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ORIGINAL ARTICLE

Optimisation of an Algorithm for Automatic Control of Transmission in a Wheeled Tractor

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ABSTRACT – The paper considers a digital model of a wheeled agricultural tractor, as well as algorithms for automatic control of the engine and transmission. Simulation of the working conditions was performed in MATLAB and its applications, Simulink, Sim-scape. The tractor model is based on a systemic approach and includes such subsystems as the engine, transmission, undercarriage, hook load, and control actions from the operator, as well as functions of logic and optimisation for gear shifting. With the help of fundamental blocks of the Matlab package, models of tractor physical components are created. The fundamental blocks of the package serve to model the physical components of the tractor: engine, transmission control system, the transmission that includes friction clutches, gears, shafts ties with the necessary characteristics. Simulation of the working processes of a tractor unit is performed with optimisation of the laws of engine and transmission control according to the criterion of fuel efficiency and maximum power usage. The control system parameters were optimised in the transport mode, as well as in the maximum power mode in the traction range. As an illustration of the use of this analysis method, a solution to the problem of optimisation of an agricultural wheeled tractor operating modes is given. The results of this mathematical simulation are presented in this paper. Parameters of tractor operation control algorithm, which provide minimum fuel consumption in tractor operating cycles, are given. The research results showed the effectiveness of the proposed algorithms and the digital model. The presented digital model allows to debug the operating tractor control algorithms and offers an engineering practice for optimising automatic control of the agricultural tractor engine and transmission.

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INTRODUCTION

An agricultural tractor is a complex technical system where the operator needs to analyse a large amount of information when choosing the optimal control laws for a machine-tractor unit (MTU) to achieve the highest productivity. Since a person is not always capable of objectively assessing the situation and choosing the correct mode of operation of the MTU, it seems relevant to develop optimal laws for automatic control of the tractor engine and transmission. The world's leading manufacturers of agricultural machinery are introducing tractors with automatic transmissions, whose laws of control of the engine and transmission unit provide an increase in MTU productivity and reduce operator fatigue. For example, according to the results of field tests of John Deere 4040 tractors equipped with automatic transmission [1], their fuel consumption was 45% lower than tractors with manual control, and the productivity (surface area per hour) increased by 50%. This transmission (gearbox) is equipped with an automatic control system (ACS). According to NATI [2], the productivity of the T-150K tractor increased by 7.89–9.84% because the tractor was equipped with automatic control of gear shifting and engine operation modes, while the fuel consumption decreased by 4.31–5.53%. Tests of tractors of different traction classes (1, 4, and 3) were carried out by organisations at different times and conditions, using various methods. Still, the results reflect the same trend, namely, an increase in the technological properties of tractors as a result of using automatic gear shifting.

A comprehensive approach has to be taken to solve the complex task of creating and debugging such an ACS of transmissions. For this reason, research methods based on creating a complex digital model of a technical system using various fields of knowledge, such as the theory of the tractor and internal combustion engine (ice), design and calculation of transmission, optimisation and programming, and computer modelling, are of particular importance [3-7]. A systemic approach to creating a digital MTU model makes it possible to study and optimise a mechanical system with greater accuracy compared to the case when the components of an object are considered separately.

The main goal of this study is to develop a digital mathematical model and mathematical methods for analysing and determining the optimal laws of automatic control of the engine and transmission of a wheeled agricultural tractor. The scientific novelty and practical value of the research lie in the selection and optimisation of control laws in accordance with the requirements for agricultural tractors with automatic speed transmission. This goal was achieved in the following stages, determining the goals of control and the requirements for ACS, building a digital model of an MTU with an ACS based on the Kirovets tractor in MATLAB, Simulink and Simscape applications, selecting and optimising the laws for

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controlling the ACS engine and transmission and simulating the work processes of the MTU with ACS and assessing the effectiveness of the results obtained.

Objective

The research object is an MTU based on the Kirovets tractor with a 16F/8R speed gearbox with hydraulically controlled friction clutches. This transmission was described in [8, 9]. The existing ACS used on various agricultural machines are divided into two classes: constant power systems that maintain a constant engine operation mode and power for a given position of the system adjuster, and constant speed systems that maintain the machine speed [10]. Therefore, the ACS must contain two modes of the constant power mode and the constant speed mode of the machine.

The speed was set in a constant speed mode, with the fuel pedal position unchanged and must be maintained constant by automatically switching gears and simultaneously changing the engine speed mode. The ACS must control the current fuel supply to the engine and, at the same time, select the gear to ensure the given speed of the tractor, operating in the zone of minimum fuel consumption. It makes sense to consider the speed stabilisation mode where the engine power is not used to the full extent, with a fairly wide speed control zone. At the same time, this problem can be solved by taking into account a large number of different factors, such as the traction characteristics of real tractor units, unsteady driving modes, and slipping of the driving wheels [11-19]. The well-known universal (multi-parameter) characteristics of tractor engines are also used here [20]. Topographic lines of specific fuel consumption (fuel consumption per unit of power) on such characteristics indicate that the engine operation should be maintained in a certain zone from the standpoint of fuel efficiency.

The specific flow function is a second-order curve and is an objective function at a constant speed. To calculate its value, the ACS must measure two parameters at each time: the current speed and the engine torque. In this case, the ACS must be an extreme system that brings the engine operation closer to the extreme of the fuel consumption function in accordance with the given speed by selecting the appropriate transmission. The operation of such an ACS must be tested with active speed control, for example, in transport mode.

i. In view of the above, the following requirements are imposed on the ACS in constant speed mode:
ii. The ACS should be a dynamic optimal system for fuel consumption.
iii. The ACS should ensure the speed of the car set by the driver by regulating the fuel supply to the engine.
iv. The ACS should ensure that the engine operates with minimal fuel consumption at the given speed by automatically switching gears and selecting the optimal gear.

In the maximum power mode, the engine and the transmission are controlled depending on the load and speed modes of the engine. The following conditions must be met.

i. The engine should be maintained in a mode close to the rated mode.
ii. The gearbox should be switched to a minimum gear ratio providing the above-mentioned operation of the engine.
iii. The target function for the ACS, in this case, is the engine power. Since the accelerator pedal is in the extreme position, and the fuel supply is maximum, power control only occurs by shifting gears, and the speed of the MTU changes only discretely.

Figure 1 shows the beam nomograms of transmission ratios combined with the regulatory characteristics of the diesel engine. The bold line shows the operation of the ACS. The load on the engine increases with increasing tractive resistance, and after reaching the level of M_{kmax} at the points a_i, it switches to a lower gear. When the load is reduced at the points b_i, switching to a higher gear occurs. In this case, the range of engine operation between two gear changes is limited to the M_{kmax} and M_{kmin} points. The 'up' or 'down' gear shift for two adjacent gears is performed at the same RCR value. Thus, switching to the highest gear (when the load is reduced) should occur at points b_1, b_2, b_3, b_4, b_5 and switching to the lowest at points a_1, a_2, a_3, a_4, a_5. The upper (potential traction characteristic) and lower dashed lines in Figure 5 connect the points of the highest and lowest values of traction power, respectively, outside which the tractor with automatic gear shifting cannot operate. The operation of the automatic control system in this case guarantees strict compliance with the programmed law of gear shifting. Here, the traction characteristic is as close as possible to the potential traction characteristic of the tractor. The control interval is selected based on two conditions. On the one hand, it is necessary to maximise the potential of the engine, that is, to reduce the width of the control range as much as possible, on the other – to prevent cyclic gear shifts.

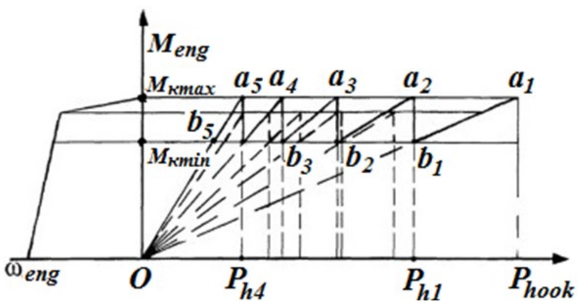

Figure 1. The beam nomograms of transmission ratios and the regulatory characteristics of the diesel engine.

Controlling the skidding of the tractor's driving wheels is especially important in the maximum power mode. Skidding by more than 30 % should not be allowed since this can significantly aggravate the performance of the MTU and result in soil destruction [9]. Therefore, in case of increased skidding of the ACS, it is necessary to lower the transmission in the gearbox and reduce the speed mode of the engine, generating a signal that operation is impossible if maximum permissible skidding is reached for the given conditions of preserving soil fertility. Based on the above analysis, we can formulate the main requirements for the ACS in the maximum power mode:

i. The ACS should maintain the operation of the tractor engine in a certain minimum range, close to the rated power.
ii. The ACS should not allow cyclic gear shifts when the load on the engine fluctuates.
iii. ACS should not allow the tractor's driving wheels to slip by more than 30%, as this can lead to the destruction of the fertile soil layer.

METHODOLOGY

The MATLAB package with Simulink and Simscape applications was used to solve the problem posed in the study. The package makes it possible to carry out simulations of MTU and ACS based on the systemic approach, where the operation of the tractor unit is considered an integral system. In this case, it is possible to make a rational selection and optimise the system parameters. A digital Simulink-Simscape (SS) model of an MTU with an ACS based on the Kirovets tractor was created for mathematical modelling. Figure 2 shows a general view of the mathematical model. The Simulink-Simscape (SS) MTU model consists of the following main subsystem blocks: Driver, Engine, Gearbox, Transmission controller, Actuators, Body, Driving Axle, Tire, Fuel Consumption, Monitors.

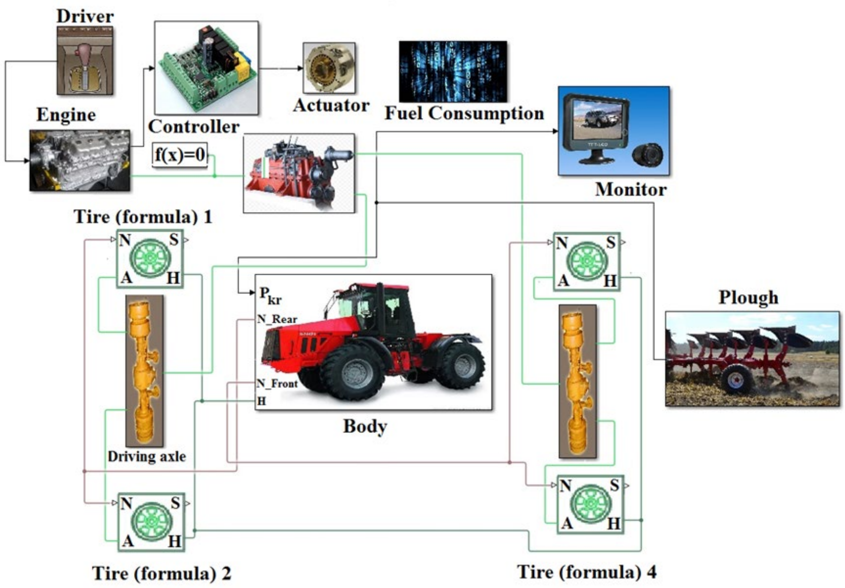

Figure 2. General view of the mathematical model.

The Driver module is a system for controlling the tractor speed (see Figure 3). Two signals are sent to the control system input: the first signal is the current speed, and the second is the required speed of the tractor, set by the driver with the fuel supply pedal. The operation of the system is based on a PI controller, which, in accordance with the control error, gives signals for fuel supply to the engine and determines the level of braking torque. PI controller is used here because it provides zero error in steady-state operation. Deceleration of transient process speed with PI controller is compensated by high inertia of tractor.

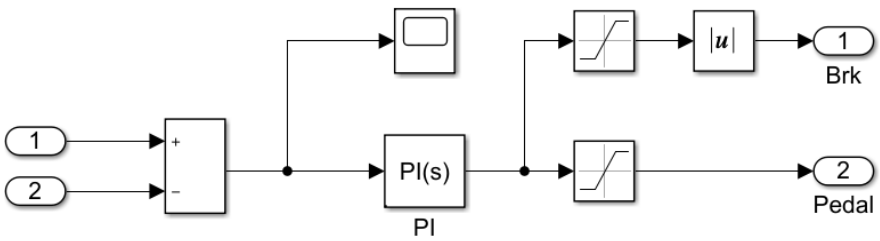

Figure 3. Driver subsystem.

The Engine Subsystem in Figure 4 includes a 2D Lookup Table, which calculates the engine torque depending on fuel supply (input port Pedal), and engine speed (input port Speed). The Engine Map block is built in accordance with the

YAMZ–536 engine map [20]. The Transfer Fcn block filters (smoothes) the data given in tabular form. Then the data are converted to a physical Simscape signal and fed to the Ideal Torque Source, which generates torque proportional to the input signal. The Sensor unit measures the torque and angular velocity of the engine.

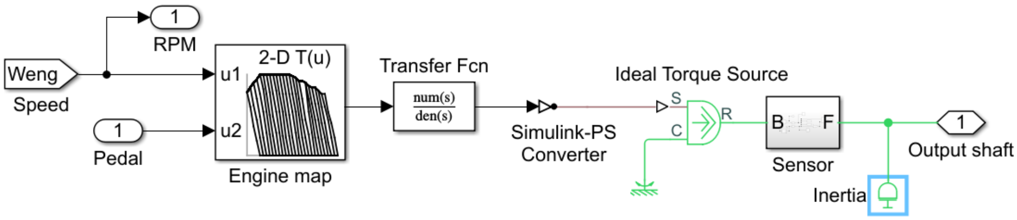

Figure 4. Engine subsystem.

In the Gearbox Subsystem, a physical signal from the output port of the Engine Subsystem, i.e., the engine torque, is fed to the input of the subsystem. The torque is transmitted from the output of the module to the front and rear axles of the tractor. The SS model of the gearbox subsystem is considered in [21], showing the kinematic scheme of the gearbox, the order of gear shifting using friction devices, the elements included, and the gears engaged. The gear properties of the subsystem are modelled using standard Simple Gear blocks. The inertial properties of the driving and driven masses are represented by inertial rotating masses denoted as inertia. Hydro-compression friction units are described by the Disk Friction Clutch blocks. All of the above blocks are digitised in the corresponding parameter windows in accordance with the design of the parts and components of the gearbox. The task of the control unit (ECU) is to select the transmission gear depending on the conditions in which the MTU operates. The ECU is based on a shift map, which determines the moment to switch to a higher or lower gear. Figure 5 shows an example of a shift map for forwarding of the transmission gears 9 to 16.

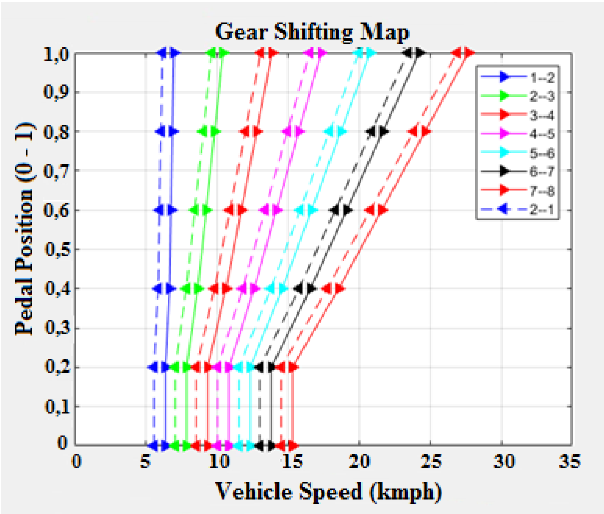

Figure 5. Example of a shift map for forwarding of the transmission gears 9 to 16.

It can be seen from the graph that the moment of switching depends on the current speed of the tractor and the level of fuel supply to the engine. Dotted lines show the moments of switching ‘down’, solid lines the moments of switching ‘up’. The block diagram of the Transmission Controller ECU, based on the switching map, is shown in Figure 6.

The input parameters of the logic block (in Figure 5) for the mode in which constant speed is maintained with minimal fuel consumption are the current and threshold speed values (Vehicle Speed, Up_ Speed, Down_ speed), the delay time of the switching command (shift_time), and engine speed (rpm). The output port is the number of the transmission (Gear). The input parameters of the logic block in constant power mode are the current and threshold values of the torque (Torque, Up_Torque, Down_Torque), the delay time of the switching command (shift_time), and the engine speed (rpm). The output port is the number of the transmission (Gear). The initial state of the system corresponds to the zero speed of the tractor with the engine on and the neutral gear on (gear=0). If the engine speed increases to 1200 rpm, the first gear of mode II is activated (gear=1).

Next, the switching processes are based on comparing the current speed of the tractor with the upper and lower switching thresholds. For example, if the current speed has reached the upper threshold, then the transfer rate increases in accordance with the shift map. Conversely, if the speed has fallen to the lower threshold, it switches to lower gear. If the engine speed drops to idle, regardless of whether the gear is switched on, it switches to neutral. The state diagram of the selected speed mode for the constant speed mode with minimal fuel consumption corresponds to Figure 7, and for the constant power mode to Figure 8.

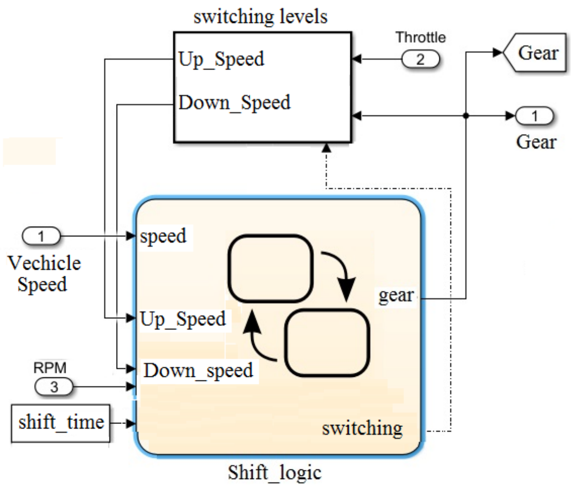

Figure 6. Input and output parameters of Transmission Controller in constant speed mode.

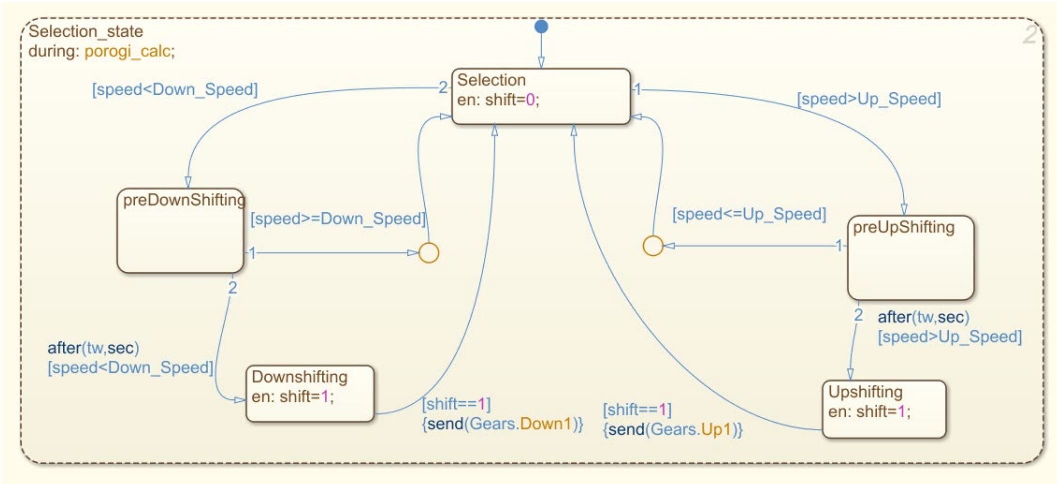

Figure 7. State diagram of selected speed mode for the constant speed mode with minimal fuel consumption.

After the transmission number is selected, the ECU transmits this information to the Actuators block, which forms the pressure in the friction units in accordance with the switching scheme (see Figure 9). The control signal passes through a smoothing filter and is amplified. A combination of switched-on clutches with a pressure of 0,9 MPa in each is obtained at the output.

The model of the tractor chassis and hook load was built in Simscape based on the well-known two-dimensional mathematical model describing the movement of a tractor with two driving axles and a hook load. The Simscape body block diagram of the tractor chassis corresponding to this mathematical model is shown in Figure 10. The Body block calculates normal and longitudinal responses on tractor wheels. The torque from the gearbox goes to the front and rear axles of the tractor (Axle blocks) and through the differentials and side gears is transmitted to the driving wheels (Tire blocks).

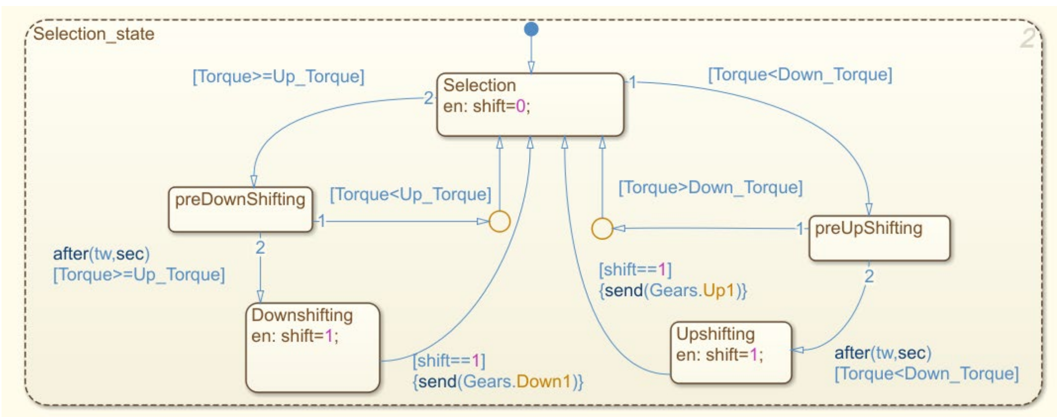

Figure 8. State diagram of selected speed mode for the constant power mode.

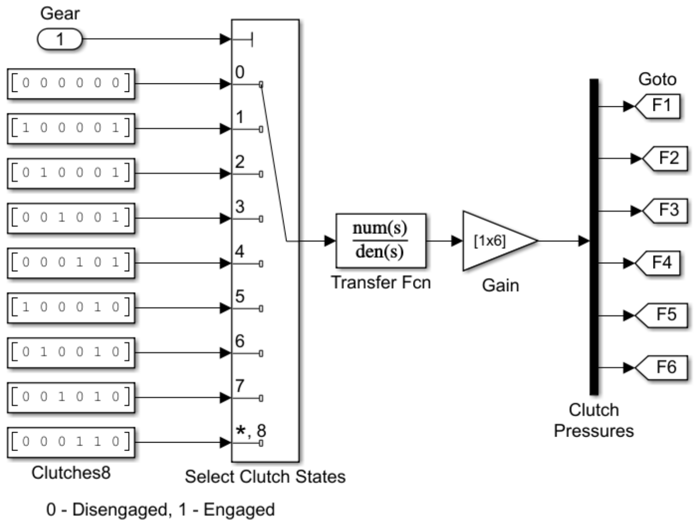

Figure 9. Block diagram of actuators subsystem.

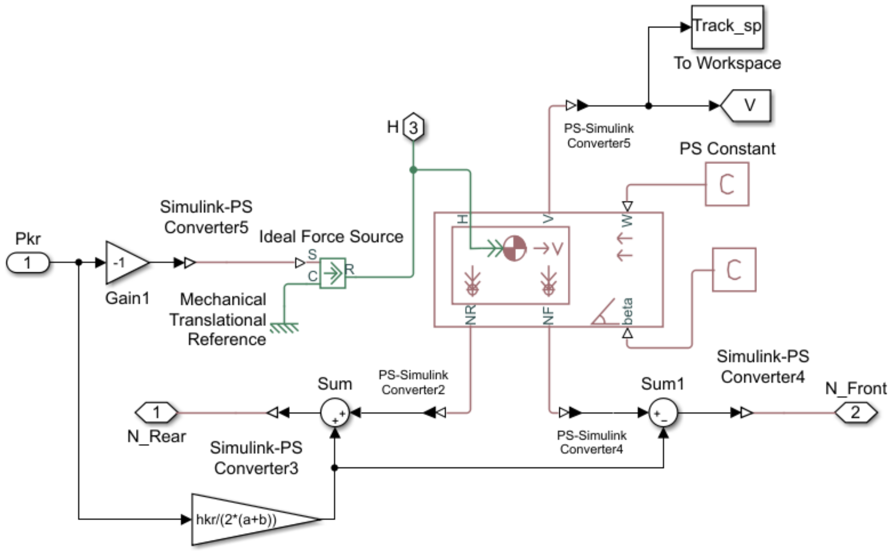

Figure 10. Structure of body block.

The target function for the ACS operating at a constant speed with the engine's full power not used is the fuel consumption function. Within the digital model proposed in this paper, this function can be defined in tabular form depending on the engine speed and torque. For a more accurate calculation, the flow function can be represented as a second-order polynomial. As a result of correlation analysis, we obtain the function for specific fuel consumption of the MTU, g(M,ω), as shown by the graph in Figure 11.

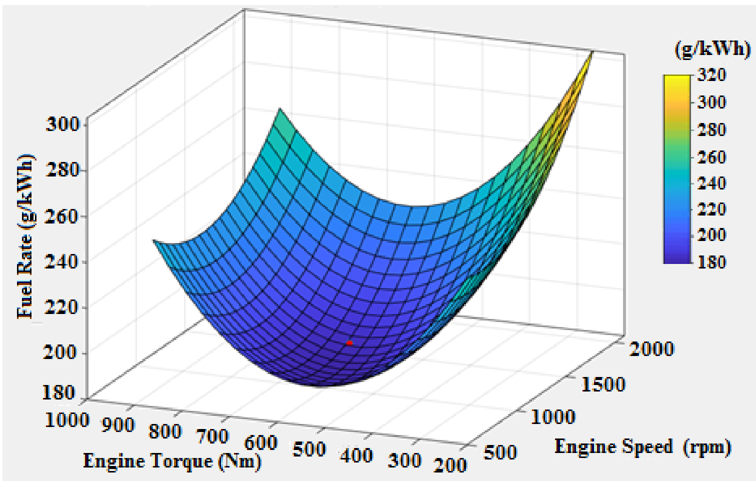

Figure 11. Graph of specific fuel consumption function g(M,ω).

Let us consider the arguments and constraints of the objective function. Two factors affect the speed of the engine in this model. The first is the position of the fuel supply pedal, which sets the required speed. The second is the number of the gear engaged in the tractor's gearbox. The following formalisation is obtained for the optimisation problem:

$$g(M, w) \rightarrow \min;$$
$$pedal(t) = P \cdot e(t) + \frac{1}{I}\int_0^t e(t) \cdot dt, \text{если } e(t) > 0;$$
$$brake(t) = P \cdot e(t) + \frac{1}{I}\int_0^t e(t) \cdot dt, \text{если } e(t) \leq 0;$$
$$e(t) = V_{treb} - V_{tek};$$
$$M = F(pedal, w);$$
$$V(t) = w(t) \cdot \frac{r_k}{i_g};$$
$$i_g = f(pedal, V);$$
$$P = 0{,}2; \quad I = 0{,}015; \quad pedal \in [0{,}1]; \quad brake \in [0, 1]; \quad M \geq 0; \quad w \geq 800.$$

where, pedal(t) is the level of fuel supply to the engine; brake(t) is the level of braking, e(t) is the speed error in m/s, M is the engine torque in Nm, V(t) is the tractor speed in m/s, i_g is the gear ratio of the tractor transmission, P and I are the proportional and integral components of the PI controller, respectively, and t is time in s

The equations indicate that the optimal form of the function $i_g = f(pedal, V)$, which is a map of gear changes that has to be determined in order to keep the engine running in the optimal fuel consumption zone. The optimal form of this function is found by setting additional parameters that modify its behaviour. Two additional parameters were set for the shift map (see Figure 12): α (rad.), which is the angle of the shift lines to the abscissa axis, and h (km/h), which is the distance between adjacent shift lines.

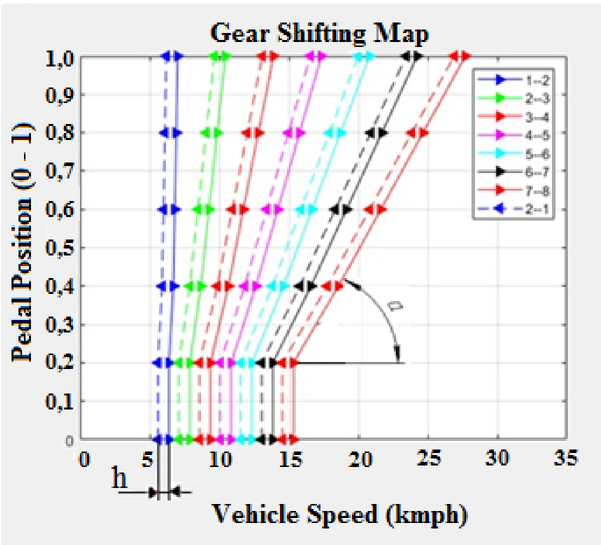

Figure 12. Additional parameters of switch map.

Notably, the tilt angles are not constant and take large values at higher gears, which corresponds to the real-world experience. The angle of inclination of the shift line from the first to second gear is taken as the base. The angles subsequently increase in accordance with Eq. (1).

$$\alpha(i + 1) = \alpha(i) \cdot i \quad (1)$$

where i is the number of the switching line.

The minimum is found by the iteration method with a limited number of iterations. At each iteration, the gearshift map is recalculated, the digital model is simulated, and the total absolute fuel consumption for the duty cycle is calculated. The optimal angle α of inclination of the transmission lines is obtained at the output, corresponding to the minimum flow rate for this calculation cycle. The maximum power mode is the main mode of operation of an agricultural tractor. The main requirements for the ACS in this mode are formulated above. Formally, the control problem can be written by the following equation:

$$numgear(t) = f(Ndv, S) \quad (2)$$

where: numgear(t) is the number of actuated transmission rate in time t, Ndv is the current engine power, S is the current slipping of the tractor driving wheels.

The ACS must not only maintain the engine power close to the nominal but also control the slipping of the engine. It was noted previously that it is necessary to determine the minimum possible range of power regulation. The engine's full power is not used if the range is too wide, and gear cycling occurs if the range is too narrow. For example, the minimum control range for the Kirovets tractor was determined by the formula, $\Delta N_{min} = 150 \cdot (1 - 0{,}84) = 24$ kW. The block diagram of the ACS operation without skidding at maximum power is shown in Figure 8. According to the algorithm proposed for ACS operation, switching 'up' occurs when the power decreases below the lower threshold and switching 'down' when the power increases above the upper threshold.

RESULTS AND ANALYSIS

The application of the given analytical method is illustrated by solving the optimisation problem for a tractor accelerating to a speed of 21-25 km/h. The force on the hook in transport mode is set to constant, $F_{hook} = 6000$ N. The tractor moves on a flat surface with a coefficient of rolling resistance of the wheel f = 0,08. The results of the iterative calculation are shown in Figure 13. The obtained optimal angle of inclination of the switching lines is α = 1.55 rad. The minimum fuel consumption in a calculation cycle G = 418.8 gr/h. The given speed is provided with the fuel supply to the engine at the level of 45–50%. The engine operating mode was set at 1400 rpm with engine torque of 700 Nm. This mode corresponds to the minimum on the target function (see Figure 14).

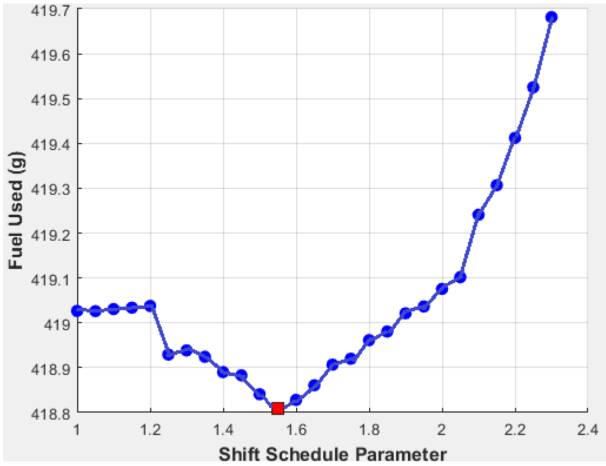

Figure 13. Fuel consumption (Fuel Used, gr.) for calculated cycle depending on inclination angle α (rad) of switching lines (Shift Schedule Parameter).

The minimum fuel consumption is provided by driving in the 8th gear. The ACS operates adequately in the mode with stabilisation and speed control. The graph in Figure 13 shows that there is a single global minimum corresponding to a certain transmission in the gearbox. At the same time, the simulation results indicate that the speed is maintained in the given range, and the engine operation mode reaches the zone with minimal consumption. The optimisation problems considered should be solved by the ACS in real-time, constantly calculating the driving conditions of the MTU and choosing the optimal operating modes of the engine and transmission. The gearshift map must be dynamic, i.e., changeable after each iterative calculation pass.

The ACS can operate by controlling the tractor speed, engine speed, level of fuel, storing the engine performance and specific fuel consumption in memory. For the maximum power mode with variable force on the hook, the ACS operates adequately at maximum power; cyclic switching does not occur, engine operation is maintained in a zone close to the rated power of 150 kW, tractor skidding does not exceed 3%, which is acceptable. In this mode, the ACS has a single control parameter that is engine power. This allows simplifying the design of the ACS. The power (torque) of the engine does not fall below the controlled range; the ACS has selected the minimum gear ratio of the gearbox, ensuring the operation of the tractor with maximum performance (gears 2, 3).

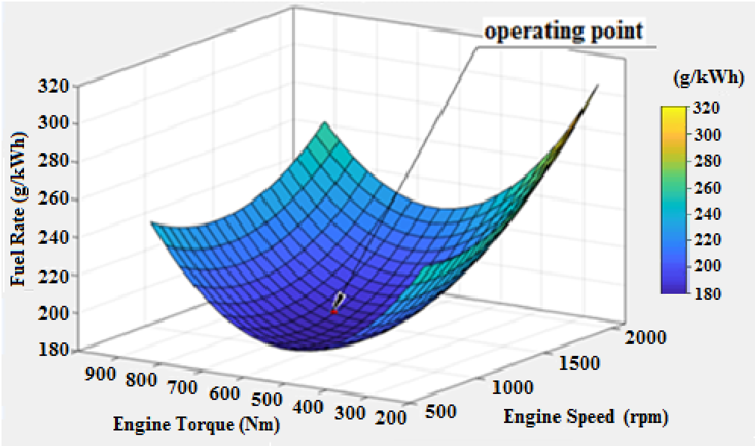

Figure 14. Operating point on the function for specific fuel consumption of the MTU.

CONCLUSION

We have developed a digital model of the MTU based on the Kirovets tractor in the MATLAB-Simulink-Simscape environment to simulate the operation of the ACS. We considered the algorithms controlling the ACS operation in low-fuel-consumption mode with the full engine power not used (transport mode) and in maximum power mode (maximum performance), which can be used for designing the ACS for engines and transmissions of new tractors with automatic step transmission equipped with hydraulically controlled friction units. The study has confirmed the effectiveness of the proposed algorithms and digital models.

The ACS operating in the mode where the engine power is not used to the full extent should be a self-adjusting extreme (optimal) system. During operation, the ACS should search for optimal modes based on the current situation and rebuild the gearshift map in the gearbox. The more additional parameters are introduced into the optimisation problem, the more accurate the search for optimal transmission will be. Virtual tests of the digital model showed that the ACS fulfils the requirements for stabilising the speed of the MTU and also selects the optimal transmission for minimum fuel consumption.

The maximum power mode is characterised by a simple algorithm and a small number of measured parameters. This greatly simplifies the driver's work, and the MTU operates with the highest possible performance. Simulation of the maximum power modes has shown for an oscillating load on the hook that the power is maintained in the given control range, no cyclic gear shifting occurs, and the transmission in the gearbox is selected with the lowest gear ratio. The results of the study have proved that the using digital model of the MTU is effective. The digital model of the MTU as a single system allows to debug the working algorithms of the ACS and offer an engineering procedure for optimising the automatic control of the engine and transmission of an agricultural tractor.

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