

Digital twin of wheel tractor with automatic gearbox

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Abstract. This article describes the digital twin of power drive unit (engine and transmission) of 8-ton class wheel tractor with automatic gearbox. Detailed mathematical model of considered tractor power drive unit - engine with 16-speed automatic gearbox and friction shift of stages under load without breaking the power flow is given. The theoretical methods of research are based on the use of the MATLAB package. With the help of fundamental package units, models of gearbox physical components are created: friction clutches, gears, shafts with the required properties, engine mathematical model, as well as model of the transmission control system. The calculation methods of the gearbox dynamic processes going on in the gear shifts using friction clutches is proposed. A feature of the mathematical model is consideration of the resistive torque, the rate of rise of switched on clutches friction torque, both during switching to the higher and lower gears. Mathematic simulation of tractor power drive unit operation under load was performed. The results of the completed calculations are presented. The possibility of using this digital model to simulate tractor operation during its main work operations is shown.

1 Introduction

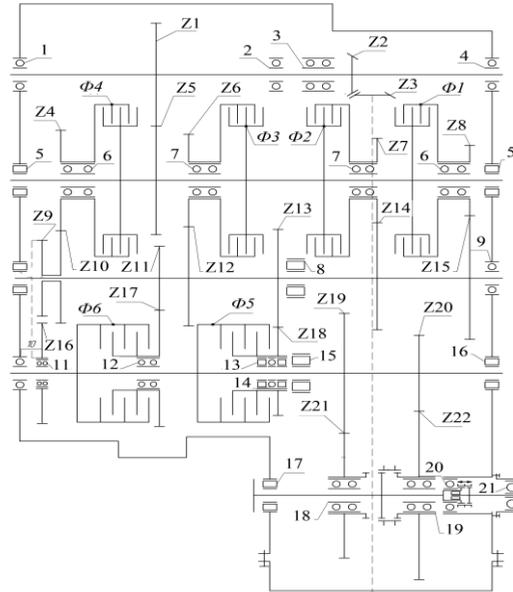
This study describes a automatic gearbox (16 gears) proposed for an 8-ton class tractor. Shifting gears under load is one of the most complex types of transient processes in transmissions of transport and traction machines [1-5]. The proposed procedure is intended for calculating the dynamic characteristics of automatic transmission of tractors.

The kinematic scheme developed for the automatic gearbox (Fig. 1) includes friction clutches located on the input, intermediate shafts of the gearbox, simultaneously using a maximum of 4 friction clutches for shifting gears. Examples of transmission designs of foreign and domestic industrial and agricultural tractors, the main modes of their operation are given in [6-8].

One of the most effective and rapid methods for simulating the operational characteristics of the tractor with a new automatic transmission is building a digital twin of the tractor. Existing theoretical and experimental studies as well as practical recommendations are

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made for designs of gearboxes simultaneously using two friction clutches for shifting gears [9-14].



F1...F6 - friction clutches, z1...z23 - gears, 1 ... 21 – bearings.

Fig. 1. Kinematic scheme of automatic transmission of tractor.

2 Objectives

The goal of the study consisted in creating a digital twin of the tractor. The digital twin is a technology for developing and applying complex multidisciplinary mathematical models replicating real objects with a high degree of accuracy. Numerical simulation of a wheeled tractor as a system is a multidisciplinary task, covering such interacting subsystems as the internal combustion engine with a variable-speed governor, the automatic transmission with a control system using preset algorithms, the running gear interacting with soil and road, transport and traction loads on working bodies of agricultural machinery; mechanical, hydraulic, frictional, thermal processes occurring in the units and assemblies of the machine.

3 Methods

The MATLAB package combining numerical simulations, visualization and programming is an optimal tool for creating multidisciplinary mathematical models. Applied problems are solved in MATLAB package. This provides an interactive environment for nonlinear modeling and analysis of a wide class of dynamic systems. The theoretical methods in this study are based on the MATLAB package and its applications. Fundamental application blocks are used to build models of the tractor's physical components: internal combustion engine, friction clutches, gears, shafts with the required elastic and dissipative properties, driving wheels with traction characteristics. The blocks are also used to program the inertial properties of objects, as well as the system for controlling the automatic transmission.

Fig. 2 shows the full-load curve of the TMZ-8483 engine of the «Kirovets» family tractor.

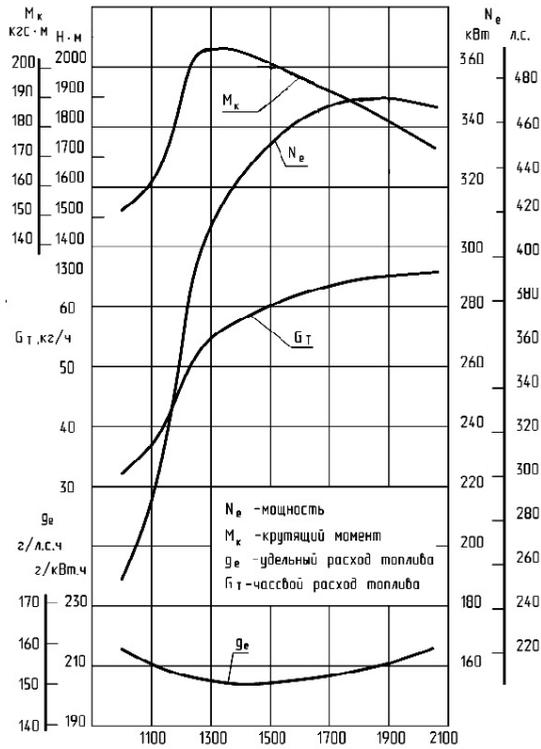


Fig. 2. Full-load curve of TMZ-8481.10-02 engine: M_e is the torque; N_e is the rated power; g_e is the specific fuel consumption; n is the crankshaft speed.

Fig. 3 shows its digital Engine model complemented by engine’s regulatory characteristics.

The Engine Subsystem includes the 2D Lookup Table block. This block compares the input data (fuel supply, engine revolutions) with the output values by interpolating the table of values determined with the block parameters. The matrix for the 2-D Lookup Table block corresponds to the parameters of the full-load and speed regulation curves of the engine.

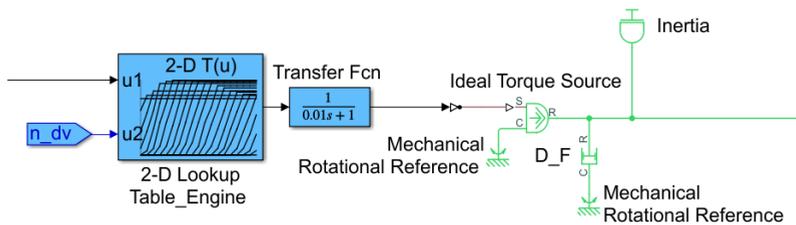


Fig. 3. Engine Subsystem.

The digital model of the mechanical system of the automatic transmission of the tractor is shown in Fig. 4. The input shaft of the transmission is shown in the figure as a segment connected through the port to the Engine subsystem.

The properties of the automatic transmission gearbox are described using the Simple Gear blocks: R1,..., R9, Rear. The inertial properties of the driving and driven members of the friction clutches are represented by inertial rotating masses, the Inertia blocks. The bearing supports of the shafts are represented by Rotational Damper blocks with Mechanical Rotational Reference supports D_F_11,..., D_F_42.

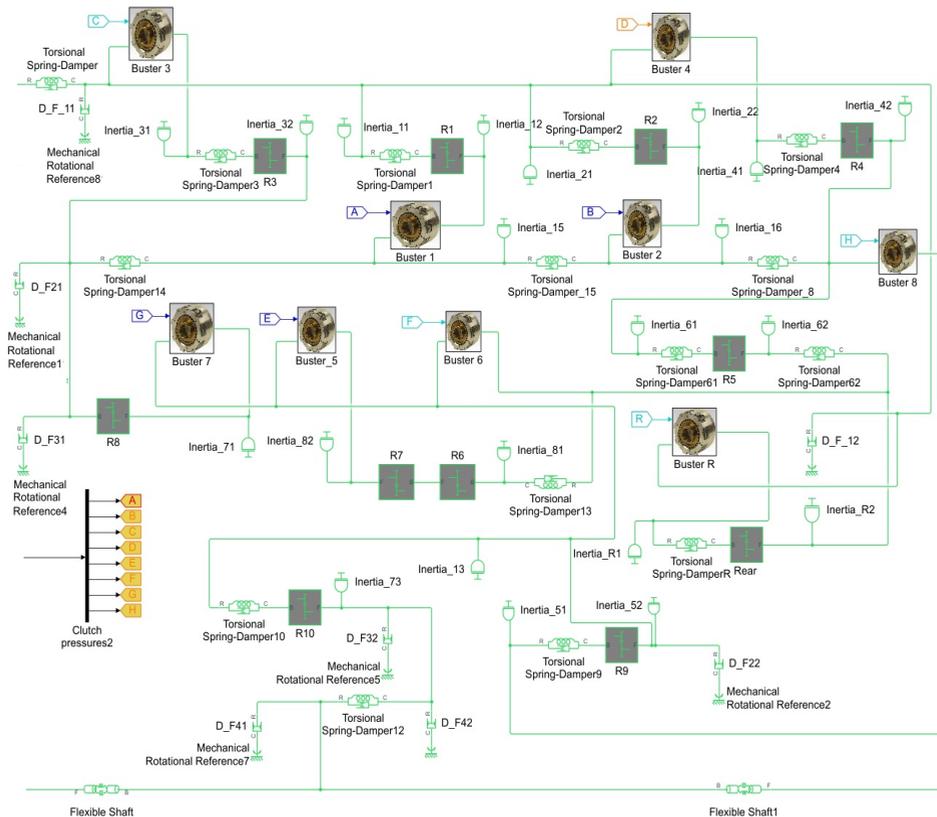


Fig. 4. Transmission Subsystem.

The friction units of the automatic gearbox, Buster 1,..., 8, R, which are friction clutches for shifting gears, have block diagrams corresponding to Fig. 5. The clutches are switched on or off via a controller using Clutch Pressure commands A,..., H in appropriate combinations.

The Disk Friction Clutch block is a friction clutch with sets of friction disks. The clutch is bidirectional and can slip in both positive and negative directions. The block provides an input port for the physical signal (P) for applying pressure to the friction disks.

The subsystem controlling the automatic transmission is shown in Fig. 6. The subsystem includes the Driver (Signal Builder) block generating the level of fuel supply by the operator as a percentage of the maximum value (100%), which, combined with the actual tractor speed V , selects the optimal gear using the ShiftLogic block and the gearshift map. The Select Clutch States block is then used to transform the input signal into supply (discharge) of pressure in the corresponding combinations of clutches switched on or off (Actuator Dynamics and Gain blocks).

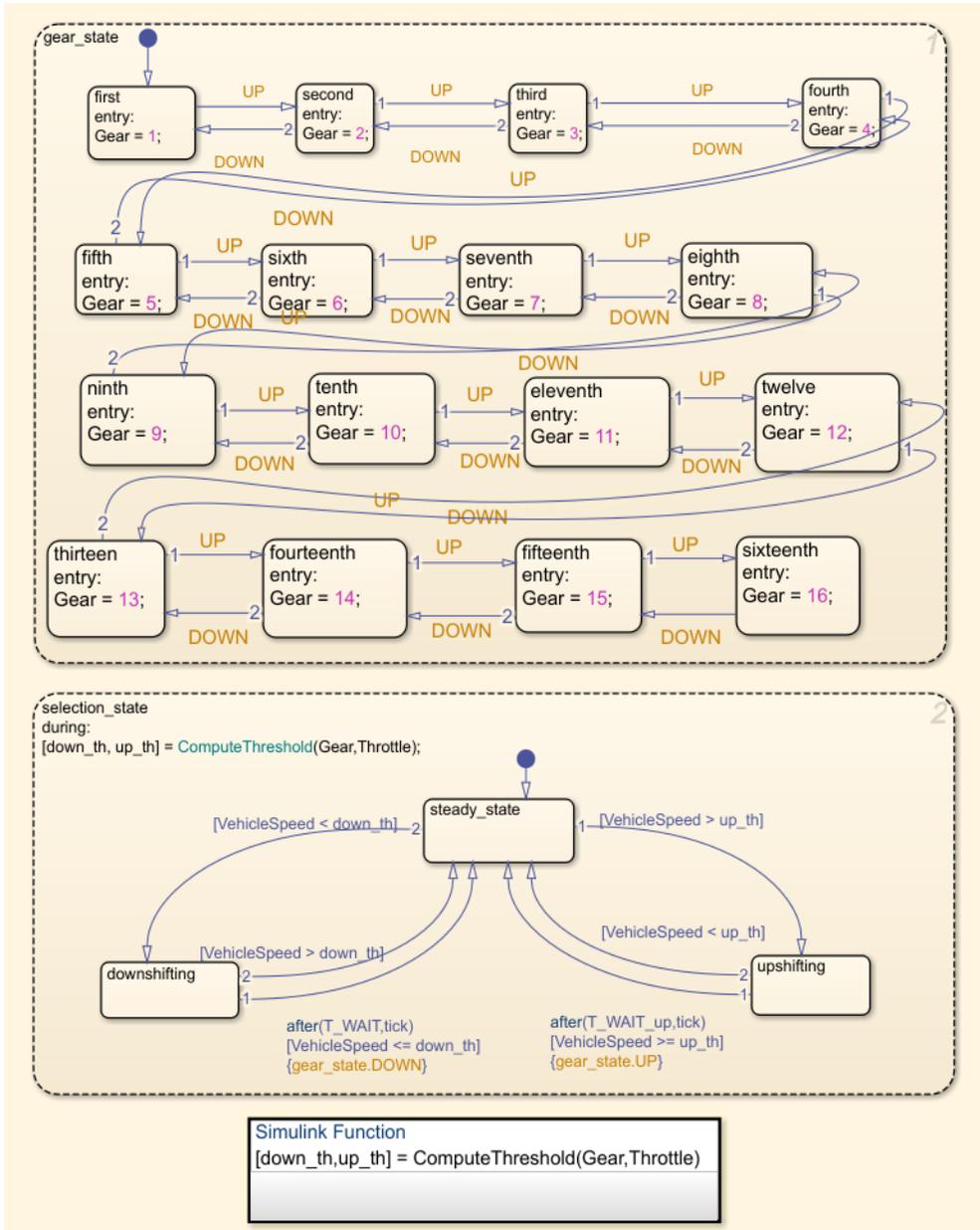


Fig. 7. Shift Logic Block.

The second diagram *selection_state* processes the actions performed while the state is active

during: $[down_th, up_th] = ComputeThreshold(Gear, Throttle);$

Three new states were introduced in *selection_state*: *steady_state* (current state), corresponding to the data of the current state of the *gear_state* diagram.

downshifting, receiving control from *steady_state*, if the speed is below the lower threshold. The lower threshold, updated by the *ComputeThreshold* block, is checked in this state. Return to *steady_state* is performed by two paths: without generating an event if the speed has exceeded the lower threshold, and generating the *gear_state.DOWN* event if the

speed remains below the lower threshold (the downshifting procedure is repeated in the second case).

upshifting, receiving control from *steady_state* if the speed exceeds the upper threshold updated by the *ComputeThreshold* block. Return to *steady_state* is performed by two paths: without generating an event if the speed has exceeded the lower threshold, and generating the *gear_state.DOWN* event if the speed remains below the lower threshold (the downshifting procedure is repeated in the second case).

The default start state is *steady_state*, marked with the *Default Transition pointer*.

Speed thresholds are calculated using the *Simulink Function* block of the *function* $[down_th, up_th] = ComputeThreshold (Gear, Throttle)$

Fig. 8 shows the internal structure of *Simulink Function*.

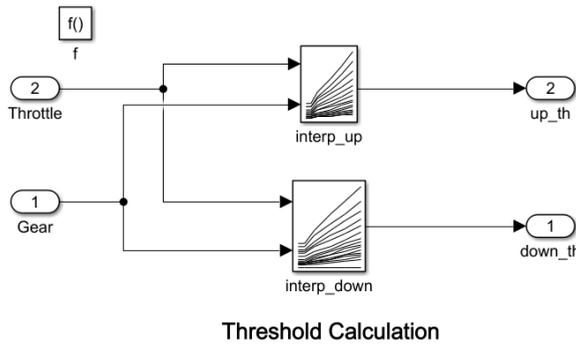


Fig. 8. Simulink Function Structure.

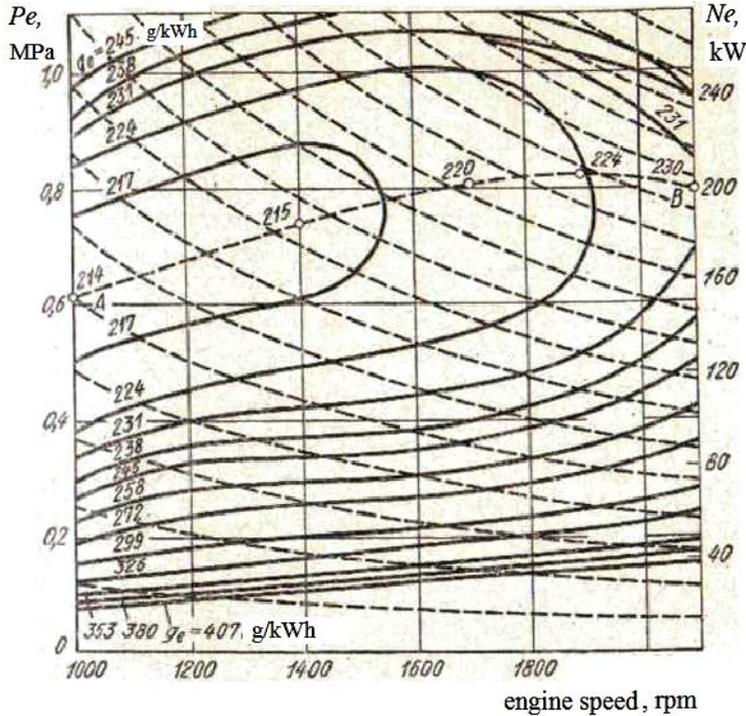
Speed thresholds are generated by the *ComputeThreshold* block. The command *f* sends a signal to the addresses determined by the *Gear* (inport 1) and *Throttle* (inport 2) values to extract the values of the upper (Table_UP) and lower (Table_DOWN) speed thresholds from the interpolation tables.

Gears (*gear*) are shifted in the *ShiftLogic* block by comparing *speed* with the speed thresholds: the upper *up_th* (when the speed is too high) or the lower *down_th* (when the speed is too low), with the respective output 2 or 1.

The *Lookup Table (n-D Lookup Table_Up)* block interpolates the *TABLE_UP* threshold speeds for shifting from lower to higher gears depending on fuel supply (*UP_Th*) and gear number, given as tables.

The *Lookup Table (n-D Lookup Table_DOWN)* block interpolates the *TABLE_DOWN* threshold speeds for shifting from higher to lower gears depending on fuel supply (*DOWN_Th*) and gear number, given as tables.

The gearshift map corresponding to the *interp_up* and *interp_down* tables (Fig. 8) is built based on the gearshift map. Such maps are based on the universal multi-parameter performance curve of a diesel engine (an example is shown in Fig. 9).



(dashed curves correspond to constant power N_e , kW; solid curves to specific fuel consumption g_e , g/kWh; AB is the curve for minimum specific fuel consumption; P_e is the effective average pressure, MPa).

Fig. 9. Multi-parameter performance curve of YaMZ-238N diesel engine of Kirovets tractor

Let us consider the universal performance curve of the tractor diesel engine in Fig. 11, showing the topographic curves of specific fuel consumption g_e , along with the curve AB corresponding to minimum specific fuel consumption g_{e_i} of the engine operating in the given gear. Evidently, the minimum fuel consumption can be obtained with a relatively high engine torque load (for example, the corresponding load for the YMZ-238N is 70–75% in the range of moderate speeds with engine angular speeds 1200–1800 rpm). However, the load is still far from the maximum, and the lower the engine speed, the lower the load corresponding to the minimum specific fuel consumption.

We can conclude from this curve that it is inadvisable to combine the curve for gear shifts at part loads with the non-regulatory branch of the engine performance curve, since it does not provide for fuel-efficient operation of the engine.

Let us discuss the static traction curves of the tractor, considering two adjacent gears to simplify the simulation. The gear shift should be made at the intersection points (B_x) of the traction curves of adjacent gears for optimal performance. However, gears should not be shifted from lower to higher and vice versa at the same points to avoid cyclic gearshifts. Aside from other factors, cyclic gearshifts can be caused by periodic fluctuations in the load relative to the steady-state value, as well as by a transient process due to gearshifts, when the regulatory parameters can sharply deviate from the steady-state values.

We established that such false signals can be excluded if the deadband of the automatic gearbox should be at least 1.5–2 s in the state preceding the shift, and 4–5 s after the shift. A system with such parameters does not respond to torque fluctuations with a period below the given values.

To avoid cyclic gearshifts, the curves for shifts to higher and lower gears should not co-

incide. Therefore, the gear shift point (B_{X-1}) in this case should be lower than the point (B_X) to provide a reserve of traction force excluding a drop in machine speed that would necessitate gear reversal. Selecting the point B_{X-1} for this tractor requires experimental studies. It is preferable to bring points B_{X-1} and B_X closer to each other, in order to minimize the reduction in engine power. This curve provides engine operation at full power, and therefore, high performance. The regulation system in this case is a power stabilization system. Engine power is maintained in the range determined by engine characteristic.

The engine is underloaded in speed stabilization mode, so it is advisable to maintain efficient operation of the tractor in terms of specific fuel consumption. The optimal curve for gear shifts should coincide with the traction curve with equal specific fuel consumption for adjacent gears, which is assumed for the tractor's gearshift map.

Tractor Chassis subsystem is shown in Fig. 10. This subsystem uses free torque to calculate the acceleration of the tractor and integrates it to calculate the speed, taking into account slipping of the drive wheels under hook load.

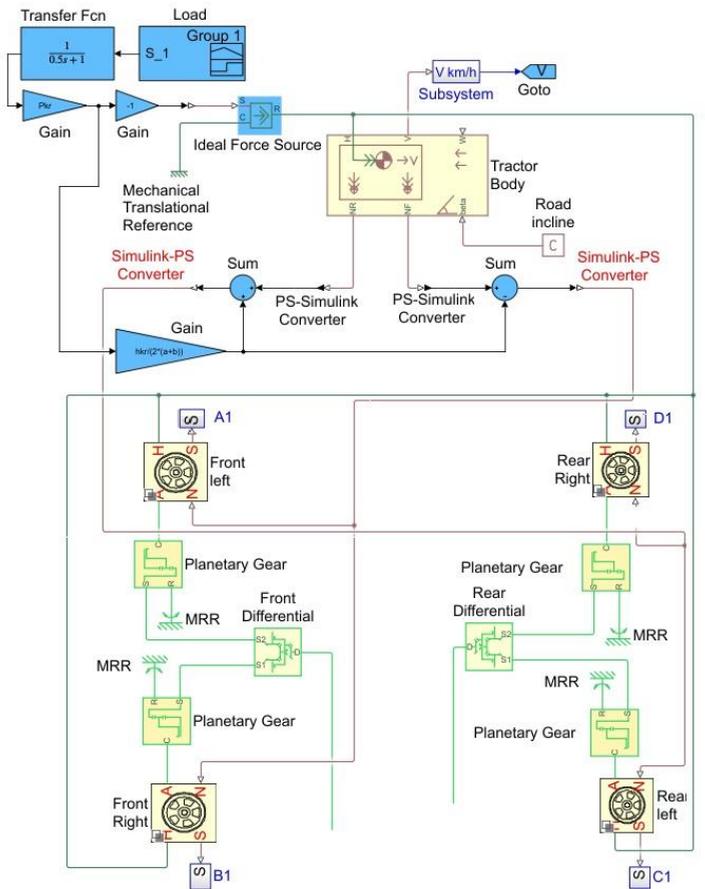


Fig. 10. Tractor Chassis Subsystem.

The Tractor Body block in Fig. 10 is a biaxial traction vehicle in longitudinal motion. The tractor has two identical driving wheels on each axis and has a center of gravity (CG) located in the tractor's plane of motion. The block takes into account the mass of the tractor (inertial load), the Road incline and the distribution of weight between the axles due to acceleration, road profile and traction load on the hook.

The tractor's motion is the result of total action of all forces and moments acting on it. The longitudinal forces of the driving wheels (Tire blocks: Front Left, Front Right, Rear Left, Rear Right) push the vehicle forward or backward through the H ports. The mass of the object acts through its center of gravity (CG). It is assumed for simplicity that the tractor's rolling resistance acts through the center of gravity.

Tractive resistance is represented by the Load (Signal Builder) block in Fig. 13 and models different types of hook load P_{kr} as a function of time.

The Tire block (Tire, Fig. 11) models a tire with its longitudinal characteristics given by a special formula or empirical equation. The block can model tire dynamics for constant or variable road surface conditions.

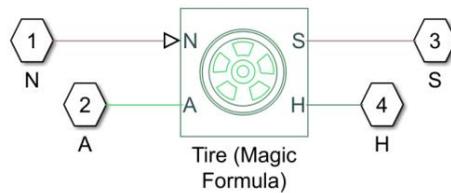


Fig. 11. Tire Block Port N is the normal force acting on the wheel; port S is the wheel slipping; port A is the power on the wheel; port H is the traction.

4 Results and analysis

The initial data for modeling the operation of the tractor with automatic transmission based on the digital prototype described above, as well as the calculation results.

With the help of the developed digital model - digital twin of a 8-ton class wheel tractor, mathematic simulation of tractor movement taking gear shift in the process into account was fulfilled. As a result, calculated data were obtained. At the same time, loads on the main elements of the transmission and engine of the machine were calculated. The torsion torque, engine crankshaft speed and tractor load in motion are determined. The characteristics of dynamic processes in the gearbox in process of shifting a gear was calculated - torsion torques and angular rates of the driving and driven discs of the friction clutches

Main initial data are given below.

$M = 18000;$	tractor weight, kg
$H = 0.7;$	tractor's center of gravity, m
$h_{kr} = 0.5;$	hook load height, m
$P_{kr} = 80,000$	rated hook load, N
$f = 0.08;$	wheel rolling resistance, stubble
$r_w = 0.725;$	wheel radius, m
$I_{sh} = 4.12;$	tire moment of inertia, $kg \cdot m^2$
$k_{demf} = 10,000;$	tire longitudinal damping ratio, $N/(m/s)$
$c_{uprug} = 200,000;$	tire longitudinal stiffness coefficient, N/m
$i_{diff} = 3.5;$	differential ratio
$I_m = 20.3;$	axle ratio
$J_{tr} = 12;$	normalized moment of inertia of reduced transmission, $kg \cdot m^2$
$F_z = (M/4) \cdot g$	static vertical load on wheel, N
$I_{dv} = 4.3;$	moment of inertia for engine with flywheel, $kg \cdot m^2$
$n_{dv_0} = 1400$	initial engine speed, rpm
$R_{clutch} = 130;$	effective radius of friction clutch, mm
$n_{fr_1} = 10;$	number of friction surfaces in clutch

$n_{fr_3} = 16;$	number of friction surfaces in first gear
$f_{tr_kin} = 0.08;$	kinetic coefficient of friction between disks
$f_{tr_st} = 0.3;$	static friction coefficient
$P_{engag} = 100;$	clutch booster actuating pressure, Pa
$F_{piston} = 0.03;$	piston thrust area, m ²
$J = 0.3;$	mass moment of inertia, kg*m ²
$C_{torsion} = 100000;$	stiffness of automatic transmission shafts
$p_{up} = 1e6;$	pressure in hydraulic clutch, Pa

User inputs to the digital twin are shown as fuel supply (*Trottle* opening, %) and load on the hook (the tractor's penetration depth, P_{cr} , N).

As example, Figs. 12, 13, 14, 15 show graphs for operation of the tractor with automatic transmission, with the operator setting a variable level of fuel supply and a variable hook load.

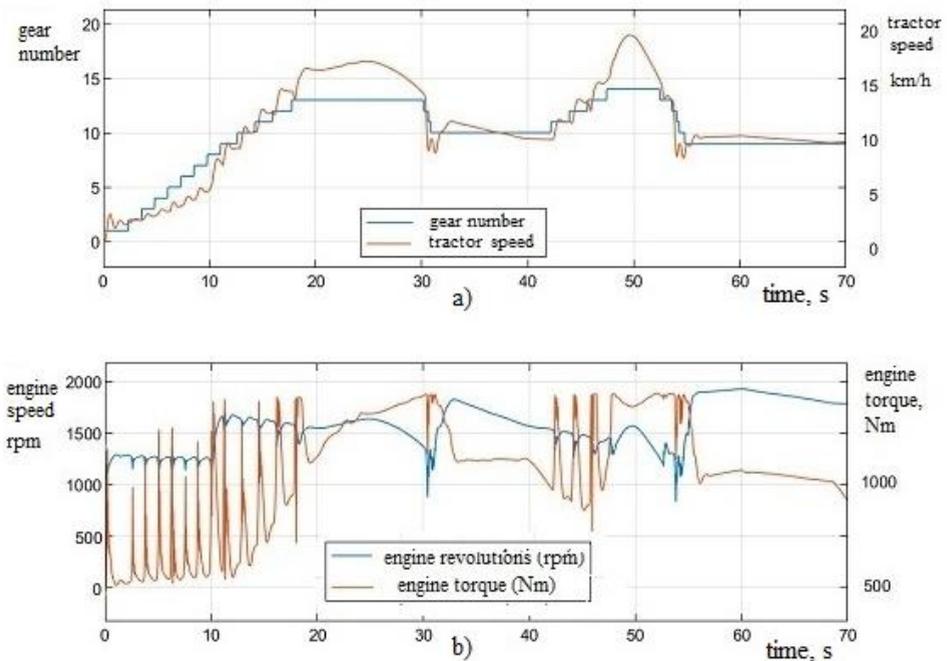


Fig. 12. Work processes corresponding to operation of tractor with automatic transmission gear number and tractor speed, km/h (a); engine torque (Nm) and engine revolutions, rpm (b)..

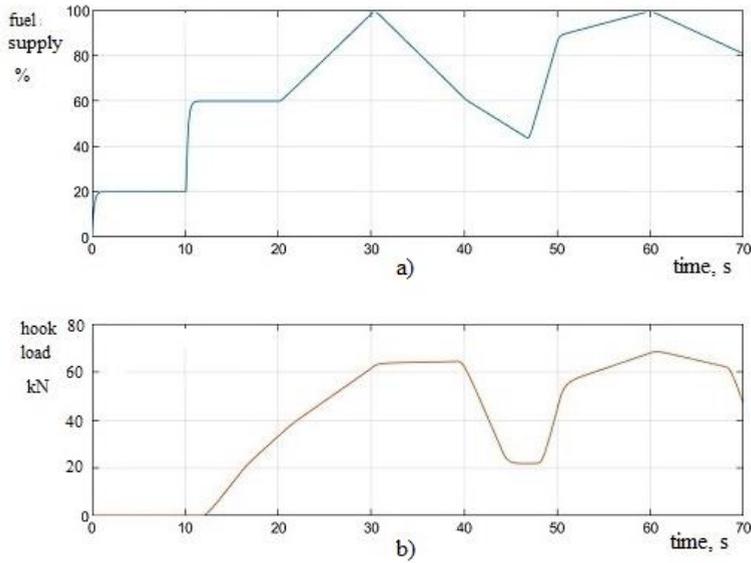


Fig. 13. Work processes corresponding to operation of tractor with automatic transmission - fuel supply set by operator, % (a); hook load set by operator, N (b).

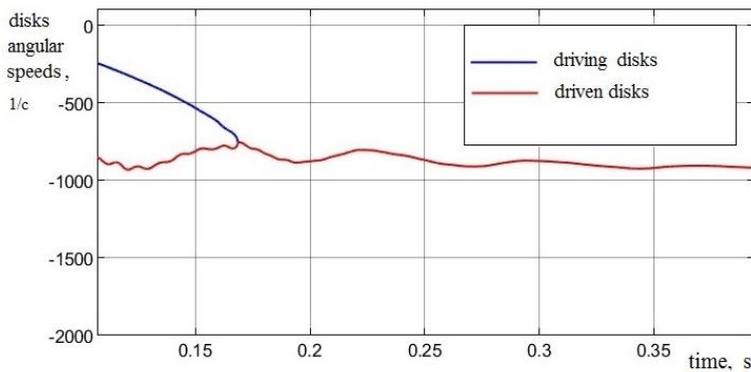


Fig. 14. Work processes corresponding to operation of tractor with automatic transmission/ Angular speeds of driving and driven disks of friction clutch for shift from first to second gear, rpm .

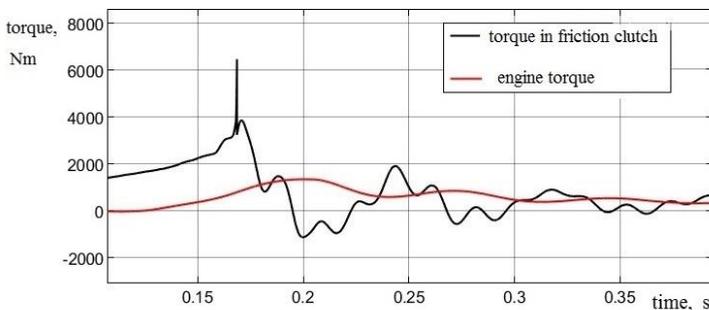


Fig. 15. Work processes corresponding to operation of tractor with automatic transmission. Torque in friction clutch and engine torque, Nm.

5 Conclusion

The digital twin developed for an 8-ton class wheeled tractor solves the multidisciplinary task of simulating the technical characteristics of the tractor's interacting systems, reproducing the real object with high accuracy.

The digital twin was constructed using visual programming technologies, allowing to obtain information about the operating parameters of the engine, automatic transmission, control system, tractor chassis interacting with soil and road, transport and traction loads.

The systemic approach used to develop the digital twin makes it possible to assess the object as an integral system comprising the operator, the tractor, the agricultural equipment, and the soil, as well as to simulate individual processes (kinematic, load, power) occurring in the machine components and assemblies.

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