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COMPUTER MODEL TO SIMULATE THE VEHICLE LONGITUDINAL DYNAMICS

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KEYWORDS

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ABSTRACT

To determine the traction or braking performances of a motor vehicle or to know the dynamic behaviour and the stress level of the drivetrain parts, the study of the vehicle longitudinal dynamics is the first step to be done. Together with experimental research, the model based computer simulation represents one of the most important tools for the automotive specialist.

The paper presents some models imagined and used by the authors to simulate the functioning of drivetrain subassemblies. The models were realized in Matlab-Simulink.

The major design idea was to obtain sub-models that can be easily modified or included in new models. Other aim was to group the input data only in few blocks – for vehicle parameters, initial kinematics values, road conditions, driver actions (and control systems, if they exist).

Assembling sub-models – for engine, clutch, synchromesh, gear, shaft, differential and wheel – was possible to study the dynamics of some vehicle types (car, 4WD SUV, tractor-semitrailer) in different travelling conditions: standing start, gear shifting, engine braking, travel on uneven road, tire friction variations. In addition, sub-models realised for actuation cylinder, solenoid or electronic control devices permitted to simulate the behaviour of vehicle having automated systems.

MAIN SECTION

DYNAMIC AND MATHEMATIC MODELS OF DRIVETRAIN

The first step in drivetrain simulation is envision of a dynamic model – an idealised model of the mechanical system, complex enough to serve aim of the study and simplest possible to be transposed in a mathematical model (a system of differential and algebraic equations) and then solved with no major difficulties.

Model presented in figure 1 consists of only four flywheels (inertial elements), idealised shafts (with no mass) and three couplings (representing clutch, synchromesh and wheel-road interface). Tough, this extremely simple model permits to obtain valuable information about the drivetrain behaviour, both qualitative and quantitative.

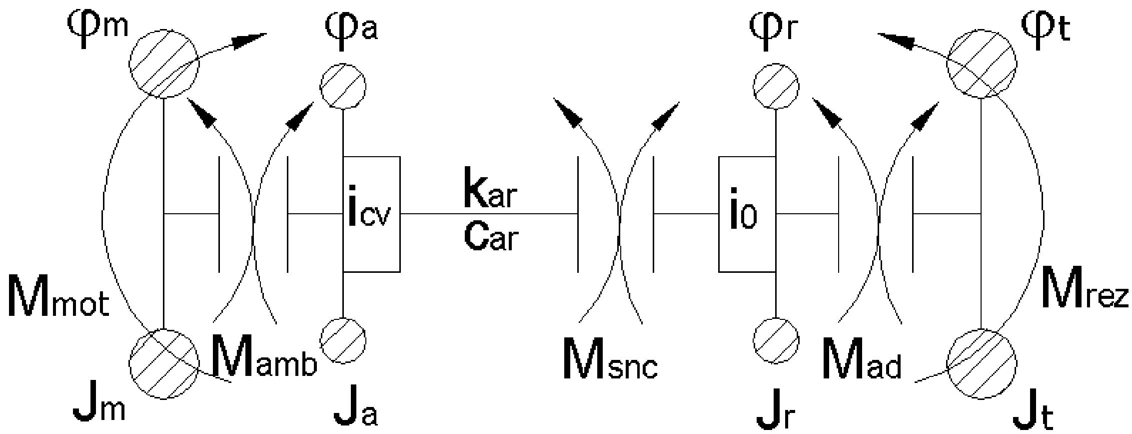

Fig. 1 Simple dynamic model of a car drivetrain

The signification of symbols used is: *Jm* – moment of inertia for elements rotating with the engine angular speed (mobile components of the engine and driving parts of the clutch); *Ja* – moment of inertia for driven parts of the clutch, gearbox primary shaft and all the gears upstream the synchromesh; *Jr* – moment of inertia for the vehicle's driving wheels; *Jt* – moment of inertia corresponding to vehicle's mass and non-driving wheels; *Mmot* – effective moment of the engine; *Mamb* – frictional moment of the clutch; *Msnc* – frictional moment of the synchromesh; *Mad* – moment of wheel-road friction; *Mrez* – moment corresponding to driving resistances; *icv* – gearbox's ratio; *i0* – final drive's ratio.

Based on their long-term experience, the authors introduced two innovative elements in the dynamic model:

- idealised gear mechanisms (symbolised by rectangles with inscription of their transmission ratios);
- torsional moments explicitly marked between each pair of two flywheels.

So, the movement equations write easier; no need to recalculate equivalent inertia, stiffness or damping exist when gear ratios change; new inertial elements can be added with no difficulty (if a more complex or a new model is needed); values for the torques acting on shafts or couplings that always interest are already available.

To obtain the mathematical model, writes the movement equations for all the inertial elements. Solving these equations obtains first the angular accelerations for each flywheel and then, by integration, the speeds and spaces.

As example, accordingly with figure 1, the movement equation of gearbox primary shaft is

$$\dot{w}_a = \frac{M_{amb} - \dfrac{M_{snc}}{i_{cv}}}{J_a}. \qquad (1)$$

COMPUTER AIDED RESOLUTION OF THE MATHEMATIC MODEL

To solve the equations system, it is possible to use integration algorithms and a high level programming language as C, PASCAL or FORTRAN. An easier way to do that is to appeal to specialised simulation software as Matlab – Simulink. His main advantage is that the transcription of model's differential or algebraic equations in instructions of a classical programming language realises by the specialised program (Simulink) on the base of graphical symbols (blocks), predefined or realised by the user and stocked in libraries. Therefore, the skeleton diagram of the model became his simulation program and this graphic language can be easier understood by the engineers. In addition, component elements can be grouped to form functional blocks that can be arranged in hierarchical structures.

Using Simulink, a new model was conceived that permits to simulate:

- the work of engine, clutch and synchromesh;
- the wheel-road contact;
- the functioning of clutch and gearbox (pneumatic) actuating systems;
- the generation of driver's command actions;
- the functioning of electronic command logic that assist the driver;
- the driving regimes.

The main module, shown in figure 2, represents the block schematic of the algorithm that solves the mathematic model and contains:

- four (yellow) blocks for the main mechanical subsystem that allow the determination of kinematic quantities (acceleration, speed and space) of engine, clutch, driving wheels and vehicle's body (translational mass); their speeds and spaces, output signals of the four blocks, group (join) in line **w_fi** to simplify the schematic and his understanding;
- block **Comenzi**, that generates the driver's or automated system's commands applied to the drivetrain; these are functions of time and kinematic quantities (from line **w_fi**) and are grouped in line **ctrl**, suggesting the multiplex network of modern vehicles;
- (left-side) blocks, that compute (based on kinematic and command quantities) the torsional moments and forces that are input values for the blocks of the mechanical subsystems;
- block **Rapoarte**, that establishes the current values of the gear ratios;
- block **Constante**, that permits the introduction of vehicle's main characteristics, constant during simulation;
- block **Initial**, that permits to assign integration initial values for the kinematic quantities;
- block **Drum** (Road), that generates road characteristics (rolling resistance coefficient, grade, tyre friction coefficient) as functions of speed and driven space;

- blocks **Viz** (on right-side), that realise graphical representation of calculated interest quantities, as time histories or characteristics (one vs. other), with their true or engine-reduced values;

- blocks **Pierderi motor** and **Pierderi cv**, that can simulate specific losses (in this case for engine and transmission) and so taking into account normal efficiencies or supplementary influences like cold or abnormal functioning;

- blocks **M_franare**, that can calculate the braking moment, directly intervening in wheels kinematics;

- block **Reactiuni** (Loads), that compute the load transfer between vehicle's axles due to the grade or acceleration;

- block **Rez. la inaintare** (Driving resistances), that compute the rolling, grade and aerodynamical resistances and their sum.

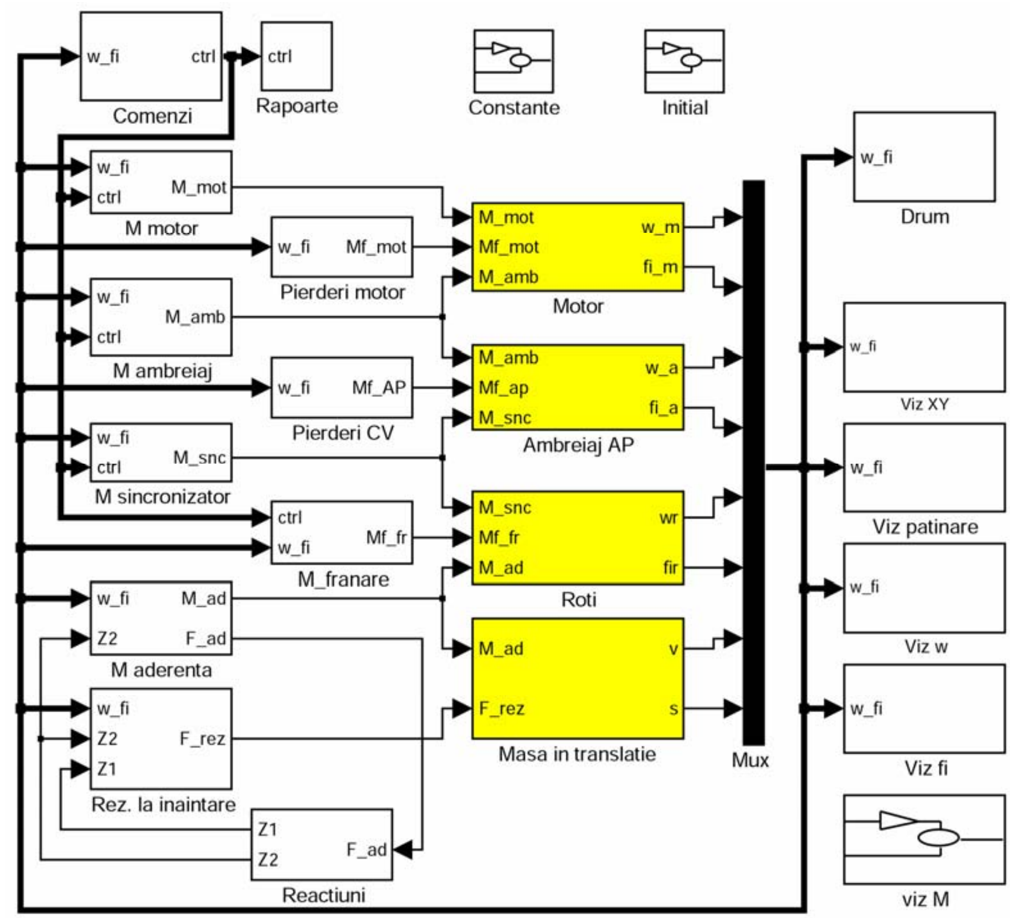

Fig. 2 Main module of the Matlab-Simulink model used to simulate the functioning of the drivetrain

Submodule **Motor**, presented in figure 3, computes kinematic quantities of engine's rotating parts. His input values are the engine's torque *Mmot*, the clutch's torque *Mamb* and the supplementary frictional moment *Mfmot*; the output values are the engine angular speed *wm* and space *fim*. Similar submodules use for clutch, driving wheels and body (translational mass).

To establish the input values for the four modules that determine the inertial elements kinematics was necessary to conceive a submodule for each torsional moment. Therefore, submodule **M_motor** computes the engine torque M_{mot}, used as input value for the submodule in figure 3. This obtains by biparametric interpolation of test bench data, as function of accelerator pedal position *pac* and engine speed *wm*.

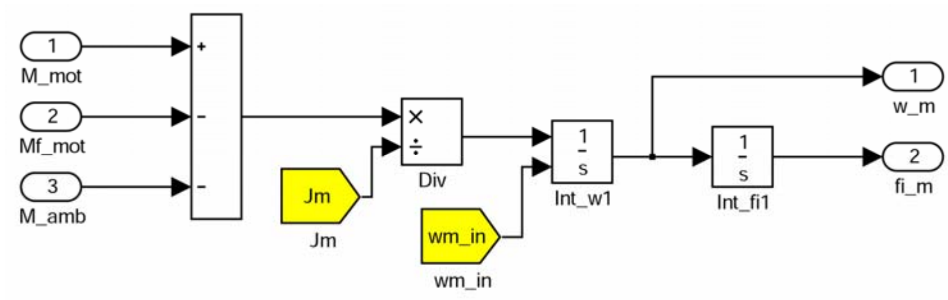

Fig. 3 Submodule for engine dynamics

The clutch and the synchromesh torques are modelled in separate blocks. So, for both submodules **M_ambreiaj** and **M_sincronizator**, the main component is a submodule that simulate the functioning of a frictional coupling (fig. 4). During simulation, this permits the transmission of power in both directions and not only the engagement, but also the disengagement, slippage occurring at very high stress. Clutch frictional moment M_{amb} calculates as function of clutch pedal position *pamb* and kinematics of both input and output shafts.

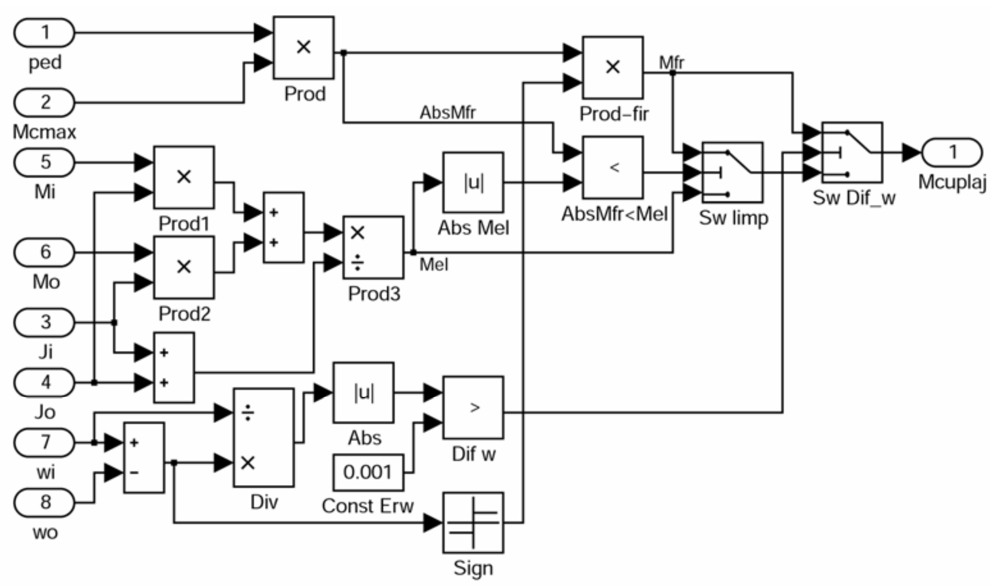

Fig. 4 Submodule to simulate a frictional coupling

The synchromesh acting moment M_{snc} computes by the submodule **M_sincronizator** (fig. 5). Function of engaged gear (indicated by the signal *trc* in line **ctrl**), activates exclusively one of the two blocks **M_sinc_fr** or **M_sinc_el-am**, first being used during synchronising time and the second when the gear is engaged.

Block **M_sinc_el-am** determine the torsional moment *Melam* that stress the synchromesh sleeve when the corresponding gear is engaged. The moment has two components (elastic and damping) that compute function of gearbox and final drive ratios (*icv* and *i0*) and of stiffness and damping coefficients (*kar* and *car*), represented in the dynamic model (fig. 1). Constants *kar* and *car* correspond to drivetrain components between clutch disk and driving wheels, their values being reduced to the synchromesh.

Block **M_sinc_fr**, determine torsional moment *Mfr* stressing the synchromesh sleeve when the gearbox is not (yet) engaged. Two cases can appear, that are indicated by the signal *snc* (of line **ctrl**), generated by the command logic. In first case, the gearbox is on neutral: *snc*=0 and *Mfr*=0. In second case, the gearbox lever actuates to shift in the desired gear: *snc*=1 and *Mfr* is the frictional moment generated by synchromesh.

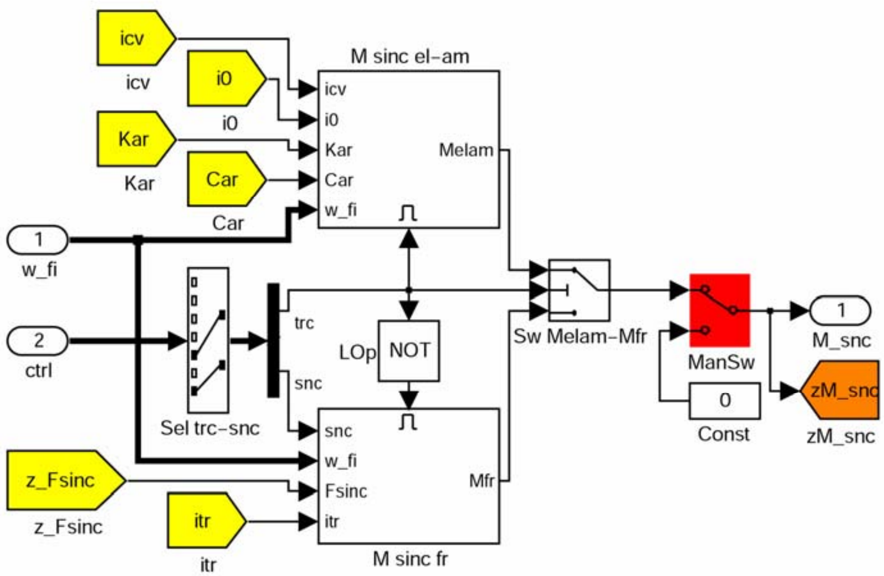

Fig. 5 Submodule for the determination of synchromesh acting torque Msnc

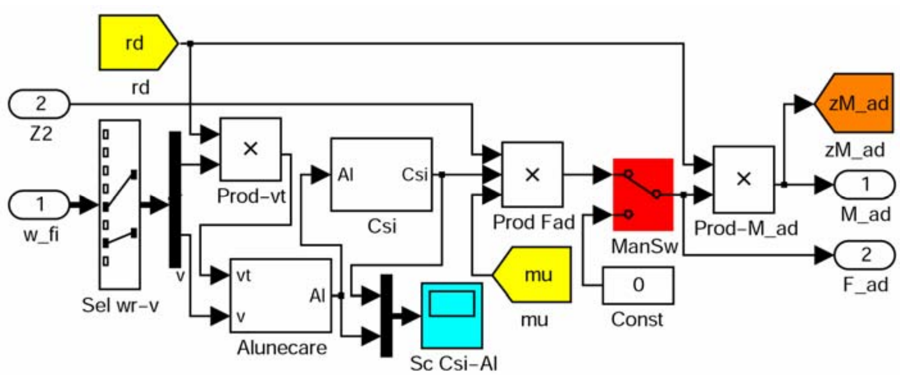

Fig. 6 Submodule to calculate the wheel-road moment of friction M_{ad}

In figure 6 presents submodule that compute frictional moment M_{ad} on the driving wheels, this being used as input value in blocks determining the kinematics of the driving wheels and vehicle's body.

First, using as input data the theoretical speed $v_t = w_r\ r_d$ and real speed v, submodule **Alunecare** calculates the driving wheels slip *al*, accordingly with next equation:

$$al = \begin{cases} 1-\dfrac{v}{v_t} & if \quad v < v_t \\ 0 & if \quad v = v_t \\ -1+\dfrac{v_t}{v} & if \quad v > v_t \end{cases} . \qquad (2)$$

The slip can take values between -1 (wheels locked during braking) and +1 (traction, immobile vehicle and total wheels slippage). Easy to define, the slip is tricky to implement in computer algorithm, because at very low speeds (for driving wheels and vehicle body), numerical errors become very annoying and must be treated carefully.

Based on the slip, submodule **Csi** calculate the used friction, defined by the relation

$$\xi = \frac{\frac{X}{Z}}{\mu}, \qquad (3)$$

where X is tangential force (for traction or braking); Z – driving axle dynamic load; X/Z – specific tangential force; μ – friction coefficient.

The graphic representation of used friction ξ function of slip s (output versus input in submodule **Csi**) shows in figure 7.

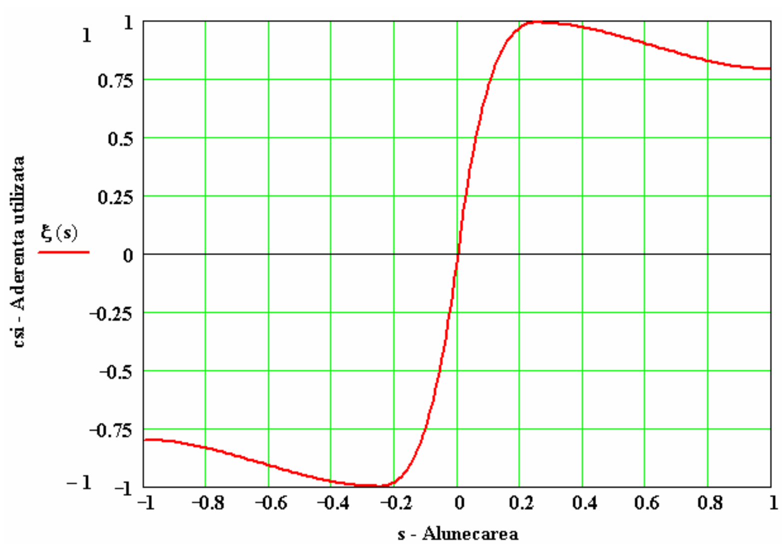

Fig. 7 Rolling characteristic of the wheel

Submodule presented in figure 8 serves to obtain all the commands received by the powertrain, imposed either by driver or by electronic command logic, designated to assist or to release the human during driving. Therefore, function of driver intentions and vehicle kinematics, generates positions signals (presented also in figure 11) for three pedals (*pac* for accelerator, *pfr* for brake, *pam* for clutch) and other four gear shifting signals (*trd* for desired gear; *trc* for engaged gear; *sch* for need of shifting; *snc* for synchronisation process). All these signals group together (multiplex) in line **ctrl** and go to all blocks in figure 2 that need one of them.

The most complex figure's 8 submodule, **Treapta_CV**, simulates the signals generation at a gearshift and shows in figure 9.

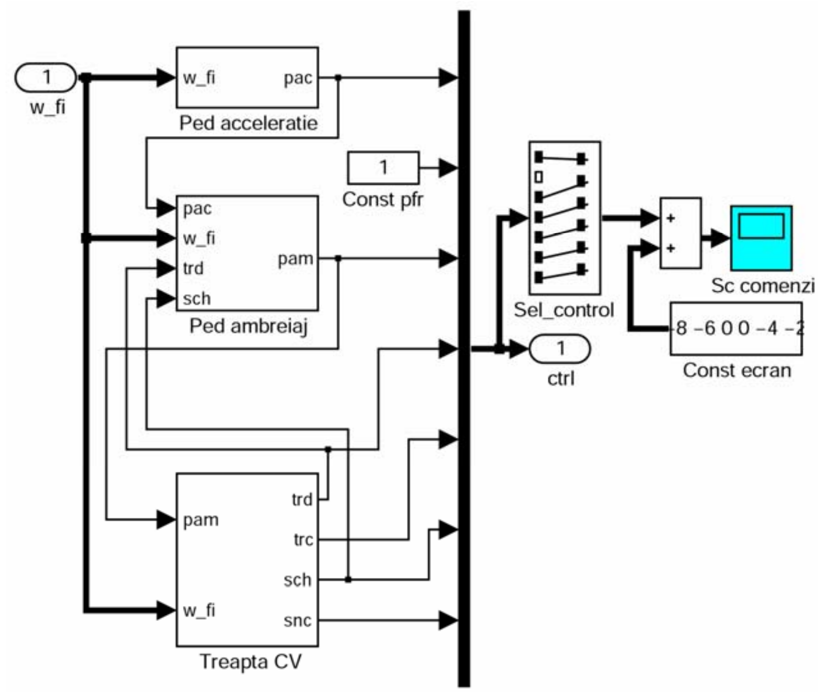

Fig. 8 Submodule for generation of powertrain commands

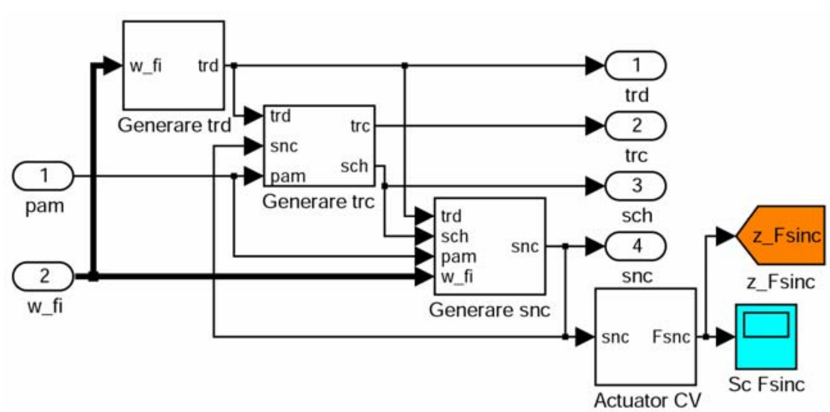

Fig. 9 Submodule for generation of signals related to gear shifting

Block **Generare_trd** simulates the driver intention to initiate a gearshift, including the neutral position. The desired gear indicates by output signal *trd* that take integer values (0 for neutral).

Block **Generare_trc** produces two signals:

- *trc*, signal of currently engaged gear; he become equal with *trd* only if the clutch is totally disengaged (pedal completely pressed – signal *pam*=0); supplementary, for a "drive" gear (i.e. not "neutral") is necessary waiting the final of synchronisation process (when *snc* fall for 1 in 0);

- *sch*, logical signal of shifting, indicates that a engaging or disengaging process was initiated, but this wasn't finished; so, if *trc* is equal to *trd*, *sch*=0, and if *trc* differs *trd*, *sch*=1.

When *sch* is high, a "drive" gear is wanted (*trd*≠0) and clutch is totally disengaged, a high value of signal *snc*, produced by the block **Generare_snc**, indicates a synchronisation process in course. Also, this commands the servomechanism (block **Actuator_CV** in figure 9, with the scheme showed in figure 10) that generates actuation force of the synchromesh sleeve.

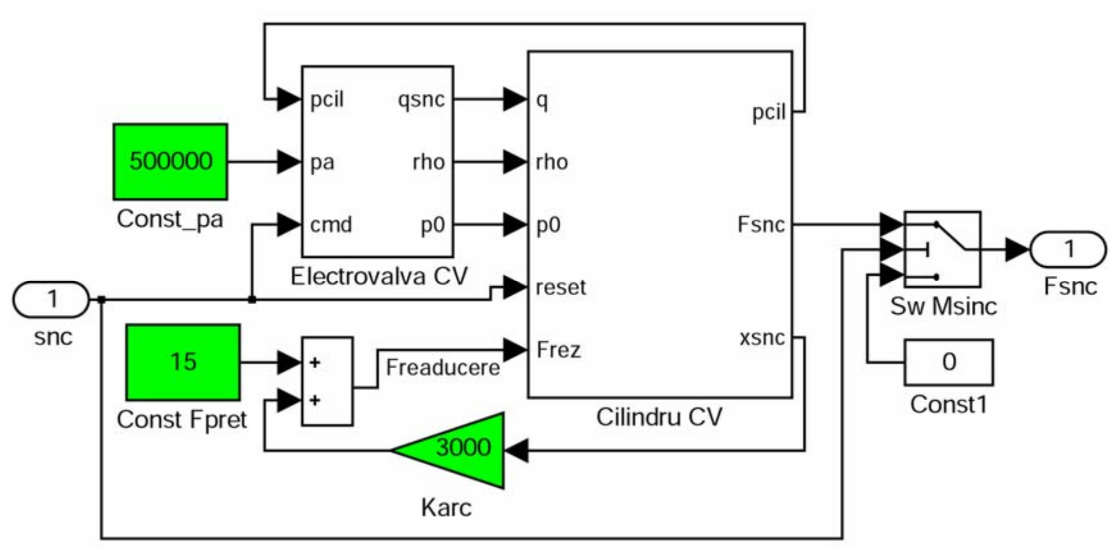

Fig. 10 Submodule for the synchromesh electro-pneumatic actuator

Other block (included in block **Ped_ambreiaj** in figure 8), much similar with **Actuator_CV**, simulates the actuation of the clutch, but the output quantity is not a force, is a displacement. Each two blocks includes as subsystems an electrovalve and a working cylinder, taking into account the laws of pneumatics governing their behaviour.

ALGORITHM APPLICATION – SIMULATION OF DRIVETRAIN BEHAVIOUR

The computer model was used to simulate drivetrain behaviour in different road and functional regimes, to improve dynamic and fuel consumption performances. The acceleration and the gearshifts realised in two different manners:

- as a manual-automated transmission, for the driver remaining only the task to actuate the accelerator pedal and to indicate the desired gear and the moment of shift, while the other decisions being taken by the command logic;

- as a full-automatic transmission, the driver acting only on the accelerator pedal and all other actions being judged by the command logic.

As a practical application example of the shortly described algorithm, next figures show one of the most difficult working situations for the automated actuation system – gear downshift.

These present simulated time histories for a standstill start followed by a shift and gearing up in second gear and then by a downshift and an engine brake (shifts 0-1-2-1).

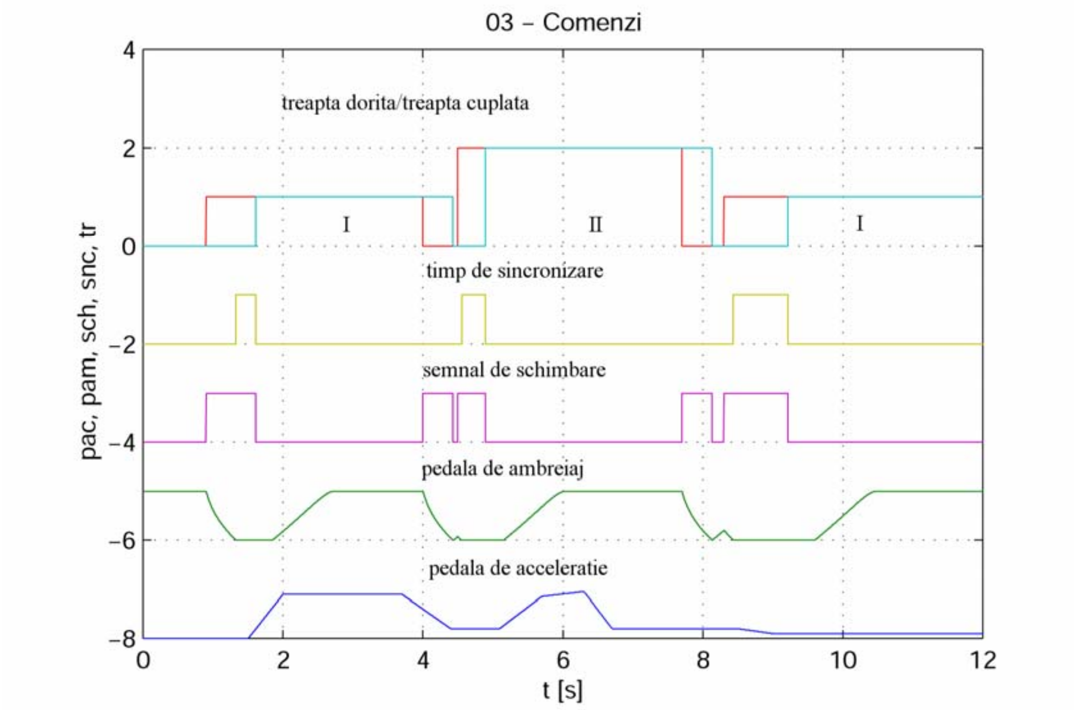

Fig. 11 Command signals
blue – pac (accelerator pedal); green – pam (clutch engagement); violet – sch (shift); yellow – snc (synchronisation); cyan and red – trd and trc (desired and engaged gear)

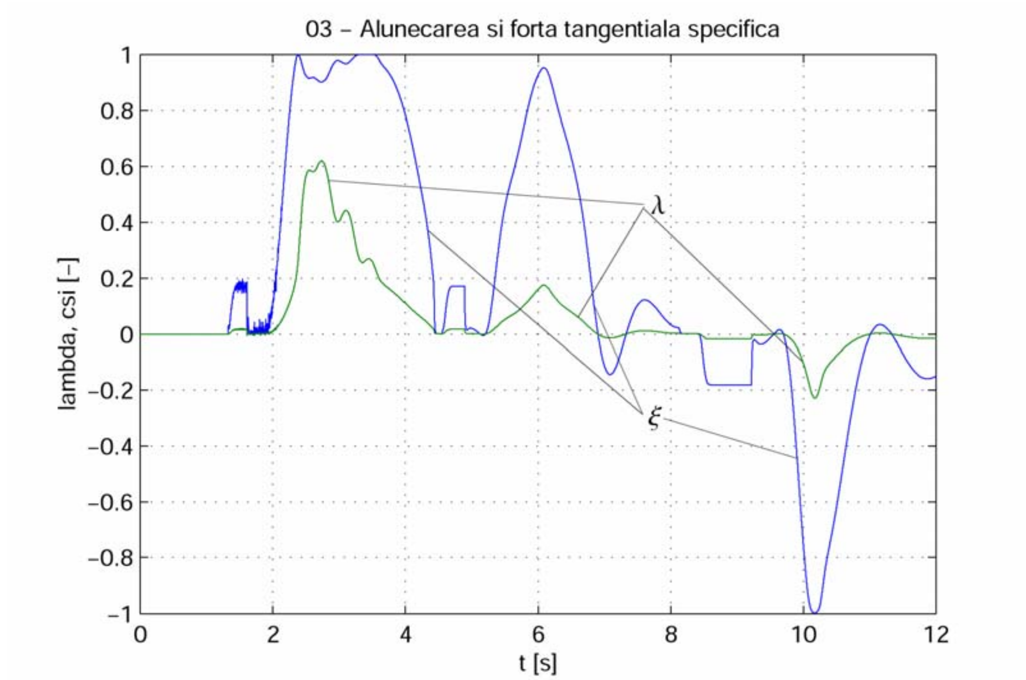

Fig. 12 Driving wheels slip (green, λ) and used friction (blue, ξ)

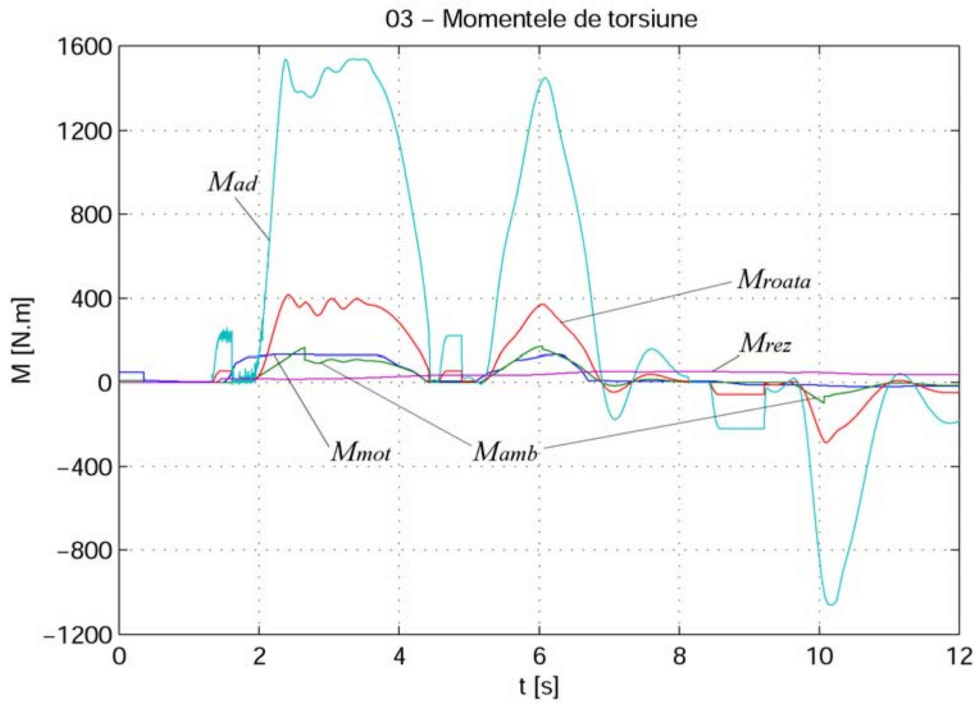

Fig. 13 Real torsional moments
blue – Mmot (engine); green – Mamb (clutch); red – Mroata (axle shaft);
cyan – Mad (driving wheels friction); violet – Mrez (global resistance)

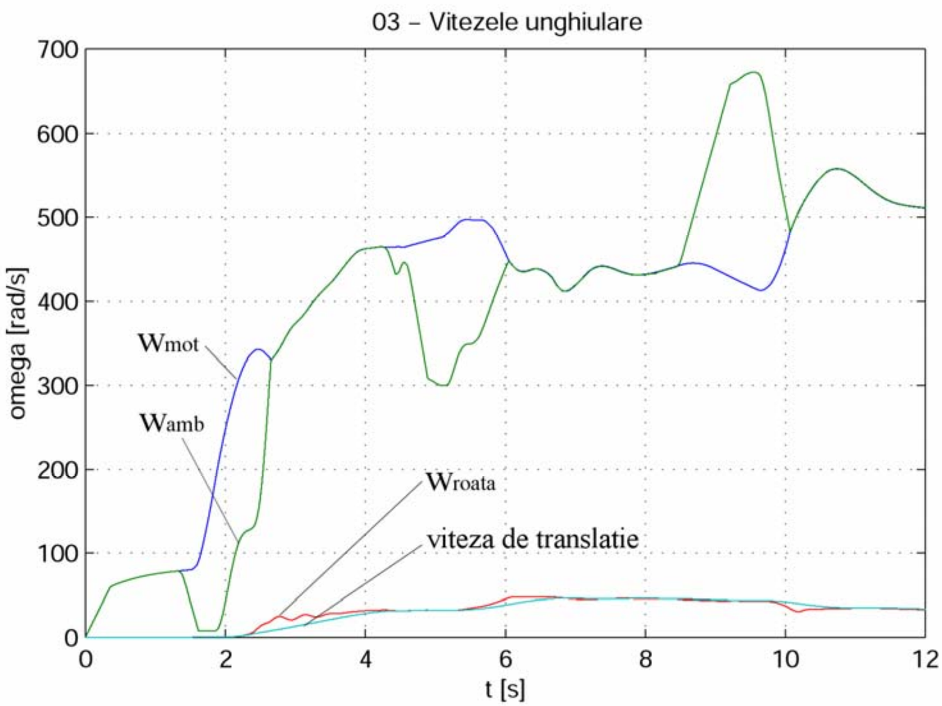

Fig. 14 Real angular speeds
blue – wmot (engine); green – wamb (clutch disk); red – wroata (driving wheels);
cyan – angular speed equivalent to the body translational speed

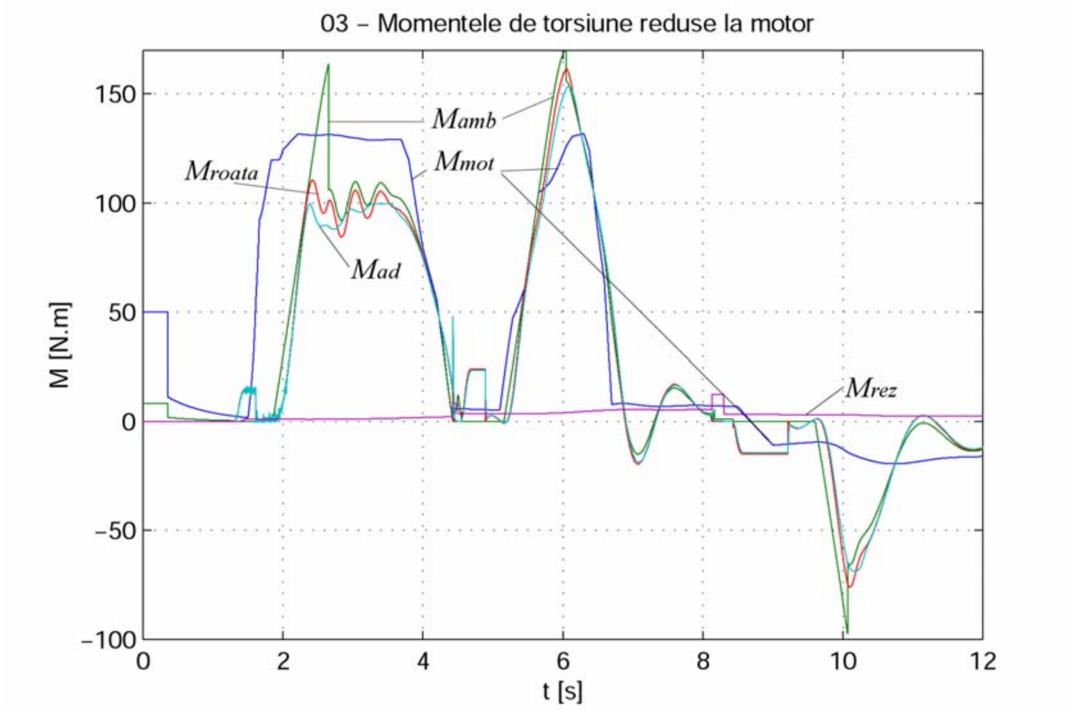

Fig. 15 Torsional moments reduced to engine
blue – Mmot (engine); green – Mamb (clutch); red – Mroata (axle shaft);
cyan – Mad (driving wheels friction); violet – Mrez (global resistance)

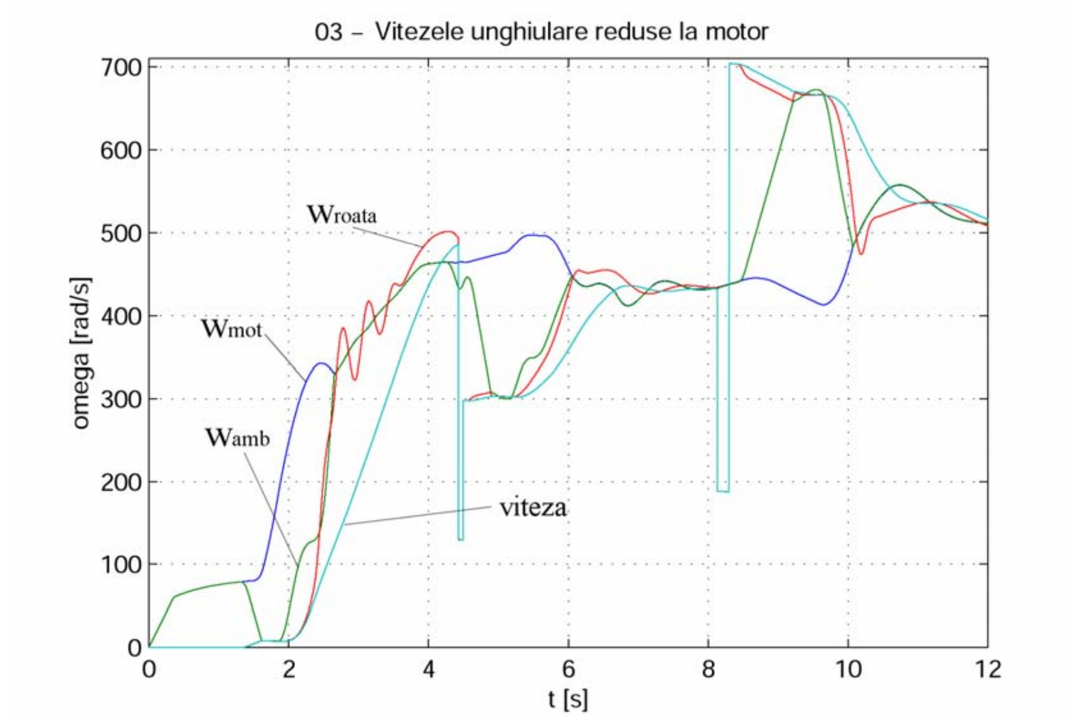

Fig. 16 Angular speeds reduced to engine
blue – wmot (engine); green – wamb (clutch disk); red – wroata (driving wheels);
cyan – angular speed equivalent to the body translational speed

In addition to the quantities used in figures 11…16, many other can be represented as functions of time or characteristics.

As a results interpretation, it observes that synchronising time necessary to shift from second to first gear is approximately double than for the inverse situation (from first to second).

CONCLUSIONS

This article shows a way that the authors used to simulate vehicle longitudinal dynamics. Here were presented only aspects regarding a car with automated transmission, but other vehicles types (all-terrain car, industrial tractor or truck-semitrailer combination) were also studied, using models that are more complicated. To solve the models, Matlab-Simulink and original FORTRAN or PASCAL programs were designed. The obtained results were confronted with many experimental data that permitted to calibrate or to perfect the models.

The computer model shortly presented here can be exploited in many useful ways, not only to better understand how a complex mechanical (and not only) system behave, but also to obtain important values for kinematics, stress level, different process durations or energetic consumption of the actuation servomechanisms. In addition, such models can facilitate the correct chose of parameters and the design optimisation of the system.

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