The results of simulation modeling of the operation of the regenerative fifth wheel hitch of a timber trailer

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Abstract. A three-dimensional mathematical model of the movement of a timber hauler with a semi-trailer along an uneven supporting surface and a computer program developed on its basis are presented that made it possible to evaluate the possibility of equipping the fifth-wheel coupling with an energy recovery system in various driving modes and to study the effect of recovery system parameters on its efficiency.

1. Introduction
An important role in increasing the turnover of timber is played by semi-trailers, the effectiveness of which is to a certain extent hampered by the design flaws of some components and assemblies of timber hauling tractors and, in particular, by the structural imperfection of fifth-wheel coupling devices. In the process of pulling away a hauling truck with a semi-trailer, accelerating, braking and driving in difficult road conditions of forest objects in the fifth wheel coupling, increased dynamic loads occur, which lead to a reduction in the speed of the hauling truck with the semi-trailer, its fuel consumption increase, and consequently performance. Increased loads in the fifth wheel coupling increase the wear of its mating parts, impair the stability of the hauling truck with the semi-trailer when braking.

The improvement of the fifth wheel coupling of a timber hauling truck with a semi-trailer, aimed at reducing the fuel consumption of a timber hauling tractor, requires in-depth study and generalization of the actual material available on the fifth wheel coupling design, accumulated both in our country and abroad. The results of numerous studies confirm the promise of reducing the fuel consumption of specialized cars by using various types of energy recovery mechanisms in their structures, which allow energy that is dissipated into the environment to be accumulated and reused in its work [1–6].

![Diagram of the recuperative spring-hydraulic fifth wheel coupling](image)

**Figure 1.** Scheme of recuperative spring-hydraulic fifth wheel coupling of a hauling truck with a semi-trailer: 1 – base plate; 2 – king pin; 3 – guides; 4 – springs; 5 – hydraulic cylinders; 6 – hydraulic tank; 7 – pneumohydraulic accumulator; 8 – port of the user recoverable working fluid.
Based on research conducted at the department of production, repair and operation of machines FSBEI of VGLTU named after GF Morozov, the authors propose a perspective design of a recuperative spring-hydraulic fifth-wheel hitch of a hauling truck with a semi-trailer, the scheme of which is shown in figure 1.

The work of the regenerative fifth wheel coupling of a timber hauling truck with a semi-trailer is based on the use of kinetic energy, arising from the mass inertia force of the semi-trailer when braking, accelerating, turning, changing gears and hitting obstacles in the process. Recuperative fifth wheel coupling allows accumulating and reusing hydraulic energy in the technological process of loading and unloading the assortments by a hydraulic manipulator mounted on a hauling truck with a semi-trailer. To assess the feasibility and feasibility of using a fifth wheel hitch with hydraulic energy recovery system and determining its optimal parameters, the task was set to develop and investigate a mathematical model of the movement of a hauling truck with a semi-trailer equipped with an energy recovery system in a fifth wheel hitch. Modeling is based on the methods of classical mechanics.

2. Materials and methods

The timber tractor and semi-trailer are represented in the model as two absolutely rigid bodies that perform translational and rotational movement in three-dimensional space and interact with the supporting surface in an elastically viscous manner at ten points (the number of wheels and twin wheels) figure 2. The bodies of the timber tractor and semi-trailer interact with each other through a fifth wheel coupling: between the points $A$ and $B$, which is proposed to be equipped with recuperative elements. Timber tractor and semi-trailer have mass $m_T$ and $m_N$ and moments of inertia $J_T$ and $J_N$, which are calculated for the current time relative to the current axis of rotation of the body. The position of the timber tractor and semi-trailer in space is characterized as the coordinates of their centers of gravity ($x_T$, $y_T$, $z_T$), ($x_N$, $y_N$, $z_N$), and angles of deflection ($\phi_{xT}$, $\phi_{yT}$, $\phi_{zT}$), ($\phi_{xN}$, $\phi_{yN}$, $\phi_{zN}$) local coordinate system of bodies from the base coordinate system.

Figure 2. Design scheme for building a dynamic model of a timber hauling tractor with a semi-trailer (only the left-side wheels are shown).

The movement of a road train in a model is described by a system of differential equations based on the basic laws of the dynamics of translational and rotational motion:

for the truck tractor equation (1):
for semi-trailer equation (2):

\[
\begin{align*}
\frac{d^2 x_N}{dt^2} &= m_N \sum_{i=4}^5 F_{Li}^z + \sum_{i=4}^5 F_{Ni}^z + F_{Bz}, \\
\frac{d^2 y_N}{dt^2} &= m_N \sum_{i=4}^5 F_{Li}^y + \sum_{i=4}^5 F_{Ni}^y + F_{By}, \\
\frac{d^2 z_N}{dt^2} &= -m_N \cdot g + \sum_{i=4}^5 F_{Li}^z + \sum_{i=4}^5 F_{Ni}^z + F_{Bz}, \\
J_{Nx} \frac{\partial^2 \phi_{Nz}}{\partial t^2} &= \sum_{i=4}^5 M^x(F_{Li}) + \sum_{i=4}^5 M^y(F_{Ni}) + M^y(F_b); \\
J_{Ny} \frac{\partial^2 \phi_{Ny}}{\partial t^2} &= \sum_{i=4}^5 M^x(F_{Li}) + \sum_{i=4}^5 M^y(F_{Ni}) + M^y(F_b); \\
J_{Nz} \frac{\partial^2 \phi_{Nz}}{\partial t^2} &= \sum_{i=4}^5 M^x(F_{Li}) + \sum_{i=4}^5 M^y(F_{Ni}) + M^y(F_b),
\end{align*}
\]

where \( t \) – time; \( F_{Li} \) and \( F_{Ni} \) – forces acting on the hull of a hauling truck or semi-trailer from the wheels of the \( i \)-th axis through the suspension on the left (index "L") and right (index "N") bead; \( F_{Ax}, F_{Ay}, F_{Az} \) – cartesian components of the force acting on the truck tractor from the fifth wheel coupling; \( F_{Bx}, F_{By}, F_{Bz} \) – cartesian components of forces acting on a semi-trailer from the side of the fifth wheel coupling; \( M^i \) – moments of the indicated forces about the axis \( i \).

To set the perturbing effect of the bearing surface on the bodies of the timber hauling and semi-trailer, a simplified elastic-viscous wheel model was used, simplifying the “wheel” - “suspension” system to a simpler system characterized by two coefficients: stiffness and damping. The force from the side of the wheel on the hull of the hauling truck was calculated using equation 3:

\[
F_i^z = c_i \left( z_{Ni}(x_i, y_i) + R_K - z_{Ki} \right) - d_i \left( \frac{\partial z_{Ni}(x_i, y_i)}{\partial t} - \frac{\partial z_{Ki}}{\partial t} \right),
\]

where \( i \) – wheel index; \( z_{Ni}(x, y) \) – vertical coordinate of the surface under the wheel, equal to the coordinate of the lower point of the wheel; \( z_{Ki} \) – the vertical coordinate of the point of attachment of the wheel to the body; \( R_K \) – wheel radius; \( c_i, d_i \) – stiffness coefficients and damping of visco-elastic interaction.
The system of equations of movement of the timber tractor and semi-trailer is a system of second-order differential equations. The numerical solution of differential equations consists in discretization of time $t$ into equal steps of $\Delta t$, which are numbered by variable $\tau$. At each integration step, it is necessary to calculate the forces and moments acting on the hulls of the hauling truck and semi-trailer. After that, the coordinates and velocities of the bodies for the next integration step are calculated from the known coordinates and velocities of the bodies for the current integration step. In particular, for the Cartesian component $x$, the numerical integration of the equations of motion of a certain body in the framework of the method under consideration is performed according to «equation 4»:

$$
\begin{align*}
&x_{\tau+1} = x_{\tau} + v_{x\tau} \cdot \Delta t + \frac{F_{xt}}{m} \cdot \frac{(\Delta t)^2}{2}; \\
v_{x\tau+1} = v_{x\tau} + \frac{F_{xt}}{m} \cdot \Delta t,
\end{align*}
$$

(4)

Where $x_{\tau}$ and $v_{x\tau}$ – the coordinate and velocity of a body of mass $m$ along the cartesian direction $x$ at the previous integration step over time $\tau$; $x_{\tau}$ and $v_{x\tau}$ – the same at the next time integration step $\tau + 1$. Similarly, numerical integration is performed for the remaining cartesian components $y$ and $z$, at the same time, integration is performed for both bodies: the body of the hauling truck and the semi-trailer body.

As a result of solving the differential equations by a numerical method, table-defined functions of the dependence on the time coordinates and the relative orientation angles of the timber carrying tractor and semi-trailer are obtained. These functions are analyzed further to assess the effectiveness of the recovery system. To reproduce the operation of the fifth-wheel hitch recovery system, it is necessary to create an intensive relative movement of the tractor and semi-trailer in the model. In the developed model, this is done in two ways: by moving on a supporting surface with random irregularities, by moving on a flat horizontal surface with variable speed. Random irregularities in the model are set on the basis of the actual operating conditions of the forest truck. A significant share of the path of a timber truck accounts for low-quality access asphalted roads, unpaved forest roads, winter roads. For transmission in the model of a complex random surface relief, it was considered that the perturbing function of the wheels of each bead consists of a set of protrusions of gaussian shape. The height and length of the Gaussian peaks are set randomly and vary widely: from “obstacles” (imitating stones, stumps, protruding roots, etc.) having a small length (about 0.2 ... 0.5 m) to “hills” having a greater length (about 2 ... 5 m) figure 3.

**Figure 3.** An example of a support surface for the study of loads on a fifth wheel coupling of a timber hauling tractor with a semi-trailer: fragments of functions $z(x)$ for the wheels of the left (blue line) and right (red line) sides (fragments of length 20 m).

The reference surface defined the function of the surface height from the coordinates of the point of contact $z(x, y)$, as a superposition of gaussian peaks with the parameters $(x_i, y_i)$ (protrusion position), $H_i$ (height of the protrusion) and $\sigma_i$ (standard deviation setting the protrusion width) equation 5:

$$
z(x) = \sum_{i=1}^{S_X} H_{x_i} \exp \left( -\frac{(x-x_{x_i})^2}{\sigma_{x_i}^2} \right) + \sum_{i=1}^{S_N} H_{y_i} \exp \left( -\frac{(x-x_{y_i})^2}{\sigma_{y_i}^2} \right),
$$

(5)

where $S_X$ and $S_N$ – number of hills and obstacles; $H_{x_i}$ and $H_{y_i}$ – heights of hills and obstacles; $x_{x_i}$ and $x_{y_i}$ – coordinates of the center of the hills and obstacles; $\sigma_{x_i}$ and $\sigma_{y_i}$ – характерная полуширина холмов или препятствий.
Gaussian peaks were distributed along the length of the control section of 500 m randomly according to a uniform law. In this case, the parameters $H_i$ and $\sigma_i$ were also chosen randomly according to a uniform law from intervals: from 0 to 0.6 m for $H_i$ and from 0.2 to 4.0 m for $\sigma_i$. The number of gaussian peaks that mimic hills and obstacles was calculated in accordance with the parameter tables for various types of road and ground conditions.

The considered recovery system converts adverse fluctuations in the distance between the tractor and the semi-trailer at the junction (fifth wheel coupling) into useful energy stored by the pneumohydraulic accumulator, and used further, for example, during operation of the hydraulic manipulator. In one of the variants, the model makes it possible to estimate the average value of the recovered power $N_p$ without taking into account the design of the recovery system and the hydraulic subsystem underlying it. In this case, $N_p$ is estimated by the power dissipation in the conditional damper of the fifth wheel coupling: through the coefficient of viscous friction in the approximation of the elastic-viscous contact of points $A$ and $B$.

In the process of modeling, characteristics are calculated that allow one to determine both the regenerative effect and the adverse effects of fitting a fifth wheel coupling system with a recovery system. The main indicators of the efficiency of the recovery system are the recovered power (instant and average) and the average acceleration of the semi-trailer (instant and average). At each step of the numerical integration, the instantaneous value of the recovered power $N_p$ was determined from the change in distance between points $A$ and $B$ of the fifth wheel coupling in the longitudinal direction: 

$$N_p(\tau) = d_0 \left( \frac{D}{D_0} \right)^2 \frac{\left( x_A^\tau - x_B^{\tau-1} - \frac{x_B^\tau - x_B^{\tau-1}}{\Delta \tau} \right)^2}{\Delta \tau}$$

(6)

where $d_0$ – effective damping coefficient from recuperative hydraulic cylinders; $D_0$ – base diameter of recuperative hydraulic cylinders (the main calculations used the value of 50 mm); $D$ – diameter of recuperative hydraulic cylinders used; $x_A$ and $x_B$ – the longitudinal coordinate of the fifth wheel coupling point of the tractor and semi-trailer respectively; indexes $\tau$ and $\tau - 1$ denote the current and previous steps of integrating the differential equations of motion over time.

Equipping a fifth wheel coupling system with a heat recovery system can degrade the damping properties of the fifth wheel coupling and lead to unfavorable fluctuations of the semi-trailer with respect to the truck hauler. Therefore, in the developed model, along with the recoverable power, the acceleration of the semi-trailer in the longitudinal direction is estimated. The instantaneous longitudinal acceleration of the semi-trailer at the integration step $\tau$ was calculated using equation 7:

$$a_N(\tau) = \frac{x_N^{\tau+1} + 2x_N^{\tau} - x_N^{\tau-1}}{\Delta \tau^2}$$

(7)

where $x_N^{\tau+1}, x_N^{\tau}, x_N^{\tau-1}$ – coordinates of the center of gravity of the semitrailer along the longitudinal cartesian axis $OX$ to the previous $\tau - 1$, the current $\tau$ and the subsequent $\tau + 1$ steps of integrating the time differential equations.

After each computer experiment, the $N_p(t)$ and $a_N(t)$ functions were used to determine two indicators $N_{pC}$ and $a_{NC}$, averaged over a sufficiently long time interval of the equation 8, 9:

$$N_{pC} = \frac{1}{\tau_e - \tau_s} \sum_{i=\tau_s}^{\tau_e} N_p(\tau),$$

(8)
\[ a_{\text{Ne}} = \frac{1}{\tau_e - \tau_v} \sum_{\tau = \tau_v}^{\tau_e} |a_N(\tau)|, \]  

(9)

where \( \tau_v \) and \( \tau_e \) – time integration steps at which averaging begins and ends (averaging is not done from the beginning of the computer experiment, since at the first moments of time the mechanical system comes to equilibrium and not until the end of the computer experiment, since at the end the car can leave the area with a random relief).

3. Results

For the study of the developed mathematical model, a computer program called “Program for simulating the movement of a timber truck with a semi-trailer with a recuperative semi-coupling device” was developed in Object Pascal in the Borland Delphi 7 programming environment.

The process of investigating the recovery system of a timber hauler with a semi-trailer was to conduct multiple computer experiments with changing the set of input parameters relative to the parameters of the basic computer experiment. The basic computer experiment was carried out with the most typical parameters of a hauling truck with a semi-trailer and the conditions of its movement. After the launch of the developed computer program, the preparation of the relief of the bearing surface for the left and right side wheels was carried out. In this study, the geometric parameters of the terrain corresponded to a significantly uneven logging road. At the beginning of the simulation, the forest tractor and semi-trailer were placed near the origin, at a slight height above the supporting surface. With the beginning of the numerical integration of the equations of motion, the forest truck and the semi-trailer spontaneously lowered to the surface under the action of gravity, connected with each other at the point of the fifth wheel coupling and came to a stable position, which took about 5 seconds of modeling time.

The speed of movement of the tractor in the direction of the axis \( OX \) was constant in the process of modeling and was 20 km/h. This is a characteristic value of speed when driving on access roads to cuttings with asphalt pavement of poor quality, dirt roads, winter roads. In the process of driving on an uneven supporting surface, the truck tractor and the semi-trailer made a complex translational-rotational motion, remaining connected to each other through a fifth wheel coupling with model recuperative elements. The fluctuations of point \( A \) relative to \( B \) in the fifth wheel coupling caused the conditional pumping of the working fluid into the regenerative hydraulic system, and the program calculated the instantaneous recuperative power for each integration step figure 4, a. At certain points in time, the instantaneous values of the recovered power may exceed 40 kW, however, the average recoverable power for the entire basic experiment was 6.31 kW. To calculate the average recovered power, it was assumed that the forest truck with a semi-trailer moved on a supporting surface of 100 m.

![Figure 4](image_url)

**Figure 4.** The results of the basic experiment: time dependencies \( t \) of the instantaneous recovered power \( N_p(a) \) accumulated by the energy recovery system \( E_p(b) \) and the instantaneous longitudinal acceleration of the semi-trailer \( a_N(c) \).

As the truck trailer moves, energy is accumulated in the recovery system, which can later be used, for example, in a hydraulic manipulator in the process of loading or unloading assortments figure 4, b. Energy accumulation occurs approximately linearly; deviations from linearity are associated with
fluctuations in the density of the distribution of irregularities of the support surface. To assess the smoothness of the semi-trailer, the instantaneous $a_N$ and average $a_{Nc}$ of the «figure 4, c» longitudinal accelerations of the semi-trailer were calculated. In the basic computer experiment, the instantaneous value of acceleration could reach about 0.9 m/s$^2$ with the most unfavorable random combinations of irregularities of the supporting surface. However, the longitudinal acceleration averaged over the 100 m path amounted to a significantly lower value of 0.261 m/s$^2$, which is a rather smooth movement. In a further theoretical study, they were changed in relation to the basic values: the speed of movement of a forest truck and the diameter of the recuperative hydraulic cylinder. In this case, an analysis of changes in the performance of the recovery system $N_{pc}$ and $a_{Nc}$.

From the speed of movement depends on the intensity of oscillations of the semi-trailer relative to the forest truck, and, consequently, the intensity of the accumulation of energy by the recovery system. To study the effect on the efficiency of the recovery system of the speed of movement $v$ of a forest truck, a series of five computer experiments was carried out in which they varied $v$ from 10 to 50 km/h in 10 km/h increments. This longitudinal speed was maintained constant during the computer experiment for the center of gravity of the tractor, while the longitudinal speed of the semi-trailer was calculated using the equations of the mechanical system, taking into account the mechanical coupling between the bodies and the rotational motion of the bodies. With an increase in speed, the average recoverable power $N_{pc}$ increases according to a law close to a quadratic figure 5, $a$. At the same time, as the speed of movement along an uneven surface increases, the average longitudinal acceleration of the semi-trailer Figure 5, $b$ increases approximately linearly. Thus, with an increase in the speed of a timber truck from 10 to 50 km/h on a road with roughness of an average height of 0.4 m, the recovered power increases according to a square law from 5.5 to 12.2 kW.

The geometrical parameters of the recuperative hydraulic cylinders in the fifth wheel coupling determine the intensity of pumping the working fluid into the recuperative hydraulic system. However, the same effect in the fifth wheel coupling on the efficiency of damping adverse oscillations of the semi-trailer relative to the tractor. In order to study the effect of the diameter of the recuperative hydraulic cylinders $D$, a series of nine computer experiments were carried out in which the parameter $D$ was changed from 20 to 100 mm in 10 mm increments. It was found that the optimal diameter of the hydraulic cylinder is 40 ... 50 mm figure 6. At the same time, the recoverable power is quite high – about 6.5 kW, – and a rather low average longitudinal acceleration is about 0.27 m/s$^2$. If the diameter of the hydraulic cylinders ($D$ is less than 30 mm) decreases too much, the volume of fluid pumped into the pneumatic-hydraulic accumulator with each oscillation of the semi-trailer relative to the tractor decreases, so the recovered power decreases figure 6, $a$. Also, due to insufficient effective damping, the amplitude and sharpness of unfavorable oscillations of the semi-trailer increase, which is reflected in the growth of the average acceleration figure 6, $b$. With an excessive increase in the diameter of the hydraulic cylinders ($D$ over 60 mm), the fifth wheel coupling has a very high effective damping, which leads to the fact that the tractor and the semi-trailer are too tightly coupled. Because of this, the amplitude of movement of the
pistons of the hydraulic cylinders is reduced, and the flow of fluid from the hydraulic cylinder to the pneumatic-hydraulic accumulator also decreases, figure 6, a. In addition, due to too high stiffness of the fifth wheel coupling, the movements of the mechanical system become sharper and the average acceleration of the semi-trailer figure 6, b increases.

![Figure 6](image)

Figure 6. Influence of the diameter of \( D \) recuperative hydraulic cylinders in the fifth wheel coupling on the average recoverable power \( N_{pc} \) and the average longitudinal acceleration of the semi-trailer \( a_{sc} \).

4. Conclusion

Thus, a mathematical model has been developed, implemented as a computer program, which makes it possible to evaluate the possibility of equipping the fifth wheel coupling system with energy recovery in various driving modes and to study the effect of the parameters of the recovery system on its efficiency.

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