Ways to reduce fuel consumption of a light commercial vehicle for WLTC and NEDC cycles

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Abstract: The paper presents the results of the simulation model employed for fuel consumption analysis of a light commercial vehicle in road traffic cycles; virtual tests are performed. The motor vehicle main parameters are analysed for impact on fuel consumption in NEDC and WLTC cycles. Changes of average fuel consumption are quantified for varying main parameters of the vehicle structure. The distribution of energy consumption for the vehicle in motion is demonstrated. On the basis of the regression analysis impact coefficients of individual gear ratios on the average fuel consumption of a light commercial vehicle are obtained.

Introduction

For many consumers the fuel consumption is one of the main criteria for a vehicle model selection.

Higher prices for hydrocarbon fuel and deterioration of the environment associated with high-intensity traffic brings about the development and implementation of single-approach methods for calculation and evaluation of fuel, economic and environmental properties based on standard driving cycles.

The most common standard cycles: New European Driving Cycle (NEDC) [1], American Driving Cycle (FTP-75) and Japanese Driving Cycle (JC-08). In addition to the above, the World Harmonized Driving Cycle (WLTC) [2] was introduced in 2017; it is based on the world static study of driving modes and features high accelerations and lack of steady-motion intervals.

The objective of the study is to quantify the impact of various design parameters on fuel efficiency of a light commercial vehicle with gross vehicle weight of 3500 kg in NEDC and WLTC driving cycles.

Main methods of improving the fuel efficiency of a vehicle are specified in earlier studies [3-7]. These include the reduction of aerodynamic drag, tire rolling resistance and optimization of the transmission performance. Everything stated above shall have an impact on result of the vehicle motion simulation in driving cycles.

Methods of the analysis

NEDC cycle consists of one urban driving cycle (or 4 simple urban cycles) and one suburban driving cycle. Cycle driving is performed using a detailed operational map. The map details the the gear box speeds to be used for every segment of the vehicle motion as well as accelerations of the vehicle.

The operational map and requirements for the vehicle motion in NEDC driving cycle are included in the standard [1]. The standard applies to transport vehicles of category M1, M2, N1 and N2 with reference mass not exceeding 2 610 kg.

The vehicle driving diagrams based on NEDC cycle are shown in figure 1.
As shown in figure 2, WLTC cycle is separated into four phases by short-duration stops: Low-speed phase when the vehicle accelerates to a maximum of 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).

The vehicle motion for each driving cycle is based on the operational map. The phase is selected depending on the power-to-weight ratio of a vehicle. Extra High-speed phase is not included in the study which is acceptable for the vehicle class under review. WLTC driving cycle is performed according to rules specified in [2].

The simulation model built is used for modelling of the vehicle motion. Well-known approaches to the mathematical representation of the vehicle motion are used, as specified in papers on the vehicle theory [8].

In case of WLTC cycle simulation, the vehicle acceleration is unknown. The acceleration of the vehicle is computed using the following formula:

\[
a_a = \frac{V_{j+1} - V_j}{3.6 \cdot (t_{j+1} - t_j)},
\]

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.
Gears are shifted as required in [1-2]. After gear shifting ICE starting speed of rotation is determined subject to correlation of the vehicle speed and ICE speed of rotation:

\[ V = \omega_p r_e / u_{tp} \]  

(2)

The traction force is computed by formula:

\[ F_t = T_e u_{tp} \eta_{tp} / r_k \]  

(3)

where \( T_e \) – ICE torque, \( u_{tp} \) – transmission gear ratio, \( \eta_{tp} \) – transmission efficiency, \( r_k \) – wheel rolling radius.

\( T_e \) is normally a function of the accelerator pedal position and ICE speed, or \( T_e = f(d_o) \). In the mathematical model \( T_e \) represents data array \( T_{eij} i=1\ldots17, j=1\ldots11 \).

Alternatively, the traction force can be determined based on the following dependency.

\[ F_w = F_f + F_a + \delta m_a a_v, \]  

(4)

\( F_w \) – traction force of drive wheels; \( F_f \) – rolling resistance force; \( F_a \) – air resistance force; \( \delta \) – rotational inertia coefficient, \( m_a \) – vehicle mass, \( a_v \) – vehicle acceleration.

ICE torque \( T_e \) is calculated using formula (3), and subject to the engaged transmission gear that is determined using formula (2). The specific fuel consumption in the model is represented by data array \( \eta_g \); it is a function of ICE torque and speed of ration \( g_e = f(T_e, \omega_e) \). \( T_e \) and \( \omega_e \) values are computed using expressions (2-4). For calculation of the total fuel consumption per driving cycle, the current fuel consumption values are multiplied by validity times of \( T_e \) and \( \omega_e \), and then added up. The unknowns are computed by formulae (5-7).

The rolling resistance force is determined as:

\[ F_f = f m_a g \]  

(5)

where \( f \) – rolling resistance factor; \( g \) – gravity acceleration.

The air resistance is determined as follows:

\[ F_a = 0.5 \cdot C_x \cdot \rho_v \cdot A_v V^2, \]  

(6)

where \( C_x \) – aerodynamic drag coefficient; \( \rho_v \) – air density; \( A_v \) – transverse projection area of the vehicle; \( V \) – vehicle speed.

The rotational inertia coefficient is determined as:

\[ \delta = 1 + \frac{I_e r_e^2 \eta_{fR}}{m_r^2 r_e^2} + \frac{I_o u_{Rf}^2 \eta_{fR}}{m_r^2 r_e^2} + \sum \frac{I_s}{m_r^2 r_e^2}, \]  

(7)

where \( I_e \) – ICE moment of inertia, \( I_o \) – gear drive moment of inertia, \( u_{Rf} \) – final drive gear ratio, \( \eta_{fR} \) – final drive efficiency, \( I_s \) – moment of inertia of a half-axle wheel (if any).

Results of the study

The developed simulation model shall reliably respond to the variation of input data, i.e. the reduction of the aerodynamic drag component will contribute to lower fuel consumption. Simulation results for a light commercial vehicle are specified in tables 1 and 2.

The gear box efficiency changed by 1% per shift.

It is to be noted that the results obtained conclusively prove that these parameters affect the average fuel consumption rate. Increasing the cardan drive efficiency by 5% brings down the average fuel consumption rate by 1.2% for NEDC cycle and 1.02% for WLTC cycle.

Increasing the final drive and the gear box efficiency by 1% in NEDC cycle brings down the average fuel rate by 1.3%, and 0.74%, respectively. For WLTC cycle the change of these parameters results in the reduction of the average fuel consumption rate by 1.4% and 0.93%, respectively.

If the aerodynamic drag coefficient is reduced by 5%, the average fuel rate goes down by 2% for NEDC cycle, and 1.8% for WLTC cycle.

The rolling resistance factor will have a lower 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 0.7% for NEDC cycle, and 0.65% for WLTC cycle.

The energy expended on the light commercial vehicle motion is specified in table 3.
Table 1. Impact of specified parameters for NEDC and WLTC cycles

| Index                          | Variation, % | Fuel rate, l/100 km | Variation, l |
|--------------------------------|--------------|---------------------|--------------|
| Aerodynamic drag coefficient   | 5            | 11.02               | 0.21         |
|                                | 0            | 10.81               | 0            |
|                                | -5           | 10.66               | -0.21        |
| Rolling resistance factor      | 5            | 10.88               | 0.07         |
|                                | 0            | 10.81               | 0            |
|                                | -5           | 10.74               | -0.07        |
| Ring and pinion set efficiency | 1            | 10.67               | -0.14        |
|                                | 0            | 10.81               | 0            |
|                                | -1           | 10.95               | 0.14         |
| Cardan drive efficiency        | 0.5          | 10.68               | -0.13        |
|                                | 0            | 10.81               | 0            |
|                                | -0.5         | 10.94               | 0.13         |
| Gear box efficiency            | 1            | 10.73               | -0.08        |
|                                | 0            | 10.81               | 0            |
|                                | 1            | 10.89               | 0.08         |

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

| Index                          | Variation, % | Fuel rate, l/100 km | Variation, l |
|--------------------------------|--------------|---------------------|--------------|
| Aerodynamic drag coefficient   | 5            | 10.98               | 0.19         |
|                                | 0            | 10.79               | 0            |
|                                | -5           | 10.6                | -0.19        |
| Rolling resistance factor      | 5            | 10.86               | 0.07         |
|                                | 0            | 10.79               | 0            |
|                                | -5           | 10.72               | -0.07        |
| Ring and pinion set efficiency | 1            | 10.64               | -0.15        |
|                                | 0            | 10.79               | 0            |
|                                | -1           | 10.94               | 0.15         |
| Cardan drive efficiency        | 0.5          | 10.68               | -0.11        |
|                                | 0            | 10.79               | 0            |
|                                | -0.5         | 10.9                 | 0.11         |
| Gear box efficiency            | 1            | 10.69               | -0.1         |
|                                | 0            | 10.79               | 0            |
|                                | 1            | 10.89               | 0.1          |

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

| Driving cycle       | Total resistance of motion energy | Energy of mechanical losses in transmission |
|---------------------|----------------------------------|--------------------------------------------|
|                     | Aerodynamic drag energy, % | Rolling resistance energy, % | Speed up resistance energy, % | Half-axes and hubs, % | Gear box, % | Final drive, % | Cardan drive, % |
| NEDC                | 40.16                         | 18.47                                      | 18.58                              | 14.75                         | 4.04                | 3              | 1.01              |
| WLTC                | 31.54                         | 18.89                                      | 28.51                              | 13.02                         | 4.04                | 3              | 1.01              |

It is to be noted that the energy of mechanical losses in the transmission can be as high as 23% of the total energy expended on the transport vehicle motion, as specified in table 3. The aerodynamic drag energy can be as high as 30 to 40% of the total energy used for NEDC and WLTC cycles, respectively.
Furthermore, the impact assessment of the current 6-speed transmission gear ratio optimization on fuel consumption is performed.

The Plackett-Burman plan is employed to reduce the number of simulations and, thereby shorten the time of the analysis, as specified in [9]. Transmission gear ratios are used as the factors affecting the average fuel consumption, specifically: X1 – gear ratio of 1st gear; X2 – gear ratio of 2nd gear; X3 – gear ratio 3rd gear; X4 – gear ratio of 4th gear; X5 – gear ration of 5th gear; X6 – gear ratio of 6th gear.

The range of the gear ratio variability is 10%; the changed gear ratios are specified in table 4.

| Table 4. Levels and ranges of variability of factors |
|---------------------------------------------------|
| Level of factor | X1 | X2 | X3 | X4 | X5 | X6 |
| Basic level     | 5.065 | 2.780 | 1.591 | 1.000 | 0.807 | 0.643 |
| Bottom level    | 4.5585 | 2.502 | 1.4319 | 0.9 | 0.7263 | 0.5787 |
| Top level       | 5.5715 | 3.058 | 1.7501 | 1.1 | 0.8877 | 0.7073 |

Further, regression equations are composed.

Coefficients of equation \( Y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 + \ldots + b_4 \cdot X_4 + b_5 \cdot X_5 + \ldots \) are determined using formulae:

\[
\begin{align*}
\hat{b}_0 &= \frac{1}{N} \sum_{j=1}^{N} Y_j \\
\hat{b}_i &= \frac{1}{N} \sum_{j=1}^{N} X_{ij} Y_j
\end{align*}
\]

where \( i = 1, 2, \ldots, n \) – factor number; \( N \) – number of experiments; \( j \) – experiment reference number.

Further, coefficients of interest and results of the experiments are included in table 5.

| Table 5. Target and calculated values of average fuel consumption for NEDC cycle. |
|-----------------------------------------------|
| Experiment | X1 | X2 | X3 | X4 | X5 | X6 | S | \( \sigma_j^2 \) | \( S^p \) | \( (S_{xp} - S^p)^2 \) |
|-----------|----|----|----|----|----|----|---|----------|------|----------------|
| 1         | 1  | 1  | 1  | -1 | 1  | -1 | 11.124 | 0.111  | 11.12 | 0.0000       |
| 2         | -1 | 1  | 1  | 1  | -1 | 1  | 11.400 | 0.117  | 11.40 | 0.0000       |
| 3         | -1 | -1 | 1  | 1  | 1  | -1 | 10.625 | 0.102  | 10.62 | 0.0000       |
| 4         | 1  | -1 | -1 | 1  | 1  | 1  | 10.721 | 0.103  | 10.72 | 0.0000       |
| 5         | -1 | 1  | -1 | -1 | 1  | 1  | 11.250 | 0.114  | 11.26 | 0.0001       |
| 6         | 1  | -1 | 1  | 1  | -1 | 1  | 10.774 | 0.104  | 10.78 | 0.0000       |
| 7         | 1  | 1  | -1 | 1  | -1 | -1 | 10.947 | 0.108  | 10.94 | 0.0000       |
| 8         | -1 | -1 | -1 | 1  | -1 | -1 | 10.351 | 0.096  | 10.36 | 0.0001       |
| b1        | -0.01 | 0.28 | 0.08 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b2        | 0.08  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b3        | 0.02  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b4        | 0.02  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b5        | 0.02  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b6        | 0.02  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b7        | 0.02  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |
| b8        | 0.02  | 0.08 | 0.02 | 0.02 | 0.03 | 0.14 | 10.9 | 0.856 | 0.0003 |

The problem of interest is not resolved by calculation of regression coefficients; the problem solution also requires the model quality (accuracy) to be found. According to [9], each experiment is subjected to dispersion analysis, with correction for the design model inaccuracy applied to the obtained results that amounts to 3%. Having calculated the error correction for the experiment, the model validity can be found, and the model efficiency checked based on Fisher’s criterion [9].

Tabulated value \( F \) of Fisher’s criterion, at \( P=0.95, f_1=f_{deg}=6, f_2=f_y=8; F=3.58 \). Calculated value \( F^c=0.003 \).

Since \( F^c < F \), the model adequately simulates the dependence of interest with a confidence level of 0.95.
The degree of impact of this factor is dependent on the value of the regression coefficient. The ‘plus’ sign indicates that the complex optimization parameter goes up when the factor increases; the ‘minus’ sign indicates the complex optimization parameter goes down.

According to table 5, regression coefficients b1-b6 indicate that the reduction of the first speed gear ratio causes the average fuel consumption to increase. The reduction of gear ratios for 2nd gear to 6th gear inclusive brings down the average fuel consumption. In terms of the impact on the average fuel consumption of a light commercial vehicle, it is mostly affected by the reduction in the 2nd speed gear ratio, with the regression coefficient 0.28; then 6th speed gear ratio, with the regression coefficient 0.14, and 3rd speed gear ratio with the regression coefficient 0.08.

It should be noted that reducing the transmission gear ratio for higher fuel efficiency has a negative impact on traction, speed and environmental characteristics of the vehicle. Keeping the above in view, a compromise solution is needed in the future.

Summary

According to tables 1 and 2, the following results are obtained:

- Increasing the cardan drive efficiency by 5% brings down the average fuel consumption rate by 1.2% for NEDC cycle and 1.02% for WLTC cycle.
- Increasing the final drive and the gear box efficiency by 1% in NEDC cycle brings down the average fuel rate by 1.3%, and 0.74%, respectively. For WLTC cycle, changing these parameters results in the reduction of the average fuel consumption rate by 1.4% and 0.93%, respectively.
- If the aerodynamic drag coefficient is reduced by 5%, the average fuel rate goes down by 2% for NEDC cycle, and 1.8% for WLTC cycle.

The rolling resistance factor will have a lower 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 0.7% for NEDC cycle, and 0.65% for WLTC cycle.

It is to be noted that according to table 3 the energy of mechanical losses in the 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 NEDC and WLTC cycles, respectively.

Given the simulation results, the highest potential for reducing the average fuel rate of a light commercial vehicle is associated with its improved aerodynamic shape. Higher transmission efficiency can have a substantial impact on the average fuel consumption rate, however, the potential for 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.

According to table 5, regression coefficients b1-b6 indicate that reducing the first speed gear ratio brings up the average fuel consumption. Lower gear ratios for 2nd gear to 6th gear inclusive bring down the average fuel consumption. In terms of the impact on the average fuel consumption of a light commercial vehicle, it is mostly affected by the reduction in the 2nd speed gear ratio, with the regression coefficient 0.28; then 6th speed gear ratio, with the regression coefficient 0.14, and 3rd speed gear ratio with the regression coefficient 0.08.

In the future, the developed simulation model will be used to analyse the impact of transmission gear ratios on fuel efficiency and environmental friendliness of a light commercial vehicle.

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References

[1] Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements 2015 UNECE No. 83 url:https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/R083r5e.pdf
[2] Proposal for new global technical regulations concerning worldwide harmonized light vehicle emissions test procedure 2014 UNECE url: https://www.unece.org/fileadmin/DAM/trans/doc/2014/wp29/ECE-TRANS-WP29-2014-027r.pdf

[3] Ogorodnov S M, Tikhomirov A N and Maleev S I 2015 Evaluation of potential application of analytical methods of research of automobile fuel efficiency Proceedings of universities. Mechanical engineering pp 53-61

[4] Beresnev P et al. 2017 Simulation of road impacts for forecasting of durability of VE-hcle's suspension elements and supporting system 19th International and 14th European-African Regional Conference of the ISTVS

[5] Zezyulin D et al. 2014 Modeling of roads impacts for life prediction of light commercial vehicles parts FISITA 2014 World Automotive Congress

[6] Blokhin A N 2006 Development of search methods for rational transmission gear ratios taking into account performance characteristics and designated purpose of the vehicle, PhD thesis p 256

[7] Valeev D Kh and Karabtsev V S 2014 Ways to reduce fuel consumption of freight vehicles Mechanics of machines, mechanisms and materials 4 pp 33-39

[8] Kravets V N 2013. Automobile theory Nizhny Novgorod State Technical University n.a. R.E. Alekseev p 413

[9] Lunev V A 2012 Mathematical simulation and planning of the experiment Saint-Petersburg State Polytechnic University p 153