MODELING AND SIMULATION OF MOBILE WORKING MACHINE POWERTRAIN

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Abstract

In most cases it is necessary to create dynamic model of mobile working machines. Its creation is determined by extensive knowledge of vehicle's physical behavior. In presented work we deal with creation of four wheel drive model of mobile working machine with modular structure in MATLAB/Simulink environment. Simulation and analyzing of working conditions of selected mobile working machine is realized.

1 Model of mobile working machine in MATLAB/Simulink

There are not too many authors who are writing about dynamic modeling of complex of mobile working machines. The dynamic models of powertrain are modeled in the thesis Carter [6], Prasetiawan [13] and Zangh [22]. Tinker [17] developed detailed mathematical and physical powertrain model of wheel loader. For dynamic modeling of mobile working machines can be used Vlk [18], Bauer [2], Kiencke and Nielsen [9], Rill [14]. Useful reference is work written by Guzzella and Amstutz [8]. Primary an object of above mentioned references is not working machines, but these works deal with vehicles in general.

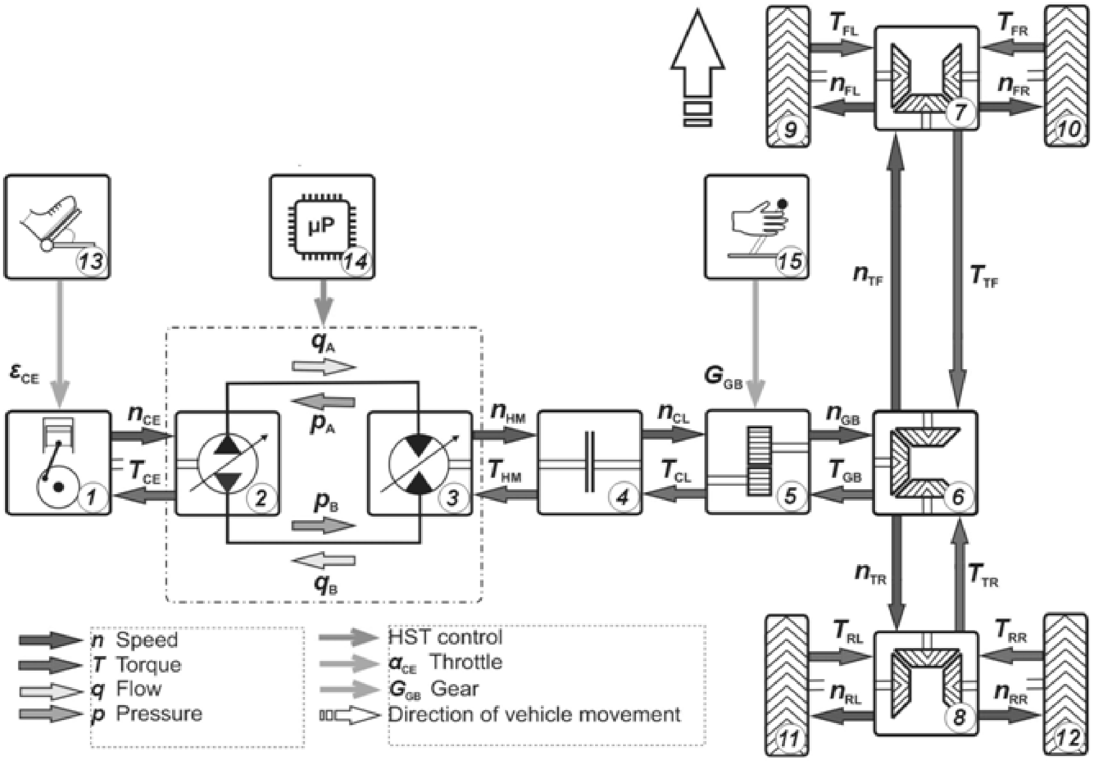

Figure 1: Structure of mobile working machine powertrain with kinematic and power variables 1-diesel engine, 2-pump, 3-motor (connection of pump and motor presented HST-hydrostatic transmission), 4-clutch, 5-gearbox, 6-central differential gear, 7-front differential gear, 8-rear differential gear, 9-front left wheel, 10-front right wheel, 11-rear left wheel, 12-rear right wheel, 13-accelerator (throttle) pedal, 14-HST control, 15-shift control

Possible powertrain structures of mobile working machine can be divided to blocks (subsystems) which are equivalent to particular physical structure in the specific powertrain of mobile working machine. A dividing into subsystems allows modular assembling of mobile working machine powertrain in MATLAB/Simulink. The modular structure allows components configuration in dependence on the type of mobile working machine. By modeling of mobile working machine must be determined:

- Variables or signals acting from environment to individual subsystems.
- Variables or signals acting from individual subsystems to environment.

Systems operate with kinematic and power variables (Figure 1). The variables and signals present input and output data coming to and from individual model subsystems. The direction of vehicle movement is defined by the sign of wheel's speed. The positive value of speed belongs to vehicle forward drive. The negative value of speed belongs to vehicle reverse drive. Analogous to the motoring mode (for example during vehicle acceleration the energy is transferred from engine to wheel) the value of the wheel's output torque is positive. During braking mode (for example during downhill drive the energy is transferred from wheel to engine) the value of the wheel's torque is negative. Velocity and force (angular velocity and torque) are important for mobile working machine powertrain simulation. Flow and pressure are important for hydrostatic transmission analyzing.

In the case of mobile working machine 2D model the powertrain consists of front and rear axle (wheel), central differential gear (transfer gear), gearbox, hydrostatic transmission and diesel engine.

2 Diesel engine model

Mathematical and physical modeling of diesel engine is extensive task. The developed models differ and depend on the model application. The models of engine control unit are usually very detailed. The engine models for complex system simulation are less detailed. The most of the engine models are based on the measured characteristics.The modeling of turbocharged diesel engine is more complicated then modeling of petrol engine because the diesel engine design is more complex.

Relatively accurate and detailed model was developed by Yanakiev and Kannellakopoulos [20]. This model is a base for another works. Comparatively detailed model was modeled by Strandh [16]. The author stated that the created petrol engine is more stable then diesel engine model. Another works were developed by Biteus [4] and Zackrisson [21]. The theory of combustion engines (CE) is analyzed by Kiencke and Nielsen [9]. A necessity of measured characteristics is prime disadvantage of the previous works.

Simpler models were developed by Tinker [17] and Donald [7]. Donald modeled complex powertrain model of racing vehicle only with petrol engine. A useful work was created by Zackrisson [21] in Dymola language. The combustion engines were also modeled by Rill [15] and Mussaeus [12].

For purposes of modeling related to mobile working machine powertrain it is required to develop simple and fast model. Also in reality it is difficult to get the engine characteristics and parameters. For this reason the created model has to use minimum of measured characteristics even by decreasing accuracy. The used model (Figure 2) is described in Zavadinka and Kriššák [24], [25].

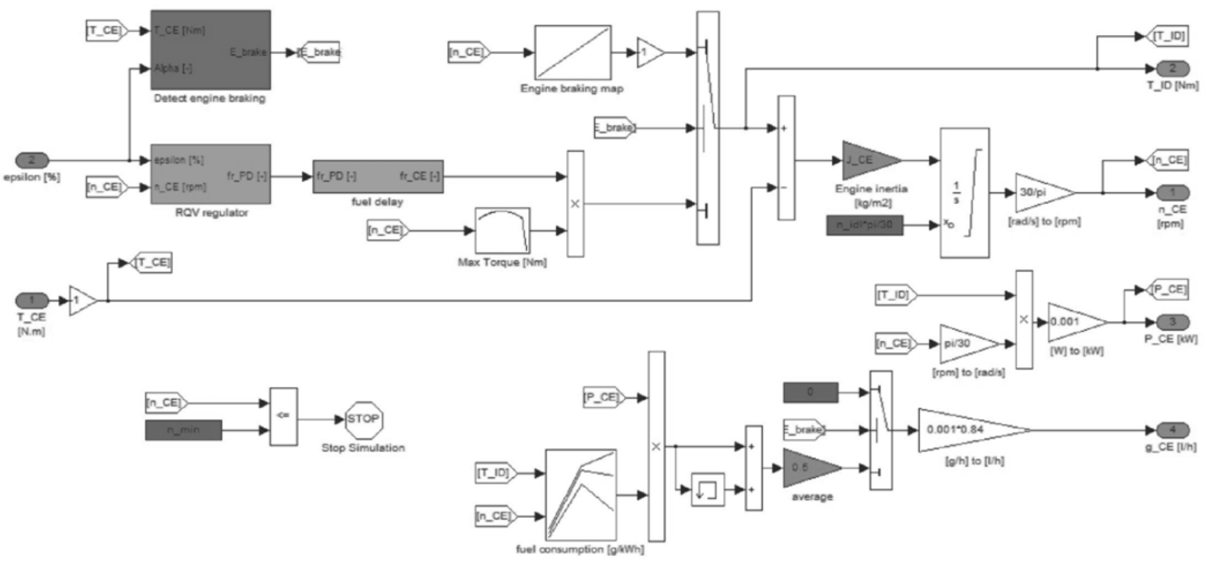

Figure 2: Diesel engine model

Diesel engine block allows simple setting of tunable parameters in subsystem mask shown in Figure 3. User can simply set up maximal engine power, minimal engine speed, maximal engine speed, idling engine speed, minimal fuel consumption, fuel transport delay, engine's moment of inertia and shuffle torque.

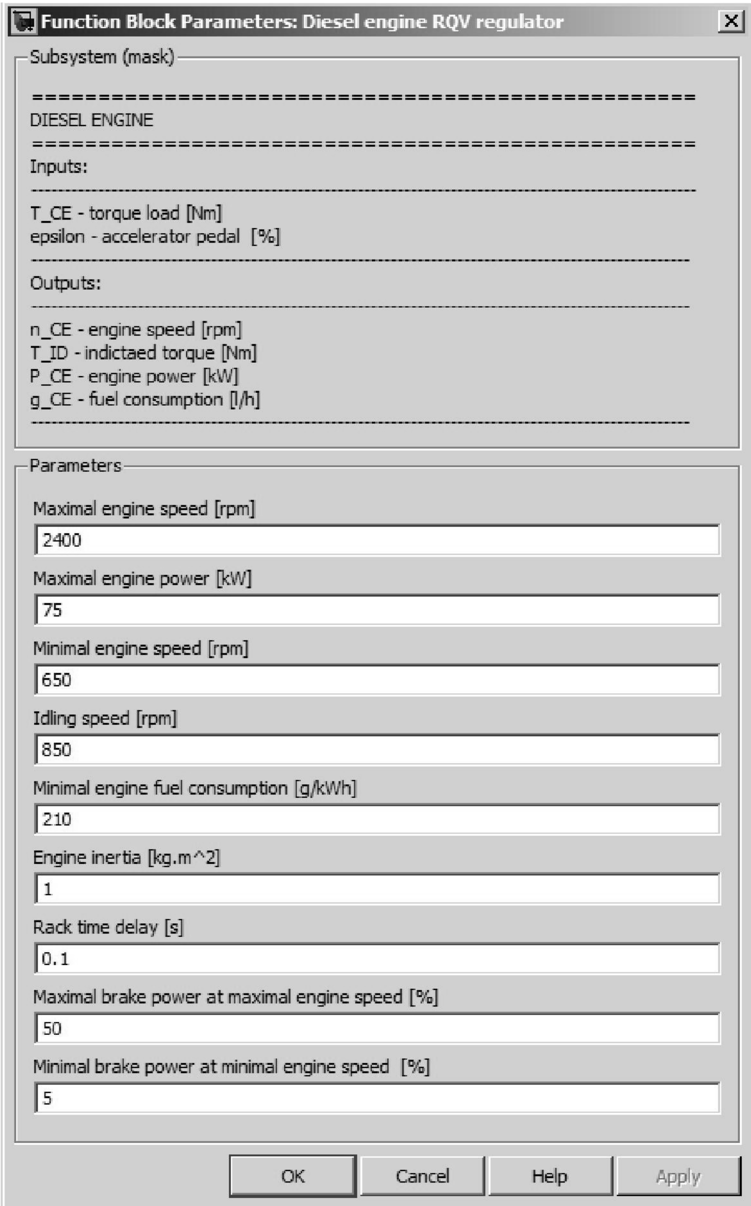

Figure 3: Diesel subsystem mask

3 Hydrostatic transmission model

The hydrostatic transmission model is based on the modeling of pump and motor. Other important components are charge pump, hoses, valves and control components. A difficulty and size of the hydrostatic transmission model depends on the detail level.

Carlosson [5] developed model in a forest vehicle. A hydrostatic transmission focused on control was modeled by Carter [6], Prasetiawan [13] and Zhang [22]. The basic mathematical description of used hydrostatic transmission model is described in Zavadinka [23].

A determination of hydrostatic efficiency is a serious problem for modeling. A total efficiency is not constant and also it is not a function of one or two variables. The pump and motor models uses function for efficiency determination based on measured data. For this reason model has a good correspondence between simulated and measured efficiencies.

The application of variable displacement pump/motor (primary and secondary regulation) allows decreasing of fuel consumption. The hydrostatic transmission model is shown in Figure 4.

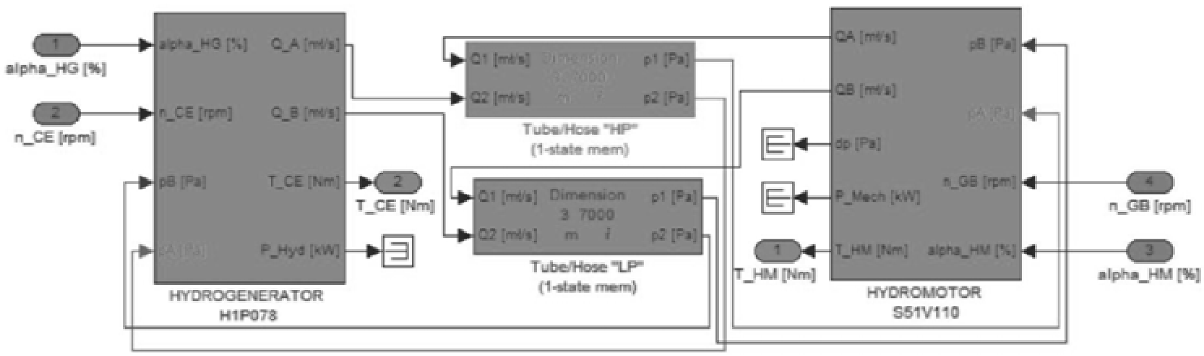

Figure 4: Hydrostatic transmission model

4 Gearbox and clutch model

The gearbox model can be developed by different methods. The first method is based on excellent knowledge of gearbox design. This way was used by Beckers [3] during hybrid drive modeling. The second method is based on the parameters obtained from producer catalogues or measurements. The correct dynamic gearbox model requires knowledge of the following parameters: gear ratio of speed gears, gearbox moment of inertia, gearbox stiffness and gearbox damping. A determination of these parameters is very difficult. This second method was used by Tinker [17] and Donald [7].

With respect to powertrain concept, a clutch (which is commonly included in automatic gearbox) does not need individual model. The clutch modeling is very difficult and inaccurate, because the clutch parameters are not available. If the clutch model is not included by gear shift modeling than this fact must be considered by evaluation of results.

A simpler gearbox model, which does not use unknown stiffness and damping parameters, is required. Then this model is more static. It is sufficient for steady states simulation and states, where the dynamic of gearbox is not important. This model type was modeled by Guzzela [8] and by Mussaeus [12].

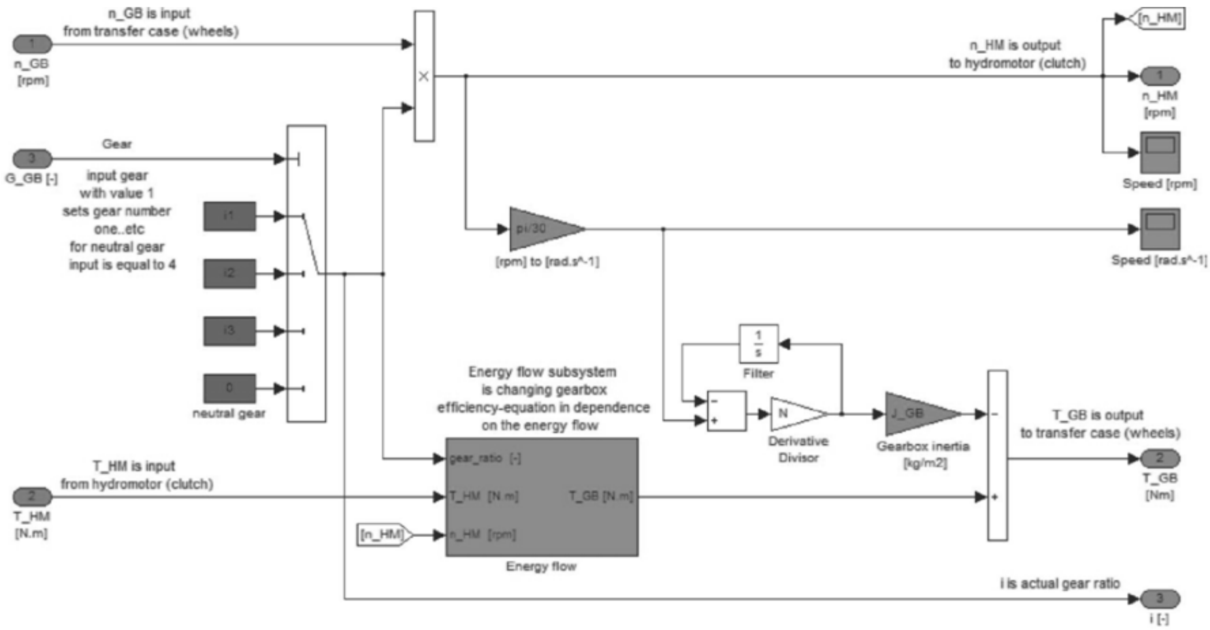

Figure 5: Gearbox model

The inputs and outputs in the MATLAB/Simulink must be compatible with other Simulink subsystems. In the last Simulink model version an influence of gearbox inertia (shown in Figure 5) is implemented. The influence of gearbox inertia is modeled only by approximation of numerical derivation. However the real influence of this inertia on gearbox dynamics must be considered carefully.

The gearbox block allows simple setting of tunable parameters in the subsystem mask. User can simple set up gearbox efficiency, gear ratios and other parameters, of which using must be further detail tested in the future (for example inertia approximation ...). All unverified parameters and setting are initially set to zero.

5 Central differential gear model

A central differential gear redistributes power between front and rear vehicle axle. More information about central differential gears was written by Vlk [19] and Rill [15]. Basic information about central differential gear is also described by Bauer [2] and Tinker [17]. There are many types of central differential gears nowadays existing and the central differential gears issue is relatively complex. The developed model is modeled as a common central differential gear (without friction effect, Haldex or Torsen clutch...). This model operates only in the locked and open mode.

The differential gear function is eliminated in the locked mode. In this case the differential gear serves as a simple transfer case. The transfer case is used in tractors [2], when the gear ratio between front and rear axle is constant. The second case is open mode. The open differential mode is more convenient for implementation in Simulink. In this case (open mode) the central differential gear fully performs its function.

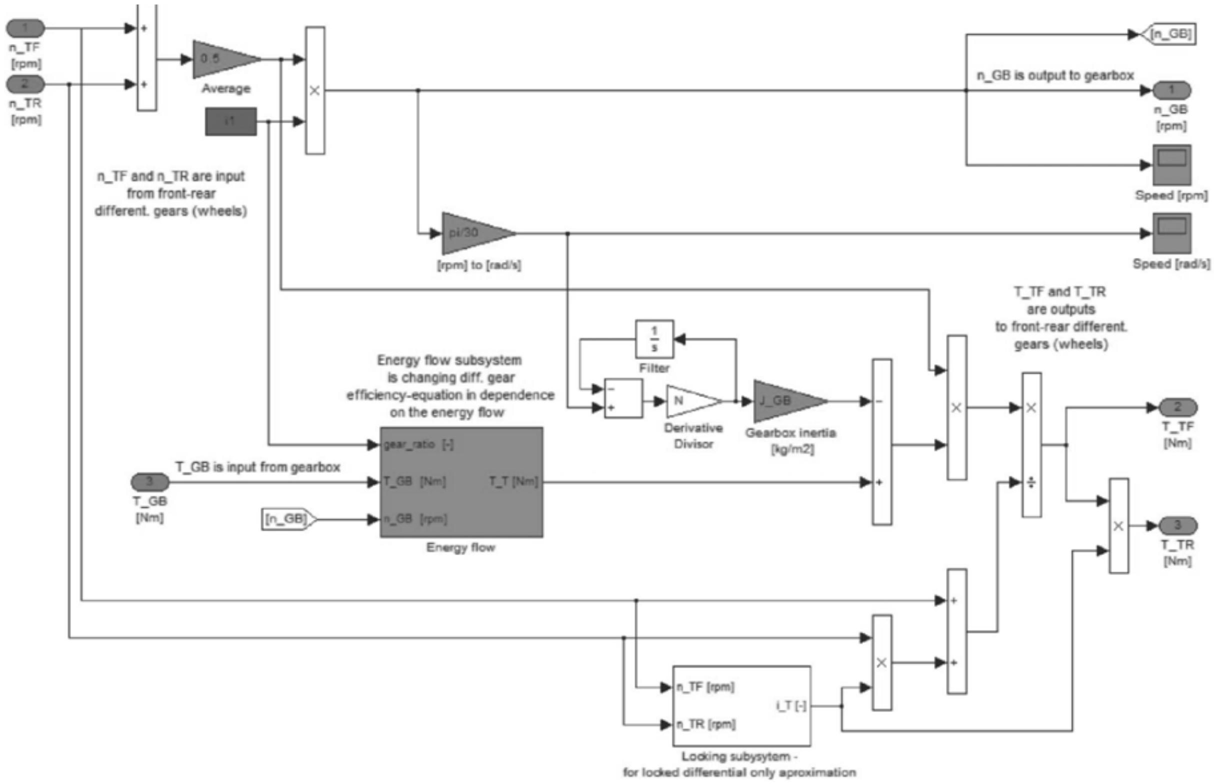

Figure 6: Central differential gear model

Equations described in Zavadinka [23] allow modeling of open central differential gear in Simulink. The locked differential gear is only approximated in regard of vehicle concept. The locked mode approximation uses proportional torque regulator, which redistributes drive torque between front and rear axle in such a way that the front and rear axle speed is the same. The model implementation in the MATLAB/Simulink is shown in Figure 6.

The model block of central differential gear allows simple setting of tunable parameters in subsystem mask. User can simply set up gear efficiency, gear ratio (final gear ratio), torque distribution ratio and other parameters or subsystems which using must be further tested in the future (for example inertia approximation, differential gear locking ...). All unverified parameters and setting are initially set to zero.

6 Wheel model

Nowadays a wheel and tire modeling is one of the most complicated issues in the vehicle simulations. The basic problem is exact determination of traction forces. For this reason the wheel and tire modeling is the most difficult part from powertrain modeling.

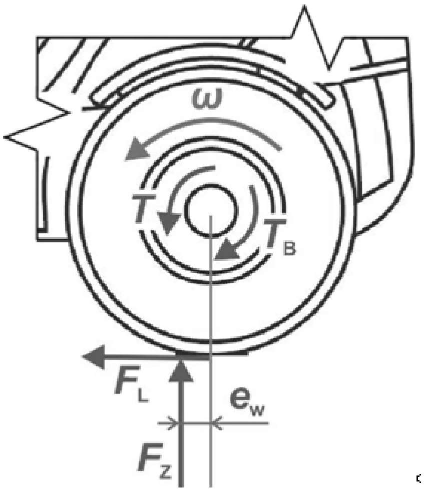

Figure 7: Forces acting on a wheel

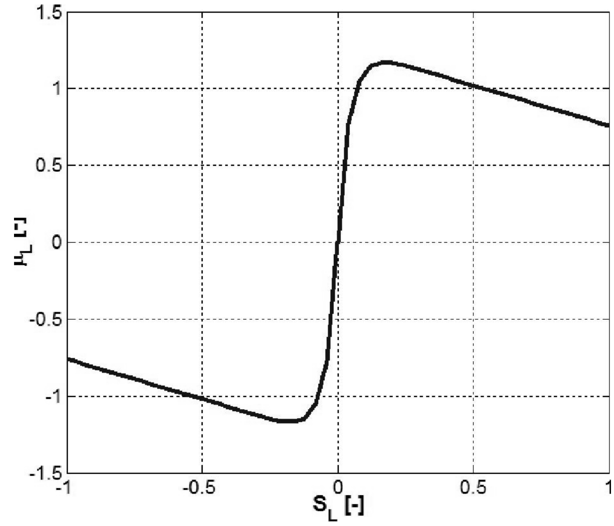

Figure 8: The longitudinal friction coefficient μ_L,
as a function of longitudinal wheel slip s_L (for asphalt dry)

Determination of tractive forces is necessary for vehicle's speed computing. The Figure 7 shows the forces acting on a vehicle. From this figure can be obtained equation described in Vlk [18]. The Pacejka magix formula [1] and Burckhadt model [9] are mostly used in vehicle simulations for define traction force F_L. For selected application the Burckhadt model is chosen. It is simpler for longitudinal wheel slip alone. The longitudinal friction coefficient as a function of longitudinal slip is shown in Figure 8.

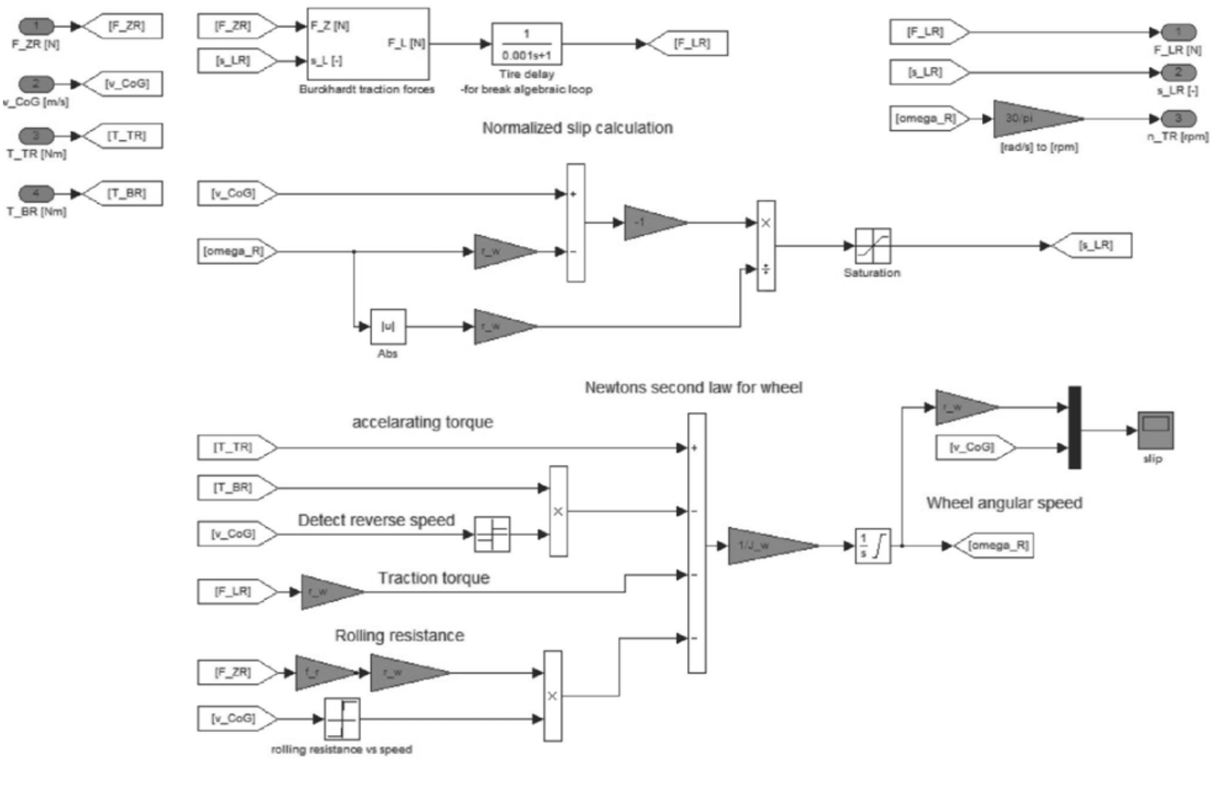

Figure 9: Wheel model

The developed wheel model shown in Figure 9 allows simple setting of tunable parameters in subsystem mask shown in Figure 10. The user can simply set up wheel surface type, rolling resistance coefficient, wheel radius and wheel moment of inertia.

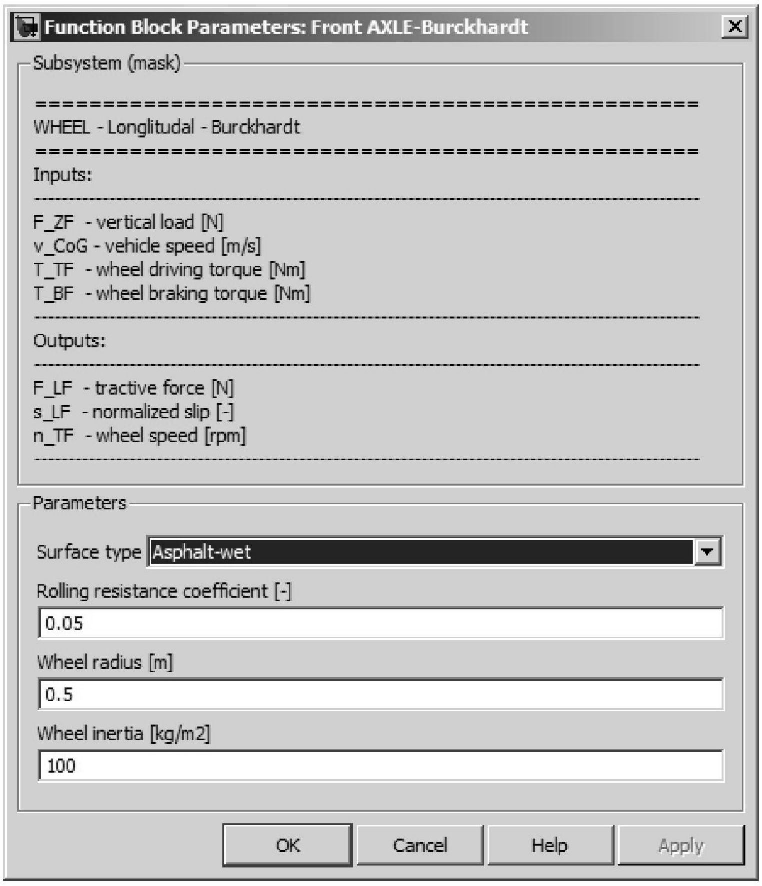

Figure 10: Wheel subsystem mask

7 Vehicle body model

The vehicle dynamic is mainly analyzed by Vlk [18], Nielsen and Kiencke [9] and Rill [14]. A simple 2D model, shown in Figure 11, is used for creating of vehicle dynamic model. This model has 3 degrees of freedom and expects only forward or reverse vehicle drive.

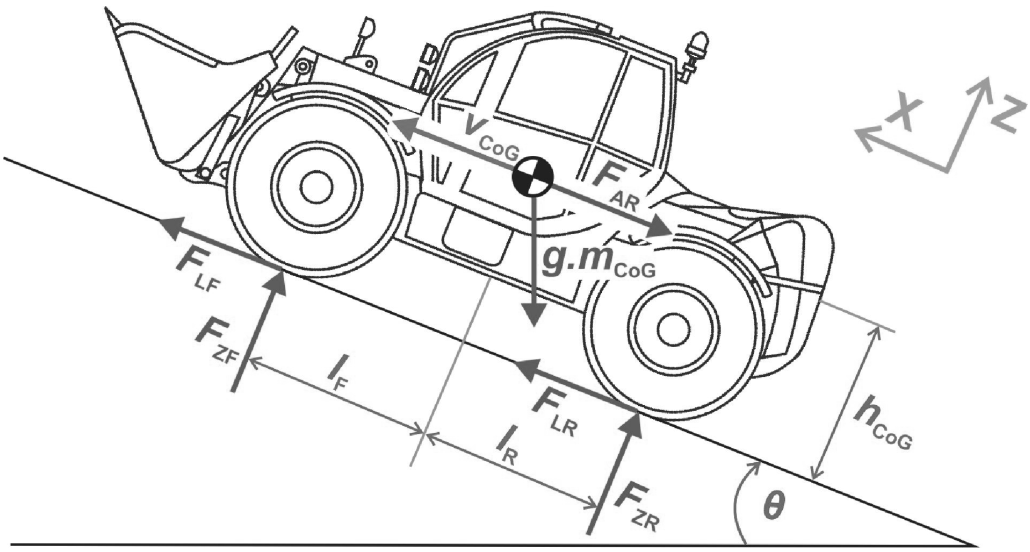

Figure 11: Forces acting on vehicle's body

The vehicle body block allows simple setting of tunable parameters in subsystem mask shown in Figure 12. User can simply set up vehicle mass, center of gravity position and vehicle cross sectional area.

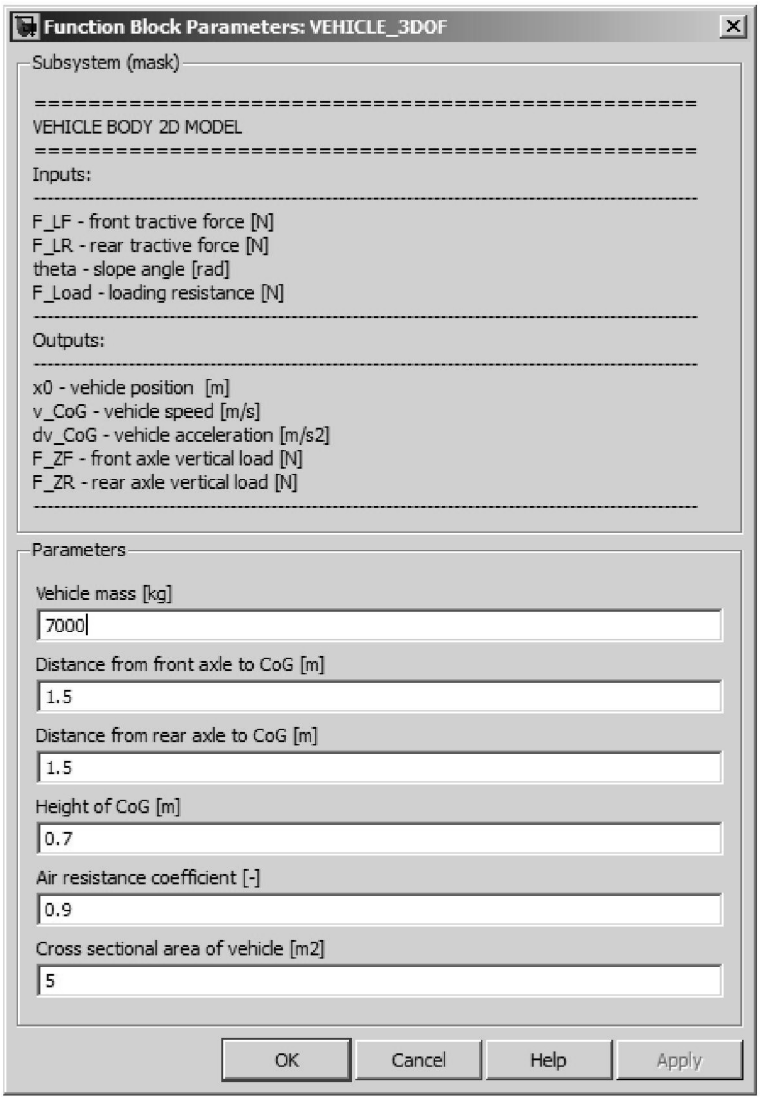

Figure 12: Vehicle body subsystem mask

8 Simulation of mobile working machine

Model simulation consists of several types of simulation. The model for simulations is combined from blocks created in Simulink. The model consists of: diesel engine block, HST block, gearbox block, central differential gear block, wheel blocks and control block.

Kick-down simulation (shown in Figure 13) - is basic test of kick-down (driver pushes the accelerator pedal to the floor) response. During simulation the first speed gear is engaged. At the beginning of the simulation the accelerator pedal is t pushed to the floor (kick-down) rapidly. The vehicle uses almost all engine power. A reaching of the maximal engine power and speed is impossible because of proportional control which is used for speed regulation.

Simulation of vehicle's acceleration and deceleration (shown in Figure 14) - is simulation which tests response of system to sequential accelerating and decelerating commands. During simulation the first speed gear is engaged, the vehicle is not loaded, and it drives on field path. The normal drive mode is selected. The vehicle speed copies diesel engine speed like in the previous kick-down test.

Maximal speed simulation (shown in Figure 15) simulates vehicle maximal speed response. During simulation the vehicle is not loaded and it drives on field path. The normal drive mode is selected. At the beginning of the simulation the accelerator pedal is rapidly pushed to the floor. After reaching of maximal speed by first gear, the gear shifts to higher gear. During the speed gear shift the engine speed shallow oscillates a little bit. It is caused by step gear ratio change.

The basic vehicle testing showed that model's behavior is realistic also by intuitive presumptions and mobile working machine producer's data. Specific limitations of speed gear shift and vehicle start must be taken into account during simulation results evaluation. Front and rear wheels slip oscillating and following torque oscillations are typical for vehicle start. These undesirable oscillations are caused by structure of equations used in the powertrain model.

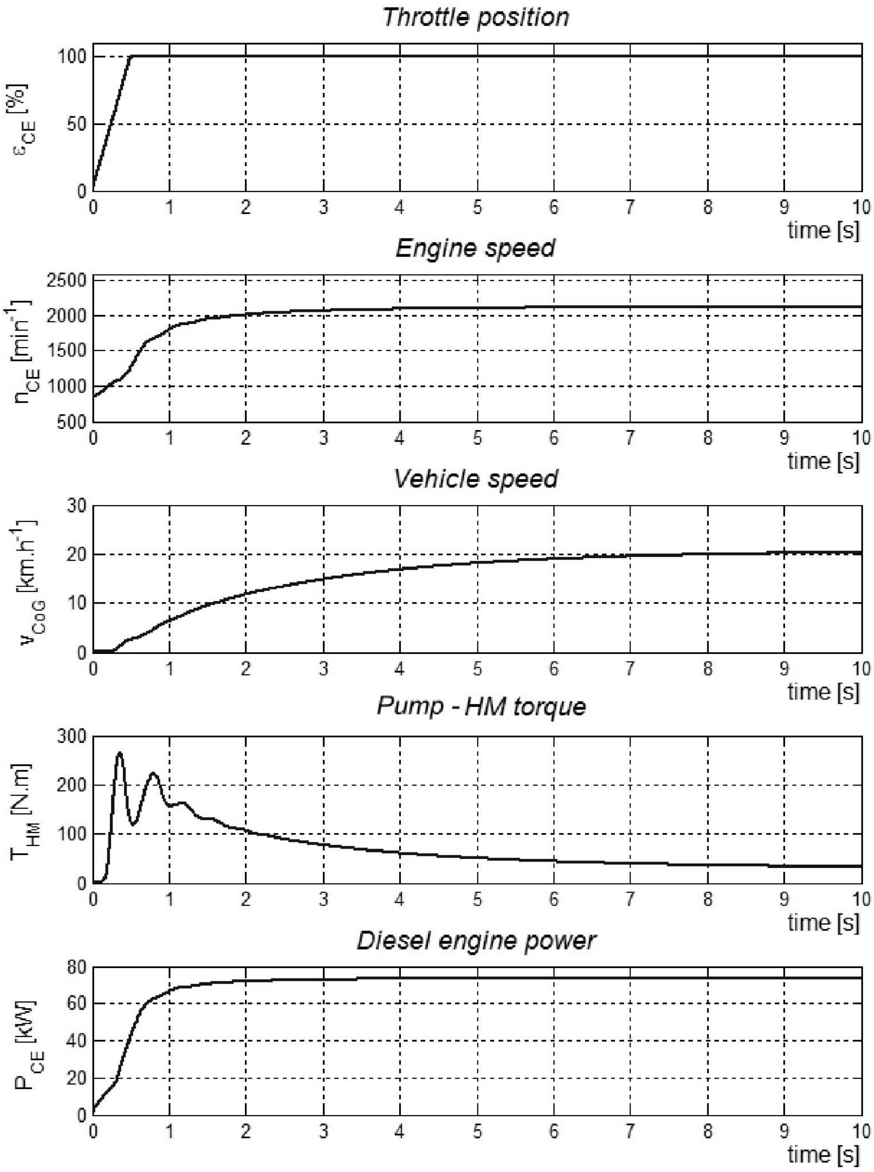

Figure 13: Kick-down simulation - gear number 1 and normal drive mode

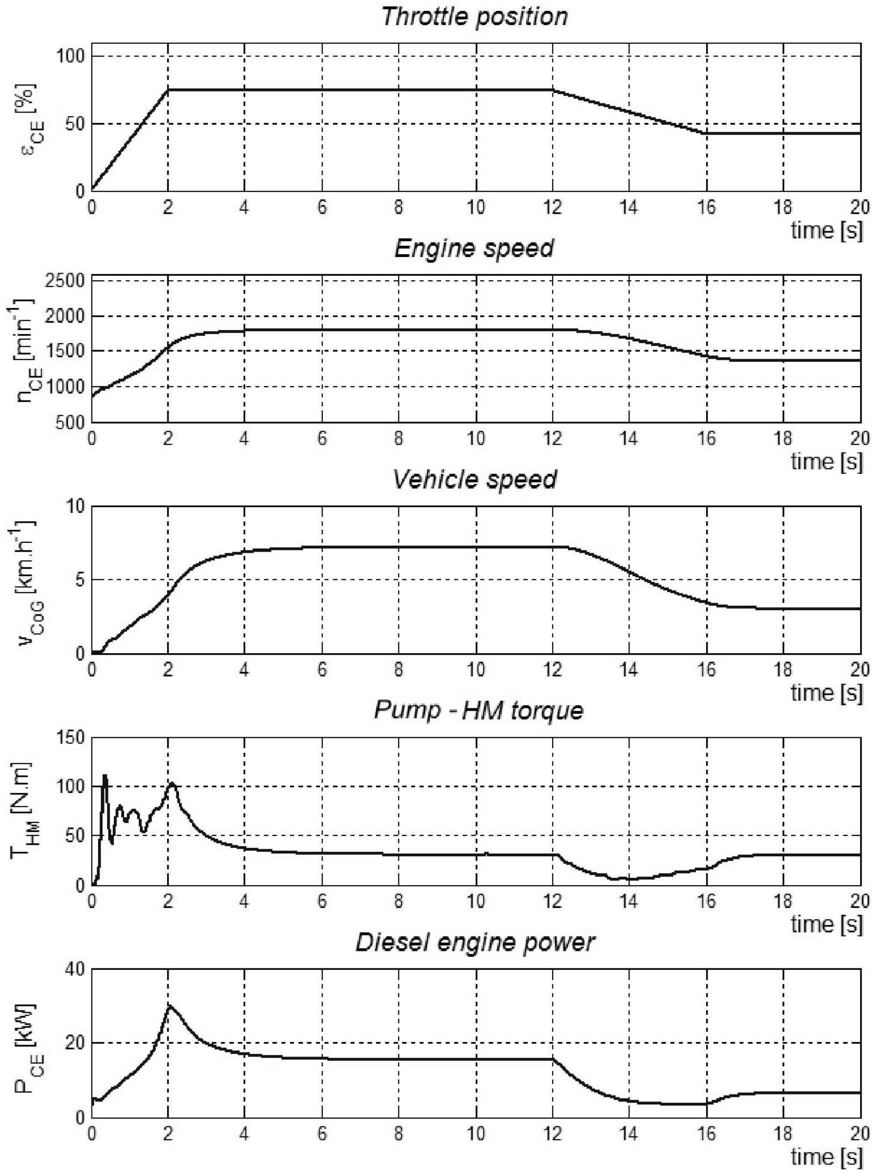

Figure 14: Accelerating and decelerating simulation - gear number 1 and normal drive mode

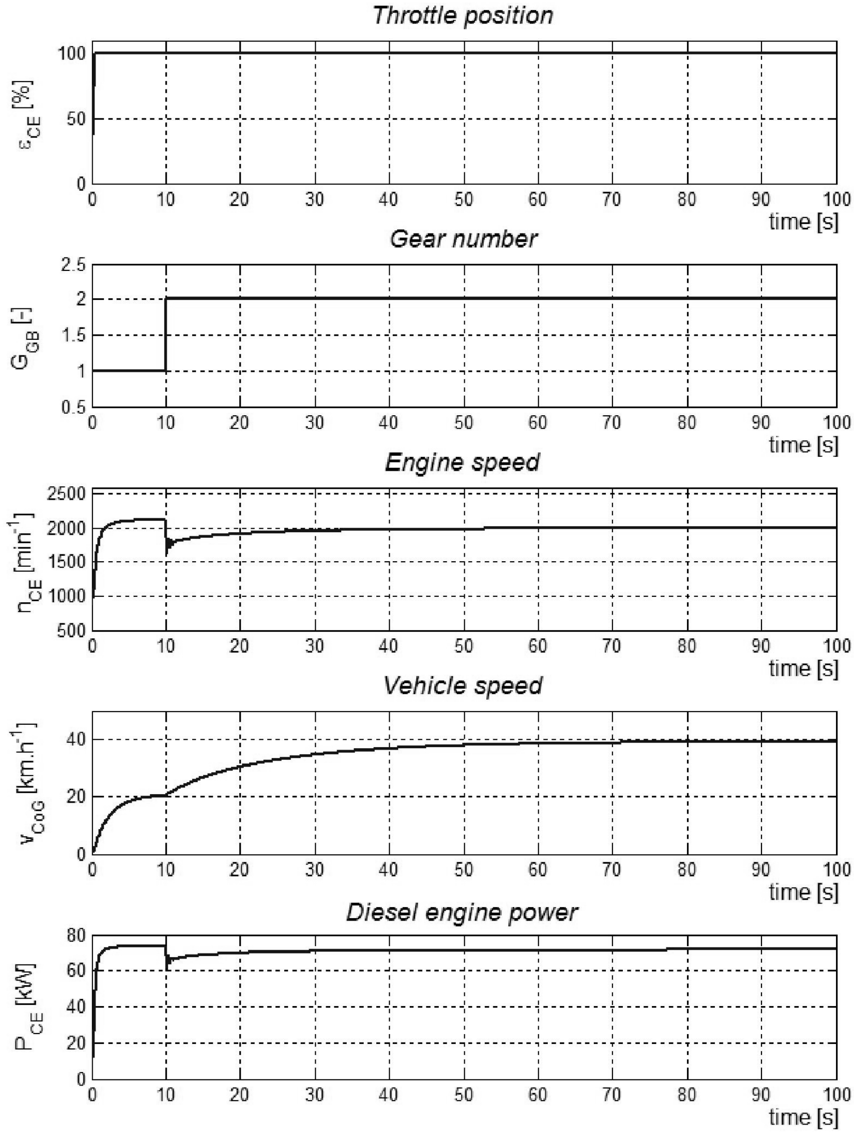

Figure 15: Maximal speed simulation - field path

9 Conclusions

In this paper subsystems of four wheel mobile working machine powertrain (diesel engine, hydrostatic transmission, gearbox, central differential gear, wheels and vehicle body) were modeled separately by blocks. Modular structure increased speed and efficiency of mobile working machine powertrain modeling. The individual blocks were created in MATLAB/Simulink program. A model of each subsystem (block) was equipped with mask, what increased user's comfort of parameters setting.

Detailed modeling of subsystem dynamics is difficult and imprecise because of model complexity and difficulties by acquiring of some parameters. For example the tire modeling is one of the most difficult fields of vehicle's modeling nowadays. Almost all modeled subsystems are non-linear. The developed powertrain model shows strong non-linear behavior, which decelerates simulation mainly at the beginning.

All performed simulations show acceptable results however in some cases (start, gear shift) it is necessary to consider physical and mathematical complexity of model's structure. During the simulation, it is important to know relationships and principles behind the user interface of these blocks, otherwise the simulation results can be misinterpreted.

Developed models of subsystem contain some options, whose using is not confirmed yet. The tendency of this application settings results from need of including the inertia during acceleration.

In the future, it is necessary to continue with developing of new blocks of drive and control and also with debugging of the initial conditions and parameter settings.

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