

INFLUENCE OF THE TECHNICAL CONDITION OF THE RUNNING GEAR OF A TRUCK TRACTOR AND A SEMI-TRAILER ON THE FUEL EFFICIENCY OF THE TRACTOR-TRAILER TRUCK

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Досліджено кути встановлення осей автомобілів-тягачів та напівпричепів. Визначено вплив перекосу осей на коефіцієнт опору кочення автопоїзда. Оцінено паливну економічність автопоїзда при русі в режимі магістрального їздового циклу на дорозі при зміні коефіцієнту опору кочення. Доведена необхідність перевірки кутів встановлення мостів напівпричепа, як в процесі виготовлення, так і експлуатації автопоїздів

Ключові слова: автомобіль-тягач, автопоїзд, напівпричеп, паливна економічність, ходова частина, кути встановлення мостів

Исследованы углы установки осей автомобилей-тягачей и полуприцепов. Определено влияние перекоса осей на коэффициент сопротивления качению автопоезда. Оценена топливная экономичность автопоезда при движении в режиме магистрального ездового цикла на дороге при смене коэффициента сопротивления качению. Доказана необходимость проверки углов установки мостов полуприцепа, как в процессе изготовления, так и эксплуатации автопоездов

Ключевые слова: автомобиль-тягач, автопоезд, полуприцеп, топливная экономичность, ходовая часть, углы установки мостов

1. Introduction

The long operating practice of vehicles proves that tractor-trailer trucks have significant advantages over single-unit trucks. Semi-trailer trucks, in comparison with trailer trucks with the same load-carrying capacity, have smaller length, are less capable of wobble, structurally simpler and have lower metal content, which explains an increase in the share in freight transportation in Ukraine. The problem has become particularly relevant recently, when there have been clear trends of increase in the number of vehicles on Ukrainian roads and increase in motion speeds.

The most important performance properties of tractor-trailer trucks include traction speed, fuel efficiency and motion stability. Structurally, the parameters of tractor-trailer

trucks are closely related to the properties of the engine-transmission system and the running gear. Thus, when designing the running gear, not only kinematic and stiffness characteristics of the suspension, but also force interaction between the wheel and the rolling surface, pressure distribution in the contact area, deformation, etc., are specified. However, operation of tractor-trailer trucks is inseparably linked with the change in the characteristics of structural elements. Thus, kinematic and stiffness properties of the running gear of the truck tractor and the semi-trailer, the distribution of reactions in the road-tire contact area, in particular, due to axle misalignment can change.

A large number of vehicles and tractor-trailer trucks in operation has different technical conditions, and accordingly, different properties. It is obvious that even with the same

technical condition of the running gear of the truck tractor and the semi-trailer during manufacture, different degrees of wear of tires, suspension elements of the truck tractor and semi-trailer axles can be revealed after a certain period of operation. As the wear rate depends on axle angles, wheel load, lateral forces, tangential forces (traction and braking) and air pressure in tires. In quantitative terms, these factors are not identical for each axle of the tractor-trailer truck. So, if there are different axle angles and different wear rates of the tread, it is possible to speak about changes in rolling resistance and axle slip. At the same time, traction speed, fuel efficiency and stability of the tractor-trailer truck also change. Since the cost of maintenance and repair of the running gear is a significant part of the total cost of the tractor-trailer truck, replacement of the entire set, in case of extreme wear of some elements, is economically unreasonable. Therefore, a large number of tractor-trailer trucks are operated with running gears having different technical conditions and, accordingly, different properties. In this case, a question arises about the fuel efficiency and motion stability of the tractor-trailer truck with different technical conditions of the running gear.

The solution to this issue is a complex task, which requires the study of processes occurring in the running gear of the tractor-trailer truck both during the manufacturing process and under the influence of operational factors.

The search for methods of assessing the tractor-trailer truck performance, in particular, fuel efficiency, taking into account the semi-trailer axle angles, is an urgent problem for further improvement of performance and technical level of tractor-trailer trucks.

2. Literature review and problem statement

Today, many tractor-trailer trucks of foreign production are used in Ukraine. Moreover, Ukrainian trailers use axles of the leading foreign companies BPW, SAF Holland, Gigant, etc. The need for constant control over the angles of steering wheels is beyond doubt. This is necessary to ensure long life of tires, low rolling resistance of wheels, proper motion stability and safety, as well as fuel efficiency. Nevertheless, until recently, little attention has been paid to the angles of non-steerable axles with axle suspension. Non-perpendicularity of the semi-trailer (trailer) axles and frame causes their misalignment.

Misalignment of rear axles causes excessive friction between tires and the road surface, leads to increased rolling resistance of wheels and creates unwanted lateral forces.

In addition, misaligned axles lead to:

- a) reduction of tire life;
- b) driving complications of vehicles, especially tractor-trailer trucks;
- c) decrease in motion stability and, consequently, safety;
- d) increase in fuel consumption.

According to studies in [1], it has been found that 80 % of semi-trailer tractors and more than 90 % of semi-trailers have problems with axle angles. Even new trucks need adjustment of non-steerable axles.

The research conducted in a fleet of 100 trucks found that up to 70 % of new vehicles require correction of the rear axle. In sixty percent of cases, tire wear of the steering axle is due to improper axle wheel alignment [2].

In [3], it has been revealed that misalignment of one semi-trailer axle leads to a significant increase in the rolling

resistance of tractor-trailer truck wheels. Besides, an increase in the overall traffic lane width of tractor-trailer trucks as a result of deviation of trajectories of the main points of the tractor-trailer truck when changing the motion trajectory has been noted [4]. Recommendations for diagnosing and forecasting the failures of tractor-trailer trucks due to changes in the running gear characteristics, including axle misalignment, have been given in [5]. But these works only state the fact of increased overall traffic lane width and do not analyze the causes.

The problem of choosing the angles of steering wheels of trucks has been considered in [6]. Rational angles are determined by solving the optimization problem, taking into account the load on the main bearing elements of the front axle. However, the recommendations on steering wheel angles cannot be applied to trailers, semi-trailers and tractors with misaligned axles (in one plane), since in the first case the optimization problem is solved with respect to alignment angles of steering wheels (in two planes).

In [7], the analysis of statistical data of parameters of trailer wheels of tractor-trailer trucks in operating conditions has been carried out. The alignment parameters of steering wheels and axle non-parallelism of trailers have been determined. The work only states the fact of axle misalignment and does not analyze the causes.

In [8], experimental studies of steerability, stability and maneuverability of tractor-trailer trucks with approximate misaligned non-steerable axles have been presented. It has been found that axle misalignment of semi-trailers leads to a change in the nature of deviation of the trailer trajectory from the tractor trajectory in different motion modes of tractor-trailer trucks, but the causes of changes are not explained.

The mathematical model of the semi-trailer truck, considering the semi-trailer axle misalignment, has been given in [9]. It has been shown that the motion of tractor-trailer trucks without axle misalignment is asymptotically stable. Misalignment of any semi-trailer axle leads to destabilization of the rectilinear motion caused by trailer oscillations.

In [10], a model of motion of the truck tractor and the semi-trailer, using separate models of the truck tractor, semi-trailer, axles, suspensions, tires and brakes has been developed. It was used to study the dynamic stability under different motion conditions. However, the model did not consider possible changes in the technical condition of the running gear during operation.

In [11], a nonlinear dynamic model of the truck tractor-semi-trailer has been proposed. The sliding angle of the truck tractor, the yaw rate of the truck tractor and the semi-trailer have been selected as variables, and the spatial equation of state has been constructed. In [12], the model has been refined and the toe-in angle of the semi-trailer has been added as a variable. The relationship between the sliding angle and steerability and stability indicators of the tractor-trailer truck has been determined. The main disadvantage is an insufficiently accurate description of the lateral elasticity of tires.

Road-holding ability and steerability of the two-unit tractor-trailer truck during changing the traffic lane at high speeds have been considered in [13]. On the basis of the developed mechanical-mathematical model, the influence of some structural and operational factors, in particular, axle angles, on the road-holding ability and steerability has been shown. In the work, misalignment of slip axles has been identified for the first time, but the relationship between these parameters has not been established.

In all the works, axle misalignment has been considered in two aspects: establishment of the fact of misalignment as the design imperfection of trailers and semi-trailers and reduction of the negative effect of misalignment, and the effect of axle misalignment on maneuverability, steerability and motion stability of tractor-trailer trucks.

Studies on the effect of axle misalignment on the rolling resistance coefficient, and, accordingly, traction speed and fuel efficiency, have not been found. This is due to the fact that the rolling resistance coefficient depends on a large number of factors, in particular, road surface evenness and increase in the rolling resistance coefficient for Ukrainian roads is almost doubled. With the development of the road sector, improvement of the road surface evenness, an increase in the rolling resistance coefficient due to axle misalignment becomes one of the major factors. This is primarily due to the deterioration of the fuel efficiency of cars and tractor-trailer trucks.

3. The aim and objectives of the study

The aim of the research is to improve the fuel efficiency of tractor-trailer trucks by means of rational installation of semi-trailer axles.

To achieve the aim, the following objectives were set:

- to analyze the axle angles of semi-trailers of tractor-trailer trucks in operation;
- to determine the fuel consumption of tractor-trailer trucks in the highway driving cycle on the road;
- to evaluate the influence of semi-trailer axle angles on the fuel efficiency of tractor-trailer trucks.

4. Influence of semi-trailer axle angles on fuel efficiency of tractor-trailer trucks

In the case of axle misalignment of tractor-trailer trucks, there are additional forces in the road-wheel contact due to a discrepancy between the planes of the tractor-trailer truck longitudinal axle, wheel rotation and rolling (Fig. 1). This leads to additional lateral forces F_y^w – due to axle misalignment and F_y^{δ} – due to the presence of the slip angle and longitudinal forces, the resultant of which changes the motion direction of the tractor-trailer truck and additionally loads the running gear components. These lateral forces increase the wheel slip, as well as the coefficient of rolling resistance of the wheel, semi-trailer, trailer, tractor.

Fig. 2 shows the influence of various factors on fuel consumption. Rolling resistance of wheels accounts for the largest segment of fuel consumption – 42.2 %. Any actions to reduce the rolling resistance of wheels, in particular, proper alignment of axles, can reduce fuel consumption.

First of all, it concerns multi-unit vehicles. Recommendations on axle angles are developed not only by manufacturers of vehicles and trailers, but also by tire manufacturers and independent organizations.

According to the world manufacturer of truck tires, Goodyear Truck Tires, any improperly installed wheel increases the overall resistance of the vehicle [14]. This is due to an increase in friction between tires and the road surface, as well as a greater aerodynamic resistance, when the longitudinal axles of the tractor and trailers are not in parallel with the motion direction. Any axle misalignment deteriorates fuel efficiency.

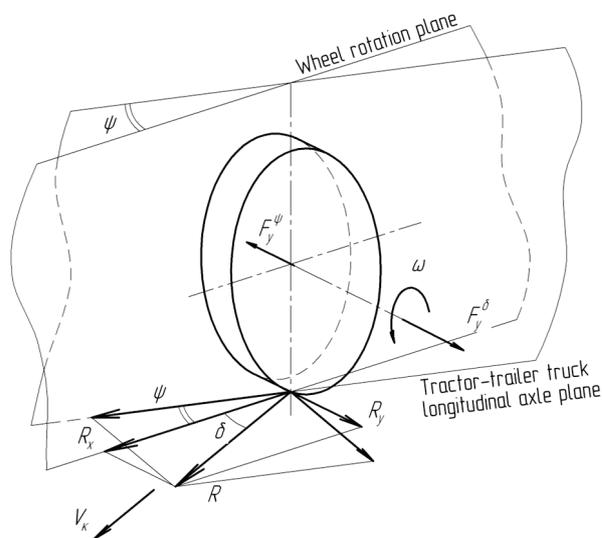


Fig. 1. Forces and moments acting on a wheel in case of axle misalignment

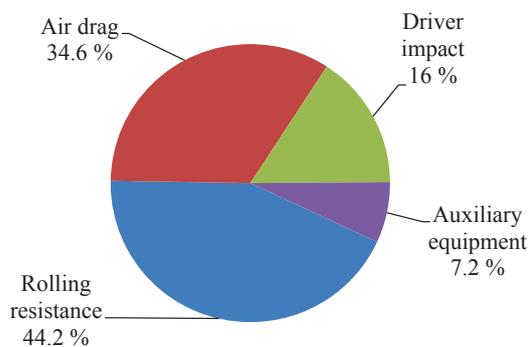


Fig. 2. Effect of various factors on fuel efficiency

The permissible axle misalignment angle, which is about ± 0.1 degrees, corresponding to $\pm 1/8$ inches is typical for the automotive industry. It is very difficult to achieve such accuracy, because there are limitations due to the measurement error. At present, there is no measurement technique that would provide accuracy of 0.1 degrees, because it is a limit measurement error of devices.

The JOSAM company uses a value measured in mm/m (millimeters per meter of the route) as an estimate of non-parallelism. This allows characterizing the angle of deviation of the rolling direction of the wheel or the axle from the longitudinal symmetry plane of the vehicle. The 5 mm/m axle misalignment is clearly shown in Fig. 3. With such a misalignment, the axle tends to shift sideways by 50 m at a distance of 10 km. This will result in deteriorated steerability and stability, increased tire wear, worsened running characteristics and increased fuel consumption (Fig. 4).

According to the maintenance of trucks and trailers carried out by the Grodsky Trans Expedition company using the equipment of the JOSAM company (Sweden), it was found that in 92 % of cases vehicles had inappropriate wheel angles with axle misalignment [15].

According to the results of studies on axle misalignment of tractor-trailer trucks, given in [3–5], an increase in

the rolling resistance force of the wheels of tractor-trailer trucks was observed in case of misalignment of one axis of the semi-trailer by 0.57 degrees by 12 %; by 1.25 degrees – 17.8 %; by 2.11 degrees – 26.2 %. Thus, in mathematical modeling of traction dynamics, fuel efficiency and stability, it is necessary to consider the longitudinal forces arising in the road-wheel contact. Let's consider fuel efficiency of vehicles in more detail.

Among a significant number of indicators that determine the fuel efficiency of a vehicle, and taking into account the comparative analysis of the impact of axle misalignment on these indicators, fuel consumption in the driving cycle on the road is taken as an estimate. The method of calculation is convenient to consider further on the basis of the provisions of GOST 20306-90 [16].

High-speed motion modes in it are determined by the operating chart and the graphic scheme of the entire cycle. The inclusion of typical motion phases such as acceleration, fixed speed, deceleration by the engine or the brake system in the cycle is characteristic. Consistent implementation of the mentioned phases (operations) at certain route segments is set (Fig. 5).

In order to calculate the fuel consumption of tractor-trailer trucks in different motion phases, the technique proposed in [17] and specified in [18–20] was used.

In the mode of steady motion at constant speed, fuel consumption is determined by the relation [17]:

$$Q_i = k_Q \cdot Q_{oc} \cdot \tau, \tag{1}$$

where k_Q is the fuel consumption correction factor; Q_{oc} is the fuel consumption per second, kg/s; τ is the time of the vehicle motion at constant speed, s.

Fuel consumption per second is determined by [17]:

$$Q_{oc} = a_{Qc} \cdot V^2 + b_{Qc} \cdot V + c_{Qc}, \tag{2}$$

where

$$a_{Qc} = \frac{a_Q \cdot U_i^2}{3600 \cdot r_r^2}, \quad b_{Qc} = \frac{b_Q \cdot U_i}{3600 \cdot r_r}, \tag{3}$$

$$c_{Qc} = \frac{c_Q}{3600},$$

U_i is the overall gearbox ratio of the vehicle in the i -th gear; r_r is the wheel turning radius, m; a_Q, b_Q, c_Q are the approximation coefficients of the function of the engine fuel consumption per hour:

$$Q_o = a_Q \cdot \omega^2 + b_Q \cdot \omega + c_Q. \tag{4}$$

In the presence of external speed characteristics of engines, the coefficients a_Q, b_Q, c_Q are determined by means of the Lagrange interpolation formula provided that:

$$Q_o = \frac{g_e \cdot N_e}{1000}, \tag{5}$$

where g_e is the specific fuel consumption, g/(kWh); N_e is the engine power, kW.

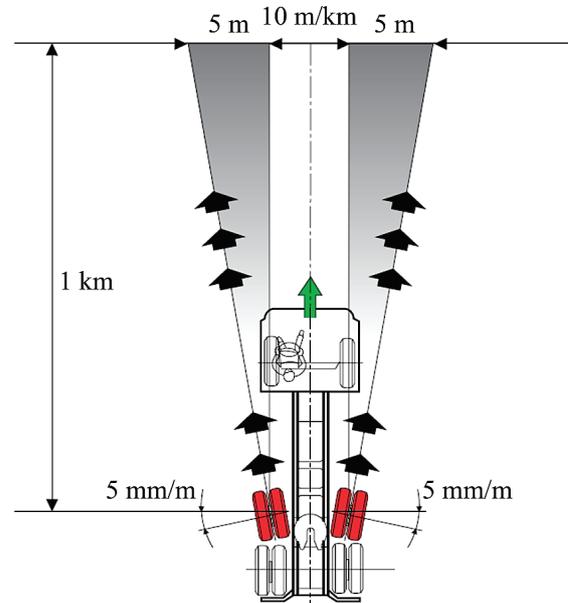


Fig. 3. Vehicle axle misalignment effects

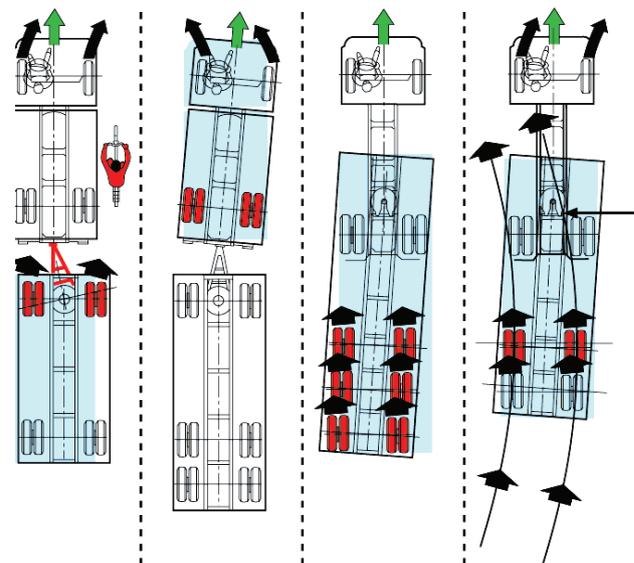


Fig. 4. Motion scheme of a tractor-trailer truck with axle misalignment

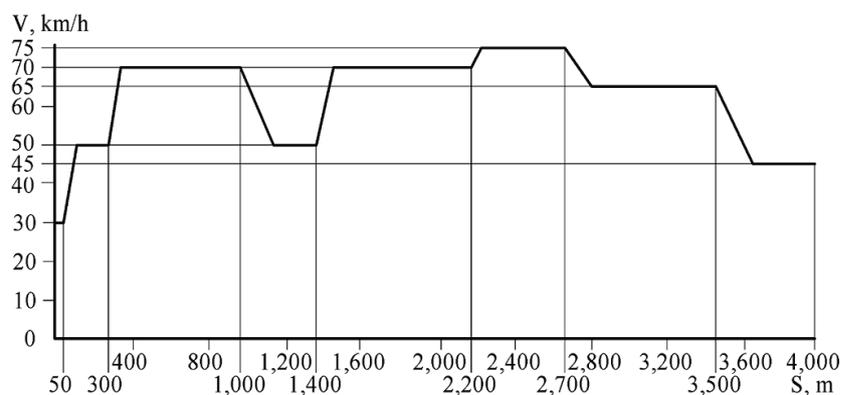


Fig. 5. The diagram of the highway cycle on the road for trucks and tractor-trailer trucks with a gross weight of more than 3.5 tons

Finally, the coefficients a_Q, b_Q, c_Q [18]:

$$a_Q = \frac{((g_N \cdot N_{\max} - g_{\min} \cdot N_{\min}) \cdot (\omega_M - \omega_{\min}) - (g_M \cdot N_M - g_{\min} \cdot N_{\min}) \cdot (\omega_N - \omega_{\min}))}{1000 \cdot ((\omega_N^2 - \omega_{\min}^2) \cdot (\omega_M - \omega_{\min}) + (\omega_{\min}^2 - \omega_N^2) \cdot (\omega_N - \omega_{\min}))},$$

$$b_Q = \frac{\frac{(g_M \cdot N_M - g_{\min} \cdot N_{\min})}{1000} + a_Q \cdot (\omega_{\min}^2 - \omega_M^2)}{\omega_M - \omega_{\min}},$$

$$c_Q = \frac{g_{\min} \cdot N_{\min}}{1000} - a_Q \cdot \omega_{\min}^2 - b_Q \cdot \omega_{\min}^2. \quad (6)$$

The greatest accuracy of fuel consumption with partial utilization of engine power is achieved with two reference graphs of dependence of the torque and fuel consumption per hour on the engine shaft angular velocity and the fuel feed control body position. These characteristics allow establishing a relationship between fuel consumptions per hour with partial and full fuel feed for the investigated range of angular velocities of the engine crankshaft. However, these characteristics can be obtained only experimentally, by determining the load characteristics of a particular engine at different crankshaft speeds.

When determining the fuel consumption on condition of partial engine power utilization, the fuel consumption correction factor k_Q is introduced, defined by [21]:

$$k_Q = a_{ki} \cdot k_i^2 + b_{ki} \cdot k_i + c_{ki}, \quad (7)$$

where k_i is the engine power utilization factor; a_{ki}, b_{ki}, c_{ki} are the approximation coefficients of the function $k_Q = f(k_i)$.

The engine power utilization factor for determining the fuel efficiency:

$$k_i = \frac{M_a \cdot g \cdot (f_0 + K_f \cdot V) + K_B \cdot F \cdot V^2}{A_i \cdot V^2 + B_i \cdot V + C_i}, \quad (8)$$

where M_a is the gross vehicle weight, kg; f_0 is the coefficient of rolling resistance at low speeds; K_f is the coefficient considering changes in the rolling resistance coefficient at increasing speed; K_B is the drag coefficient, $\text{H} \cdot \text{s}^2 / \text{m}^4$; F is the frontal area, m^2 ; A_i, B_i, C_i are the approximation coefficients of the circular force equation:

$$A_i = a \cdot \frac{U_i^3 \cdot \eta_m}{r_d r_w^2}, \quad B_i = b \cdot \frac{U_i^2 \cdot \eta_m}{r_d \cdot r_w}, \quad C_i = c \cdot \frac{U_i \cdot \eta_m}{r_d}, \quad (9)$$

η_m is the transmission efficiency; r_d and r_w are the wheel dynamic radius and turning radius, m; a, b, c are the engine torque approximation coefficients obtained experimentally.

Fuel consumption in an unsteady motion with full engine power utilization, which corresponds to the vehicle acceleration modes, is determined by the relation [17]:

$$Q_i = M_a \cdot \delta_{rot} \cdot \int_{v_i}^{v_f} \frac{a_{Qc} \cdot V^2 + b_{Qc} \cdot V + c_{Qc}}{a_i \cdot V^2 + b_i \cdot V + c_i} dV, \quad (10)$$

where δ_{rot} is the coefficient considering the vehicle rotating masses; V_i, V_f are the initial and final vehicle speeds, m/s;

a_i, b_i, c_i are the coefficients of the right member of the differential vehicle motion equation [17]:

$$a_i = A_i - K_B \cdot F,$$

$$b_i = B_i - K_f \cdot M_a \cdot g,$$

$$c_i = C_i - f_0 \cdot M_a \cdot g, \quad (11)$$

a_{Qc}, b_{Qc}, c_{Qc} are the coefficients of the equation (2), which approximates the dependence of the engine fuel consumption per second on the crankshaft speed.

In the vehicle deceleration modes, when braking (by the engine or operating brake system), fuel consumption is taken as at the engine idle speed and determined by the fuel consumption per second taking into account the braking time of the vehicle on the i -th segment of the route τ_{bi} .

$$Q_{bi} = k_{xx} \cdot (a_Q \cdot \omega_{xx}^2 + b_Q \cdot \omega_{xx} + c_Q) \cdot \frac{\tau_{bi}}{3600}, \quad (12)$$

where ω_{xx} is the engine idle speed; τ_{bi} is the engine idle time; k_{xx} is the correction factor [20].

The final fuel consumption of the vehicle in an urban driving cycle is the sum of fuel consumptions on the i -th segments of the urban driving cycle:

$$Q_{\Sigma} = \sum Q_i. \quad (13)$$

As an object of research, a 40-tonne tractor-trailer truck with the Iveco Stralis AS440 truck tractor was chosen, a brief specification of which is given in Table 1 [22].

Table 1

Specifications of the Iveco Stralis AS440 truck tractor

No.	Parameter	Value
1	Chassis configuration	4×2
2	Dimensions, L/W/H, mm	6.076/2.550/3.685
3	Wheelbase, mm	3.650
4	Gross weight, kg	18.000
5	Gross combination weight rating, kg	51.000
6	Engine	Diesel Cursor 13 – F3B
7	Engine maximum brake power, kW at min^{-1}	412/1.900
8	Maximum torque, N·m at min^{-1}	2,500/1.000-1.575
9	Gearbox	ZF 12AS-2530 TO
10	Gearbox ratios	I - 12.33, II - 9.59, III - 7.44, IV - 5.78, V - 4.57, VI - 3.55, VII - 2.7, VIII - 2.1, IX - 1.63, X - 1.27, XI - 1.0, XII - 0.78, 3.X.1 - 11.41, 3.X.2 - 8.88
11	Final drive ratio	4.111
12	Tires	13 R 22.5
13	Tire static radius, mm	521

The rolling resistance coefficient f_0 in the calculations was taken within 0.01 – 0.03 with a step of 0.001. The results of the calculations are given in Table 2 and in Fig. 6.

Table 2

The results of the calculations of fuel consumption of the tractor-trailer truck in the highway driving cycle

Rolling resistance coefficient f_0	Fuel consumption Q_{Σ} , l/cycle	Fuel consumption, l/100
0.010	1.783	44.577
0.011	1.852	46.292
0.012	1.922	48.055
0.013	1.995	49.865
0.014	2.069	51.721
0.015	2.145	53.624
0.016	2.223	55.572
0.017	2.303	57.565
0.018	2.384	59.602
0.019	2.467	61.682
0.020	2.552	63.804
0.021	2.639	65.967
0.022	2.727	68.169
0.023	2.816	70.409
0.024	2.907	72.686
0.025	3.000	74.997
0.026	3.094	77.340
0.027	3.188	79.712
0.028	3.284	82.109
0.029	3.381	84.528
0.030	3.479	86.963

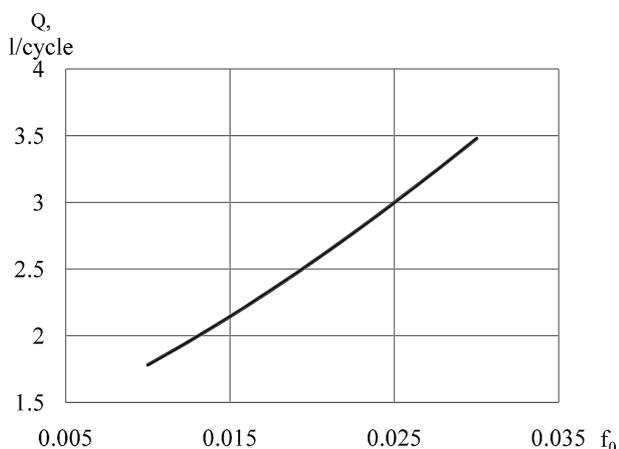


Fig. 6. Dependence of fuel consumption of the tractor-trailer truck in the highway driving cycle on the rolling resistance coefficient

Having analyzed the data of Table 2 and Fig. 6, it was found that an increase in the rolling resistance coefficient leads to an increase in fuel consumption of the tractor-trailer truck in the highway driving cycle. So, as the rolling resistance coefficient changes from 0.01 to 0.02, fuel consumption in the cycle increases by 0.769 l, and under the change from 0.02 to 0.03 – by 0.927 l. That is, the dependence of fuel consumption on the change in the rolling resistance coefficient is nonlinear.

5. Discussion of the results of the research on the influence of semi-trailer axle angles on the tractor-trailer truck fuel efficiency

The research proves the necessity to check the semi-trailer axle angles, both in the process of manufacturing and operation of tractor-trailer trucks. After all, damage due to shocks, wear and bending of the running gear elements causes axle misalignment. This, in turn, leads to a discrepancy between the rotation and rolling planes of the wheel. Thus, there are additional lateral and longitudinal forces and increased rolling losses and, as a consequence, the tractor-trailer truck performance deteriorates.

An increase in the wheel slip results in deterioration of such important performance characteristics as maneuverability, steerability, and stability of any wheeled vehicle.

Studies have shown that an increase in the rolling resistance coefficient, due to the semi-trailer axle misalignment, leads to a significant increase in fuel consumption (by 43 % and 95 %, with an increase in the rolling resistance coefficient two or three times, respectively).

The results of the research will find their application in the analysis of operational properties of tractor-trailer trucks, in particular, fuel efficiency, in order to ensure the correct adjustment of their running gears. This will improve the fuel efficiency and performance of tractor-trailer trucks and reduce the cost of their operation.

At the same time, additional research on the process of interaction between the semi-trailer wheels and the supporting surface in case of the semi-trailer axle misalignment, in particular by conducting an experiment, is required. Herewith, it is necessary to provide a possibility of installation of the semi-trailer axles with the specified misalignment and registration of forces in the wheel-supporting surface contact spot.

6. Conclusions

1. It was found that rolling of wheels of misaligned semi-trailer axles is identical to rolling of slip wheels under the influence of lateral forces. This leads to additional forces in the wheel-supporting surface contact spot and, as a consequence, an increase in the wheel rolling resistance, and, consequently, fuel consumption.

2. It was determined that in case of misalignment of one semi-trailer axle by 0.57 degrees, rolling resistance increases by 12 %; by 1.25 degrees – 17.8 %; by 2.11 degrees – 26.2 %.

3. An increase in the rolling resistance coefficient has led to the growth of fuel consumption of the tractor-trailer truck in the highway driving cycle. So, as the rolling resistance coefficient changes from 0.01 to 0.02, fuel consumption in the cycle increases by 43 %, and under the three-time change from 0.01 to 0.03 – by 95 %.

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