a simulation model quantifying the effect of the design parameters on the fuel efficiency indicator of N1 category light commercial vehicles in NEDC and WLTC driving cycles. The model building environment is matlab/simulink.

It is to be noted that a number of papers are devoted to simulation of a motor vehicle driving cycle [4] [5] [6]. Main methods of improving the fuel efficiency of vehicles are specified in earlier studies [7] [8] [9] [10] [11]. These include the engine parameters optimization, reduction of aerodynamic drag and tire rolling resistance. Also, a number of works are devoted to the study and search for optimal transmission ratios [12] [13] [14] [15] [16] [17]. Everything stated above should have an impact on the result of the vehicle motion process simulation in driving cycles.

A distinctive feature of this work is a detailed study of the dynamics and fuel efficiency of a light commercial vehicle and obtaining of the quantitative influence of each of the motion resistance forces on the total motion energy in the NEDC and WLTC cycles.

2. Methods

The light commercial vehicle motion on NEDC and WLTC cycles is considered in the paper. NEDC cycle consists of one urban driving cycle or 4 simple urban cycles of 195 seconds, and one suburban driving cycle of 400 seconds.

Driving cycle is performed using a detailed operational map included in the standard [1]. The map details the gears of the gearbox to be used for every section of the vehicle motion as well as its accelerations. Application of the standard: transport vehicles of category M1, M2, N1 and N2 with the reference mass not exceeding 2 610 kg. The vehicle driving diagrams based on NEDC cycle are shown in Fig. 1.

As shown in Fig. 2, WLTC cycle is separated by short stops into four phases:

Low-speed phase when the vehicle accelerates to maximum 56.5 km/h; medium-speed phase (76.6 km/h), high-speed phase (97.4 km/h) and extra-high speed phase (131.6 km/h).

In each phase of the cycle the driving is performed based the operational map according to [2] that details basic requirements for the gear shift timing depending on the power-to-weight ratio class of a vehicle.

Extra high-speed phase was not included in the study which is acceptable for the vehicle class under review.

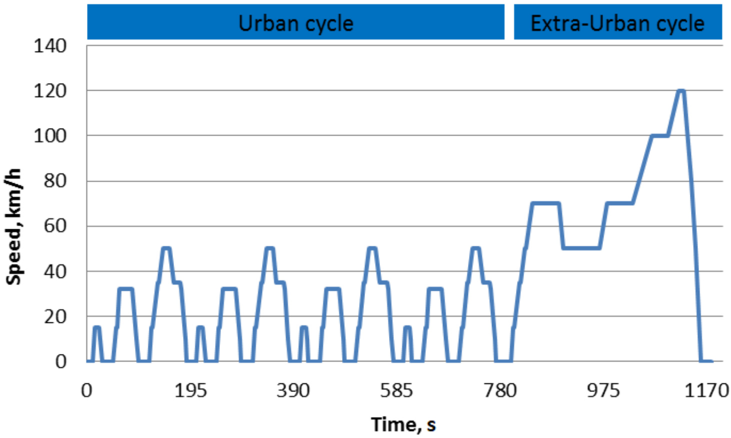

Figure 1. Vehicle motion diagram based on NEDC driving cycle

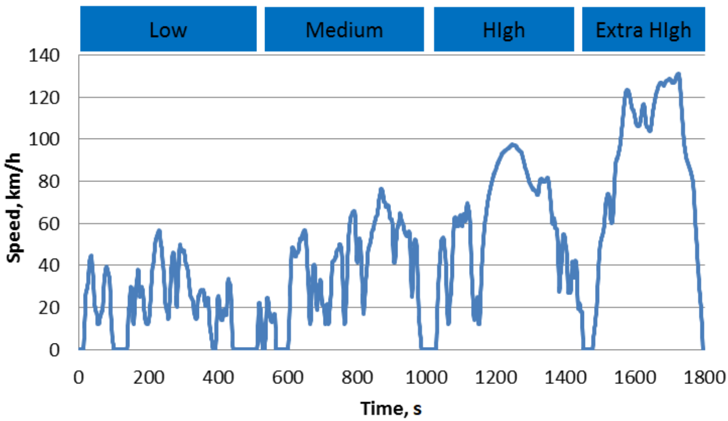

Figure 2. Vehicle motion diagram based on WLTC driving cycle

The simulation model is used for simulation of the vehicle motion. The mathematical formulation of the vehicle motion is based on the following approaches [18].

The traction force is computed by formula:

$$F_T = \frac{T_e u_{tr} \eta_{tr}}{r_w}, \quad (1)$$

where T_e – internal combustion engine (ICE) torque, u_{tr} – transmission gear ratio, η_{tr} – transmission efficiency, r_w – wheel rolling radius.

T_e is normally a function of the accelerator pedal position d(%) and ICE speed ω_e(rad/s), or $T_e = f(d,\omega_e)$. T_e is represented by data array $T_{e\ i,j}$, i =1…17, j =1…11 in the mathematical model. In this particular case, for acceleration of the vehicle at full throttle j = 11 and Te = f(ω_e).

The rolling resistance force is determined as [18, p. 22]:

$$F_f = f m_a g; \; f = f_0 + k_f V^2 \quad (2)$$

where f – coefficient of rolling resistance; g – gravity acceleration.f_0 – rolling resistance coefficient at a speed close to 0 km / h; k_f – coefficient that takes into account the influence of speed; V – vehicle speed.

Air resistance is determined as follows:

$$F_w = 0{,}5 C_x \rho_{air} A_v V^2, \quad (3)$$

where C_x – aerodynamic drag coefficient; ρ_{air} – air density; A_v – transverse projection area of the vehicle.

The rotational inertia coefficient is determined as:

$$\delta = 1 + \frac{I_e u_{tr}^2 \eta_{tr}}{m_a r_\kappa^2} + \frac{I_{ds} u_{fd}^2 \eta_{fd}}{m_a r_w^2} + \frac{\sum I_w}{m_a r_w^2}, \quad (4)$$

where I_e – ICE moment of inertia, I_{ds} – drive shaft moment of inertia, u_{fd} – final drive gear ratio, η_{fd} – final drive efficiency, I_w – moment of inertia of a wheel with half-axle (if any). Moments of inertia are determined from design documentation.

When in a steady-speed driving mode, the vehicle speeds up without acceleration. ICE torque and the instantaneous fuel consumption are the unknowns. The unknowns are computed by the following formula:

$$F_T = F_f + F_w + \delta m_a a_a, \quad (5)$$

when ICE torque T_e is calculated, given (1) and the engaged transmission gear that is determined with account for (6). The specific fuel consumption in the model is represented by data array$g_{e\ i,j}$, and is a function of ICE torque and data array $g_e = f(T_e,\omega_e)$. Therefore, the current specific fuel consumption BSFC is determined according to (6) using the Te and we values obtained with the (1), (5), (7).

$$BSFC = \frac{m_f}{P}\; ; P = T_e \omega_e \quad (6)$$

where m_f – fuel consumption rate in grams per second (g/s); P - power (W); ω_e – engine speed (rad/s)

Gear shifting is performed as required in [2] [3]. After gear shifting the engine's starting speed of rotation is determined subject to correlation of the vehicle speed and ICE speed of rotation:

$$V = \frac{\omega_e r_w}{u_{tr}}, \tag{7}$$

The acceleration of the vehicle is computed using the following formula:

$$a_a = \frac{V_{j+1} - V_j}{3{,}6(t_{j+1} - t_j)}, \tag{8}$$

where a_a (m/s) – acceleration of the vehicle; V_j, V_{j+1} (km/h) – initial and final speeds over the selected interval, respectively; t_j, t_{j+1} (s) – start and end times, respectively.

Input data for the simulation, such as the mechanical characteristics of the ICE and the data on its fuel consumption was obtained by performing bench tests. The value of the air drag coefficient was obtained using numerical simulation. Other input data were taken from the technical documentation of the automaker and component manufacturers. To be confident in the reliability of the results, obtained in this formulation, the developed model is then verified. Model initial data in Table 1.

3. Results of the study

Simulation model must reliably react to a change of input data i.e. the reduction of the aerodynamic drag coefficient contributes to lower fuel consumption while the higher aerodynamic drag coefficient results in higher fuel consumption. It can be stated the verification of the model was carried out successfully only if the response of the model is adequate and proportional to the change in the initial data. The simulation results for a light commercial vehicle are specified in Table 2.

It is to be noted that the results obtained are indicative of the indisputable impact of these parameters on the average fuel consumption. An increase of the drive shaft efficiency by 5% brings down the average fuel consumption rate by 0.36%, for NEDC and WLTC cycles, and vice versa.

Table 1. Model initial data.

Parameter	***Value***
Transmission	
Gear ratio	1 – 3.786
	2 – 2.188
	3 – 1.304
	4 – 1
	5 – 0.794
	6 – 0.643
Differential	
Final drive ratio	4.3
Car	
Vehicle kerb weight, kg	2548
Vehicle draft coefficient	0.356
Vehicle frontal area, m^2	5.375
Tire	
Tire size	185/75R16

Increasing the final drive and the gearbox efficiency by 1% in NEDC cycle brings down the average fuel rate by 0.6%, and 0.48%, respectively. For WLTC cycle the change of these parameters results in the reduction of the average fuel consumption rate by 0.72% and 0.66%, respectively.

If the aerodynamic drag coefficient is reduced by 5%, the average fuel rate becomes less by 0.84% for NEDC cycle, and 0.88% for WLTC cycle.

The rolling resistance factor will have less impact as compared to other indices reviewed, since its variation to the extent of 5% causes the average fuel rate to change within the limits of 0.4% for NEDC cycle, and 0.66% for WLTC cycle.

In general, the obtained results show an adequate response of the model to changes in the initial data and, thus, it can be stated that the model was verified successfully.

This study is the initial stage of a comprehensive search and development of practical recommendations for reducing the fuel consumption rate of a motor vehicle in the physical world. As the resulting simulation model allows a qualitative assessment of the vehicle motion parameters, it is decided to evaluate the main areas of further activities. Specifically, to analyse the distribution of the energy consumed on the movement of a light commercial vehicle.

Table 2. Impact of specified parameters for NEDC and WLTC cycles.

Index	***Index variation, %***	***Driving cycle***			
		NEDC		***WLTC***	
		Fuel rate, l/100 km	***Change of fuel rate, l/100 km***	***Fuel rate, l/100 km***	***Change of fuel rate, l/100 km***
Aerodynamic drag coefficient	5	16.87	0.14	13.79	0.12
	0	16.73	0	13.67	0
	-5	16.59	-0.14	13.55	-0.12
Rolling resistance factor	5	16.80	0.07	13.76	0.09
	0	16.73	0	13.67	0
	-5	16.67	-0.07	13.58	-0.09
Ring and pinion set efficiency	1	16.63	-0.1	13.57	-0.1
	0	16.73	0	13.67	0
	-1	16.83	0.1	13.77	0.1
Drive shaft efficiency	0.5	16.67	-0.06	13.62	-0.05
	0	16.73	0	13.67	0
	-0.5	16.79	0.06	13.72	0.05
Gearbox efficiency	1	16.65	-0.08	13.58	-0.09
	0	16.73	0	13.67	0
	-1	16.81	0.08	13.76	0.09

The motion resistance energy values were determined by integrating the corresponding motion resistance forces over the distance of the driving cycle. The energy expended for the light commercial vehicle motion is specified in Table 3.

It is to be noted that the energy of mechanical losses in transmission can be as high as 15% of the total energy expended on the transport vehicle motion, as specified in table 3. The energy of aerodynamic drag accounts for 30 to 40% of the total energy used for cycles NEDC and WLTC, respectively. It is also of major importance, and will become the main area of focus in terms of reduction of the fuel consumption rate.

Table 3. Energy consumption of the vehicle motion for NEDC and WLTC cycles.

	Distribution of energy	**Driving cycle**	
		NEDC	**WLTC**
Total resistance of motion energy	Aerodynamic drag energy, %	40.2	30.7
	Rolling resistance energy, %	26.3	26.8
	Speed up resistance energy, %	18.8	28.4
Energy of mechanical losses in transmission	Half-axles and hubs, %	5.9	5.1
	Gearbox, %	4.4	4.5
	Final drive, %	3.3	3.3
	Drive shaft, %	1.1	1.1

4. Conclusions

According to Tables 2 and 3, the following results are obtained.

Increasing the drive shaft efficiency by 5% results in 0.36% reduction of the average fuel consumption rate for a light commercial vehicle in NEDC and WLTC cycles, and vice versa.

Increasing the final drive and the gearbox efficiency by 1% in NEDC cycle brings down the average fuel rate by 0.6%, and 0.48%, respectively. Changing these parameters in WLTC cycle results in the reduction of the average fuel consumption rate by 0.72% and 0.66%, respectively.

If the aerodynamic drag coefficient is reduced by 5%, the average fuel rate also becomes less by 0.84% for NEDC cycle, and 0.88% for WLTC cycle.

The rolling resistance factor will have less impact as compared to other indices reviewed, since its variation to the extent of 5% causes the average fuel rate to change within the limits of 0.4% for NEDC cycle, and 0.66% for WLTC cycle.

It is to be noted that according to table 3 the energy of mechanical losses in transmission can be as high as 15% of the total energy used for the transport vehicle motion. The aerodynamic drag energy can be as high as 30 to 40% of the total energy used for cycles NEDC and WLTC, respectively.

Given the simulation results, the highest potential for reducing the average fuel rate of a light commercial vehicle is associated with the improvement of its aerodynamic shape. Higher transmission efficiency can have a substantial impact on the average fuel consumption rate, however, the range of improvement of this index is limited. The rolling resistance factor has the least impact on the parameter of interest. All the parameters listed above can be optimized together that can help to achieve the desired fuel efficiency index of a vehicle.

Acknowledgement

The studies are conducted under the sponsorship of the Ministry of Education and Science of the Russian Federation as part of the project High-end production of the product range of GAZelle Next vehicle fitted with new electronic systems architecture under Agreement No. 075-11-2019-027 dated 29.11.2019 (Decree No.218 dated April 09, 2010 of the Government of the Russian Federation).

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