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AUTOMOTIVE POWERTRAIN MANAGEMENT

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ABSTRACT

Given the diversity of phenomena that occur during operation of automotive powertrain and their strong impact on the environment, this paper presents a unified approach to these problems. This is a complex pattern study, composed of a mathematical model, a simulation done by inserting subroutines in the software package MATLAB 6.5 and a CATIA V5R16 environment modeling. By customizing the model obtained can define it completely stabilized operating modes of propulsion systems and their dynamic, economic and pollution parameters. This provides, even the design phase, definition of additional constructive and functional criteria against the current, to ensure stable and economic operation, in an area as extensive.

KEYWORDS: automotive powertrain, stable and economic operation

1. Introduction

In the proposed modeling is adopted as a key assumption that the entire car's propulsion system is a mechanical system consisting of solid bodies, connecting inner and outer, with a rigid motion, as outlines in **Fig. 1**. In this figure, *I* is the reduced moment of inertia of the rotating elements of the propulsion engine, *I'* is the drive wheels reduced moment of inertia, and *I''* is the reduced moment of inertia of the gearbox and main gear elements.

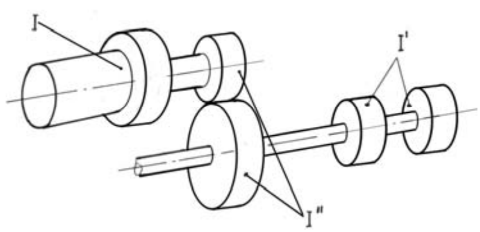

Fig. 1. *Mechanical equivalent of the entire system of the vehicle propulsion*

To study the movement of rigid, in the initial phase is necessary to generate equivalent mechanical model of the propulsion system, which involves calculating in different points the reduced masses of the real system and the corresponding reduced loads. Thus, the mechanical equivalent of automotive powertrain assembly is replaced by an equivalent mass, resulting in the model in **Fig. 2**, whose degree of freedom is given by the angle of rotation.

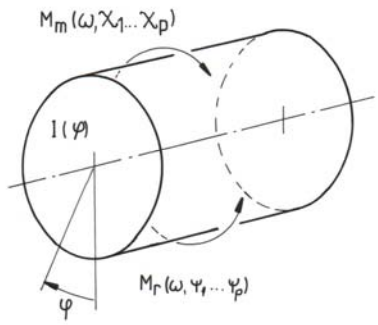

Fig. 2. *The mechanical equivalent of automotive powertrain assembly*

Considering the reduction point at the motor shaft level, mass moment of inertia, *I*, of the reduced mass is calculated, according to the equivalent kinetic energy criterion, by means of the relationship:

$$I = \sum_{j=1}^{n_r} I_j \left(\frac{\omega_j}{\omega}\right)^2 + \sum_{i=1}^{n_j} m_i \left(\frac{v_i}{\omega}\right)^2 \qquad (1)$$

where:

I_j - is mass moment of inertia of the rotating *j* mass;

ω_j - angular velocity of the *j* mass;

m_i - mass of the i element moving translational;
v_i - speed of the m_i mass;
n_r - number of rotating masses;
ω - angular velocity of low mass I (usually equal to the angular velocity of the shaft to which they reduce).

The mathematical model of evolution of the mechanical equivalent of automotive powertrain assembly is provided as a starting point total energy conservation of I mass condition, so that:

$$d\frac{I(\varphi)\omega^2(\varphi)}{2} = \begin{bmatrix} M_m(\omega,\chi_1,\chi_2,..\chi_p) - \\ -M_r(\omega,\psi_1,\psi_2,...,\psi_q) \end{bmatrix} d\varphi \quad (2)$$

and equivalent simplified form is:

$$\frac{\omega^2}{2}\frac{dI}{d\varphi} + I\frac{d\omega}{dt} = M_m - M_r \quad (3)$$

which is actually a mathematical model of mass movement I reduced its axis. Since the mass moment of inertia I variation depending on the angle of rotation φ is small, can introduce approximation,

$$\frac{dI}{d\varphi} = 0 \quad (4)$$

equation (3) becomes:

$$I\frac{d\omega}{dt} = M_m - M_r \quad (5)$$

Analyzing this equation shows that the propulsion system operation may occur several situations, depending on the relationship in which the two moments, M_m and M_r. Thus, if the M_m = M_r resulting from (5) that the angular acceleration $d\omega/dt = 0$, so the motor shaft angular velocity is constant. In this situation, powertrain operation is performed in a steady or stable. Equality of torque and moment resistant is done only at the intersection point ***a***, between the output characteristics of the engine and transmission input characteristics, as shown in **Fig. 3**.

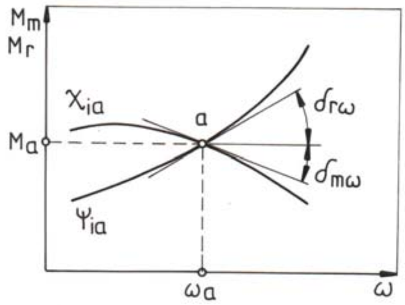

Fig. 3. *Coordinates defining the operating point of the propulsion system*

Coordinates of this point, called point of operation, is the parameters of the engine required power, represented by the torque M_a and the angular velocity ω_a during the stationary regime:

$$P_a = M_a\omega_a \quad (6)$$

Operating point stability analysis by analytical mechanical model involves studying evolution during transient processes. This development is defined by the solution of differential equation (5). Normally, to solve this equation requires knowledge of the functions that describe the output characteristics of the engine and the transmission input characteristics. But using the Taylor series development needs can be assessed in the general case, the performance of these functions in the vicinity of the operation, obtaining:

$$M_m(\omega,...,\chi_i,...) = M_m(\omega_a,...,\chi_{ia},...) +$$
$$+\frac{\partial M_m(\omega_a,...\chi_{ia},...)}{\partial\omega}\frac{\omega-\omega_a}{1!} + ...$$
$$+\frac{\partial M_m(\omega_a,...\chi_{ia},...)}{\partial\chi_i}\frac{\chi_i-\chi_{ia}}{1!} + ...$$

respectively, (7)

$$M_r(\omega,...,\Psi_i,...) = M_r(\omega_a,...,\Psi_{ia},...) +$$
$$+\frac{\partial M_r(\omega_a,...\Psi_{ia},...)}{\partial\omega}\frac{\omega-\omega_a}{1!} + ... \quad (8)$$
$$+\frac{\partial M_r(\omega_a,...\Psi_{ia},...)}{\partial\Psi_i}\frac{\Psi_i-\Psi_{ia}}{1!} + ...$$

the notations have the significance of **Fig. 3**.

Accepting a linear variation of characteristics M_m and M_r in the vicinity of the operation ***a***, which involves taking only the terms containing derivatives of order zero and first order of Taylor development and, second, entering the following variable transformations:

$$\omega = \omega_a + \Omega$$
$$\chi_i = \chi_{ia} + \mathrm{X} \quad (9)$$
$$\psi_i = \psi_{ia} + \Psi$$

and notation:

$$\Delta_{kl} = tg\delta_{kl} \quad (10)$$

Narrowing the difference $\Delta_{r\omega} - \Delta_{m\omega} = \Delta$, equation (5) becomes successively simplified forms:

$$I\frac{d\Omega}{dt} + \Delta\Omega = ... + \Delta_{m\chi_i}\mathrm{X}_i - \Delta_{r\psi_i}\Psi_j + ... \quad (11)$$

or still:

$$I\frac{d\Omega}{dt} + \Delta\Omega = C \quad (12)$$

where C is denoted by the algebraic sum of terms on the right, that is:

$$C = ... + \Delta_{m\chi_i}\mathrm{X}_i - \Delta_{r\psi_i}\Psi_i + ... \quad (13)$$

which means, in fact, the system disturbance occurs.

Solving differential equation (12) is based on the constant values I, Δ, C. But since, obviously, equivalent mechanical model is non-zero mass, we have $I \neq 0$. In this situation, to solve the equation will consider the following cases further developed.

1. If $\Delta \neq 0$ and $C \neq 0$, above equation becomes:

$$\frac{d\Omega}{C-\Delta\Omega}=\frac{dt}{I} \tag{14}$$

with solution:

$$\Omega=\frac{C}{\Delta}\left(1-e^{-\frac{\Delta}{I}t}\right) \tag{15}$$

2. When $\Delta = 0$ and $C \neq 0$ equation to customize the form:

$$I\frac{d\Omega}{dt}=C \tag{16}$$

with solution:

$$\Omega=\frac{C}{I}t \tag{17}$$

when we consider the initial condition $\Omega(0)=0$.

3. If the parameters defined $\Delta \neq 0$ and *C=0*, equation (12) becomes:

$$I\frac{d\Omega}{dt}+\Delta\Omega=0 \tag{18}$$

Solving the characteristic equation is obtained solution:

$$\Omega=\Omega_0 e^{-\frac{\Delta}{I}t} \tag{19}$$

where Ω_0 is the angular velocity value Ω at baseline, considered to $t = 0$.

If, however, the initial velocity is zero, that is:

$\Omega_0 = 0$

in (19) becomes apparent:

$\Omega = 0$

and

$\omega = \omega_a$

which is understandable because the disturbance is absent, that is $C = 0$.

Where:

$\Omega_0 \neq 0$

solution of the (18) equation remains to form (19):

4. A final case under consideration is given to values $\Delta = 0$ **,** $C = 0$

In this case, equation (12) is also a simplified form, that is:

$$I\frac{d\Omega}{dt}=0 \tag{20}$$

with solution:

$$\Omega=\Omega_0 \tag{21}$$

same question with respect to Ω_0, as for **3**.

With the developed model, based on the solutions (15), (17), (18) and (21) can be extremely useful ***analysis*** of the ***stability of the vehicle propulsion system operation***. The first case analyzed is the situation defined by:

$\Delta < 0$

that is:

$tg\delta_{r\omega} < tg\delta_{m\omega}$

In this case, the angular velocity decreases or increases indefinitely to a change in operating point position ***a***; that, in this case the operating point is ***unstable***.

In the second case, considering the situation:

$\Delta = 0$ şi $C \neq 0$,

which translates into the condition:

$tg\delta_{r\omega} = tg\delta_{m\omega}$

In this case we also get an ***unstable*** operating point.

An interesting case, revealed by this analysis, occurs when $\Delta < 0$, or $\Delta = 0$, but in both cases *C=0.* This case leads to a ***metastable*** operating point**.** Clearly, this situation should be avoided because any accidental change of the angular speed leading to the change of operating point.

Finally we discuss the case when:

$\Delta > 0$

or

$tg\delta_{r\omega} > tg\delta_{m\omega}$

and

$C \neq 0$

In this case, the angular velocity varies in time, uniquely determined, between the old and new position of operating point. It follows that in this case operating point is ***stable***, a situation particularly advantageous in the operation of vehicle propulsion. If, in addition provided $\Delta > 0$ or $tg\delta_{r\omega} > tg\delta_{m\omega}$ is satisfied the condition $C = 0$, results that the operating point returns to the old position, remaining stable.

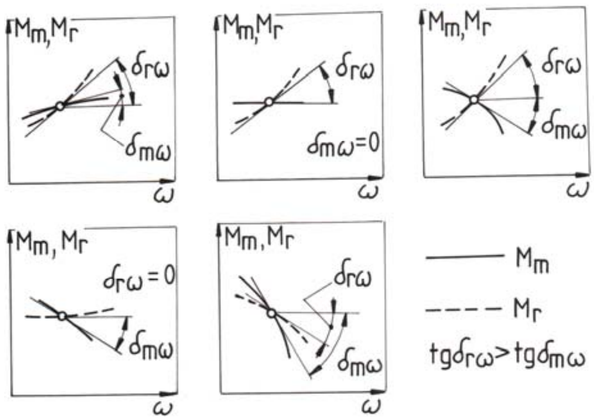

Fig. 4. *The relative positions of the characteristics that determine stable operation*

Modeling done in this phase of work and analysis on it, leading to a *general conclusion* that shows that *to achieve stable operation of automotive propulsion systems is necessary and sufficient for any*

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operating point as the slope of the input characteristic is greater than the slope of the output characteristic.

In this sense, the **Fig.4** shows different mutual positioning of the input and output characteristics, leads in all cases to a stable operating point.

2. Simulations

Starting from the mathematical model developed has made a complex simulation of the propulsion system behavior in various constructive-functional situations, called ***MATCEL-PROP***.

The simulation was performed by inserting subroutines in the software package ***MATLAB 6.5*** and ***Excel*** program. Adding a tutorial conducted to facilitate the development program. They could thus reveal a series of theoretical results, described briefly below.

Determination of basic parameters required simulation was made for a typical car, ***VW Golf IV***; significant values are highlighted in **Fig. 5**.

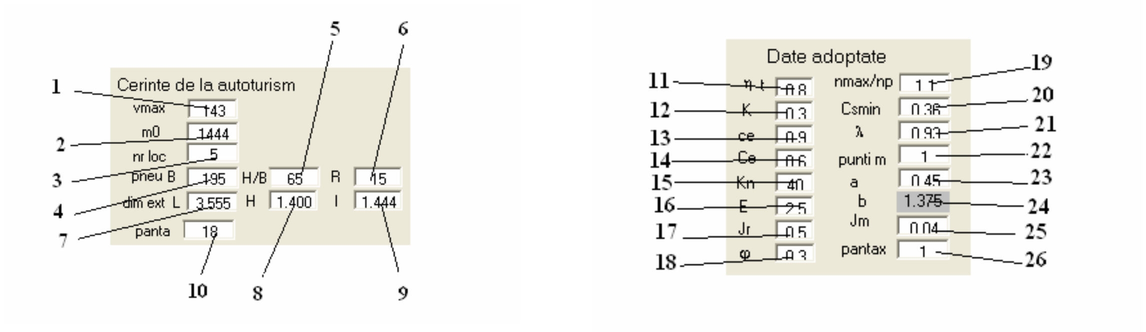


Fig. 5. *Basic parameters related coefficients picture*

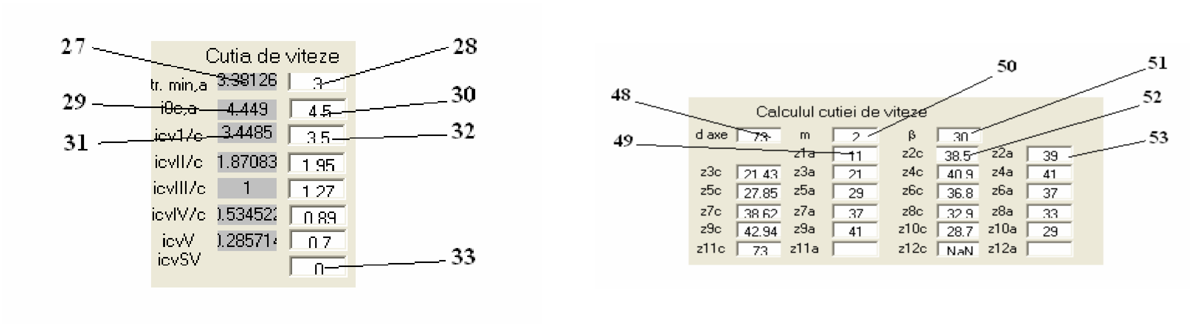
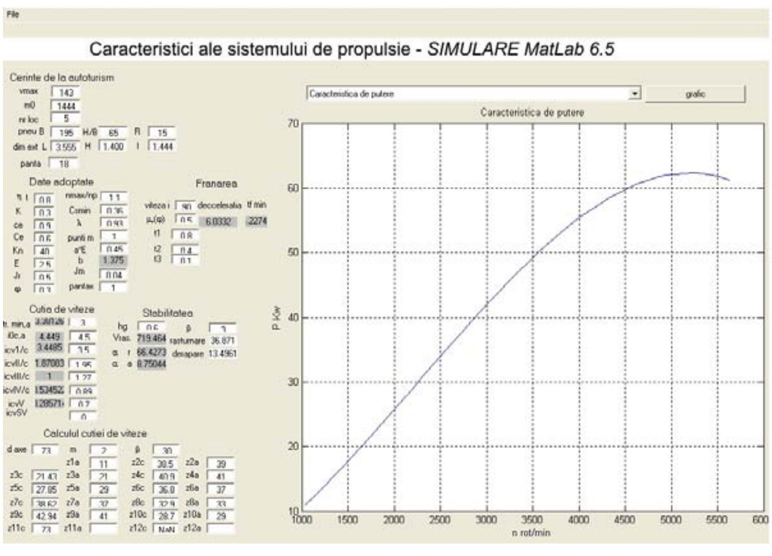


Fig. 6. *Verification of the simulation parameters*



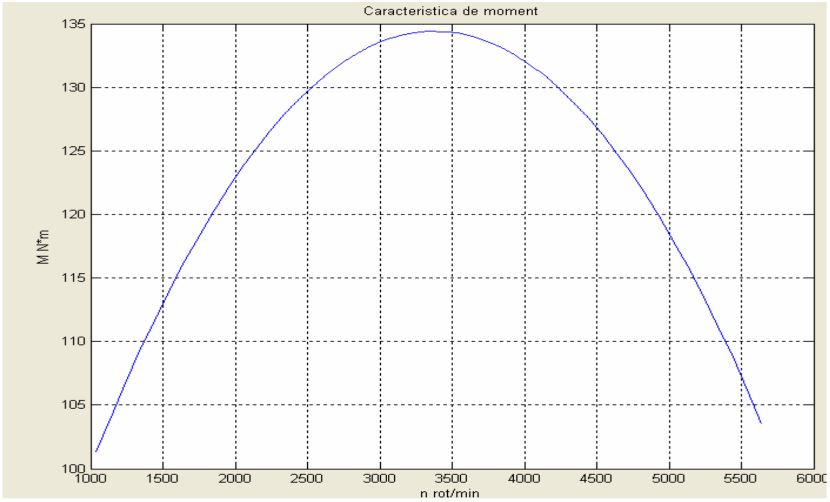


***Fig. 7.** Characteristic of the propulsion system*

Fig. 7 highlights *characteristic* of the propulsion system model is chosen, it is the actual power and timing variations in the actual engine propulsion system obtained by simulation, in the form of an executable.

From these raw elements, further presented the most significant results of simulation ***MATCEL-PROP***, looks especially the problem of propulsion system stability. Were considered, in particular, common situation of equipment for the real propulsion system model of car chosen, designed to lead to some conclusions with applicative features, useful in terms of its mechanical and functional optimization. Results are summarized using the variation diagrams of engine torque, M_m, resistant torque reduced to motor shaft, M_{rr} and specific fuel consumption, c_e, depending on the angular velocity ω of motor shaft, presented in figures below.

For each case, algorithm simulation allows determining the position of the system operating point corresponding to maximum speed of the car. On the other hand, in order to emphasize the stability of propulsion, these diagrams contain the tangent lines to variation curves of torques in the operating point, $Fct.tan.M_m$, respectively, $Fct.tan.M_{rr}$. In this respect, a ***first case*** simulated and analyzed (***ES1***) with ***MATCEL-PROP*** considers basic equipment of the propulsion system, which includes an engine having the effective power value 64[kW], assimilated in the model with an engine power (P_e=P_m), and a 15" wheel diameter.

By assigning the value 4 for main gear ratio, i_0, variations in **Fig. 8** shows a ***stable operating point*** at maximum speed of 149 [km/h], and further characterized by an acceptable specific effective fuel consumption, respectively 173[g/kWh].

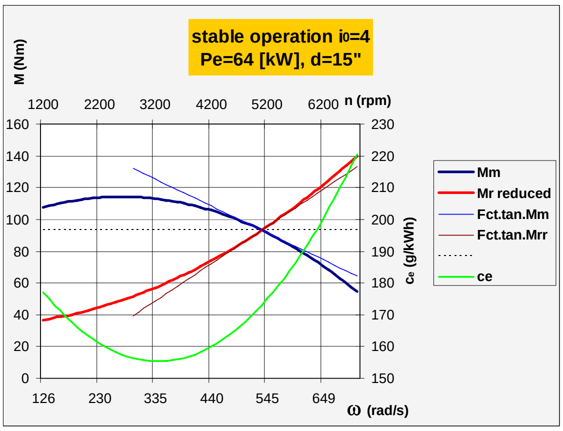


Fig. 8.** Conditions for stable operation of the propulsion system - highlighted by the simulation phase **ES1

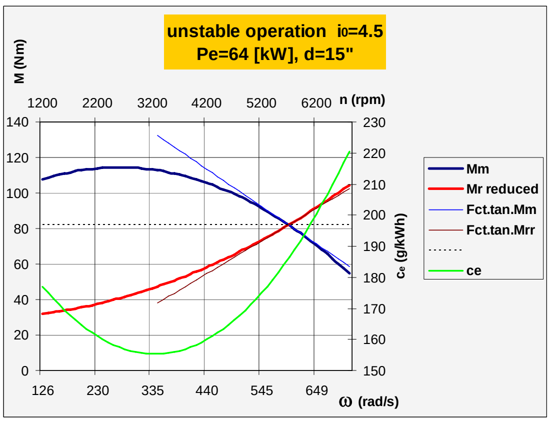


Fig. 9.** Conditions for unstable operation of the propulsion system - highlighted by the simulation phase **ES1

Still increasing main gear ratio by only *0.5*, thus leading to the value $i_0 = 4.5$, the propulsion system behavior becomes ***unstable***, speed decreases slightly the value of 148 [km/h], there the premises so that it can not be kept constant, while the value of specific effective fuel consumption rises to 173 [g/kWh] to 186.4 [g/kWh], situation highlighted by the diagrams in **Fig. 9**. On the other hand, from baseline, summarized in **Fig. 8**, reducing by 0.5 the ratio main gear i_0, it reaches $i_0=3.5$, achieve a ***very stable*** operating point, leading to maximum speed 146.9 [km/h], very stable value, made with a specific effective fuel consumption of 162 [g/kWh], which confirms the downward trend of this important parameter, with increasing stability of the system drive. This condition simulated propulsion system is presented through results obtained in **Fig. 10**.

Continuing the iteration of the ***MATCEL-PROP***, the main gear ratio value $i_0=3$ is reached ***extremely stable*** operation of the propulsion system, characterized by a maximum speed value of 136.3 [km/h], in turn extremely constant value, in fact the smallest of speed values highlighted in this stage of the simulation and effective specific fuel consumption decreased to 155.6 [g/kWh], situation presented in **Fig. 11**.

Simulate a situation leading to opposite results as shown in **Fig. 12**, the $i_0=5$ value ratio of the main gear reach a ***very unstable*** operation, the operating point is characterized in this case by the speed increased to 144.9 [km/h], but can not be maintained, obtained at engine speed of 6200 [rpm] and effective specific fuel consumption increased to a value of 200.4 [g/kWh].

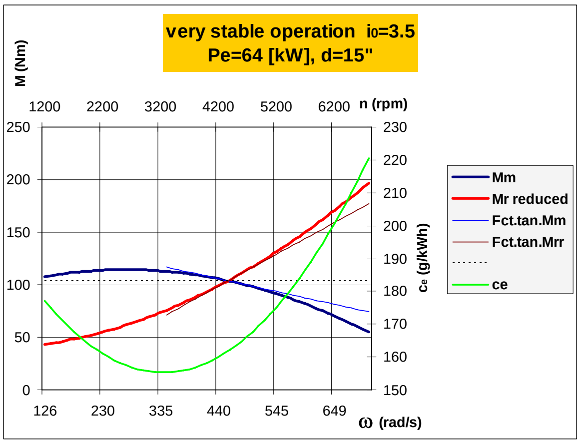


Fig. 10. *Conditions for very stable operation of the propulsion system - highlighted by the simulation phase* ***ES1***

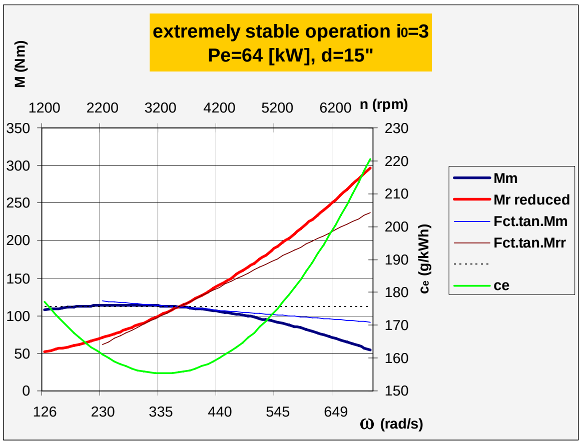


Fig. 11. *Conditions for extremely stable operation of the propulsion system - highlighted by the simulation phase* ***ES1***

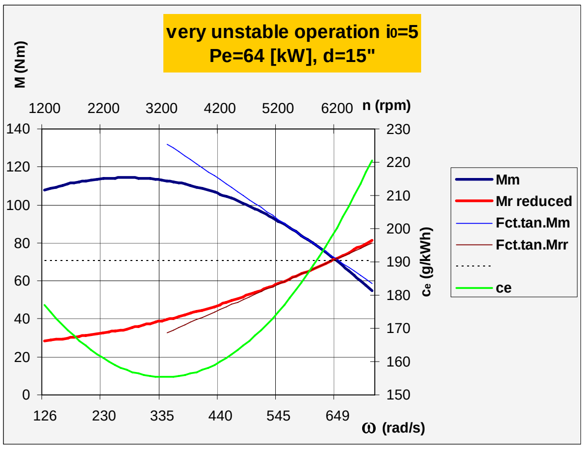


Fig. 12. *Conditions for very unstable operation of the propulsion system – highlighted by the simulation phase* ***ES1***

Simulation performed with ***MATCEL-PROP*** include a ***second phase*** of study (***ES2***), which takes into account the above stable conditions, characterized by the motorization of 64 [kW] and the main gear ratio value $i_0=4$, but with two-stage change diameter wheels. Thus, a diameter of 15"was increased to 16". The ***third phase*** of study (***ES3***) addressed through simulation ***MATCEL-PROP*** envisages an engine characterized by increased power to 74 [kW], keeping the basic diameter of the wheel motors, thus is 15", but with the i_0 main gear ratio change, with steps of 0.5in the range of normal values. ***Stable*** operation is achieved with the main gear ratio $i_0=3.7$.

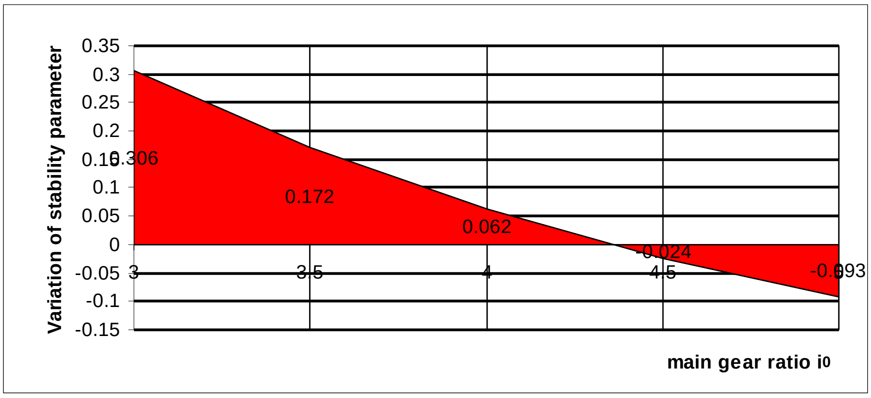


Fig. 13. *Variation of stability parameter with main gear ratio change obtained by simulating* ***MATCEL-PROP*** *for propulsion engine power of 64 [kW]*

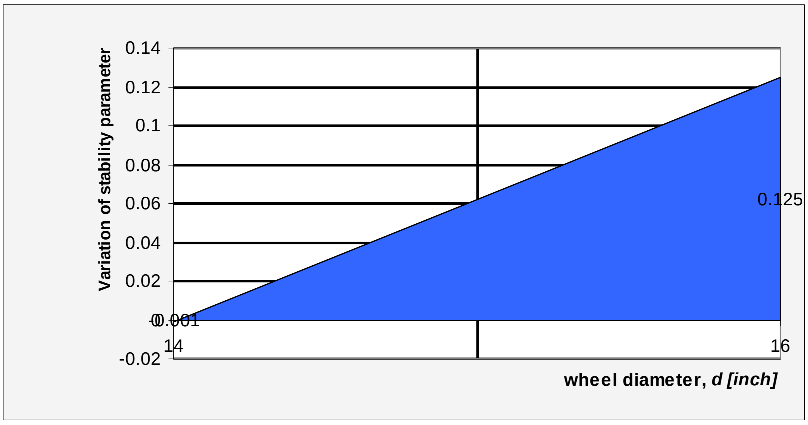


Fig. 14. *Variation of stability parameter obtained by simulating* ***MATCEL-PROP*** *for changing wheel diameter*

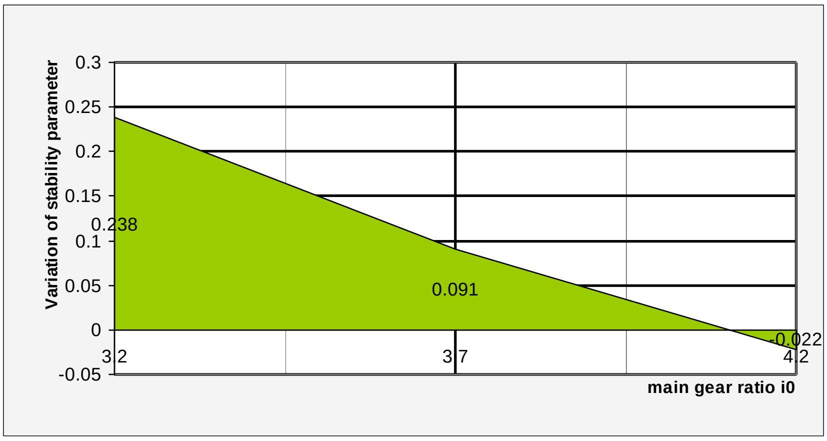


Fig. 15. *Variation of stability parameter with main gear ratio change obtained by simulating* ***MATCEL-PROP*** *for propulsion engine power of 74 [kW]*

The simulation is ***MATCEL-PROP*** addresses equally the ***fourth stage*** of the study (***ES4***), leaving, primarily from reduced engine power, thus is 54 [kW] and secondly, as described above, driving wheel diameter 15". Also, in this case is considered the i_0 main gear ratio change with steps of 0.5.

Initializing the study from $i_0=4.2$ is reached to a ***stable*** operating state. The results obtained in the ***four stages of the study*** are summarized in **Fig. 13**, **Fig. 14**, **Fig. 15** and **Fig. 16**, actually describing simulated behavior of the propulsion system, assessed by the **stability parameter variation** Δ .

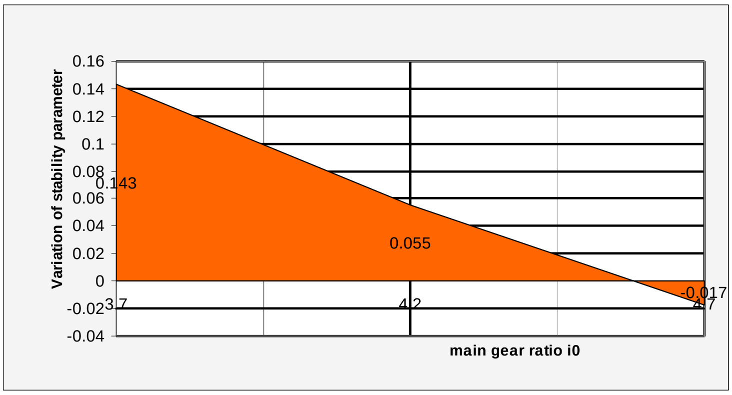


Fig. 16. *Variation of stability parameter with main gear ratio change obtained by simulating* ***MATCEL-PROP*** *for propulsion engine power of 54[kW]*

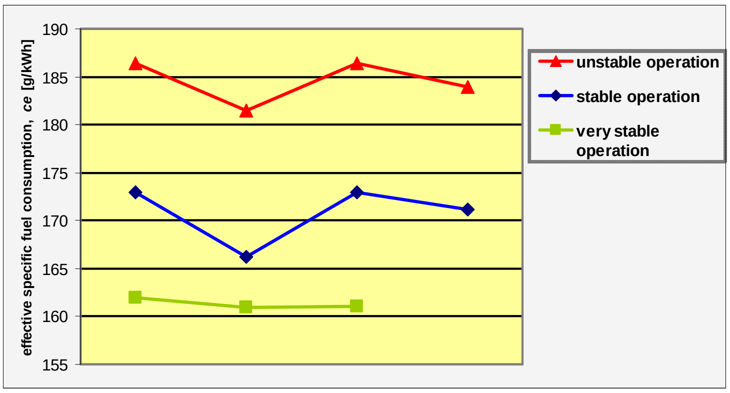
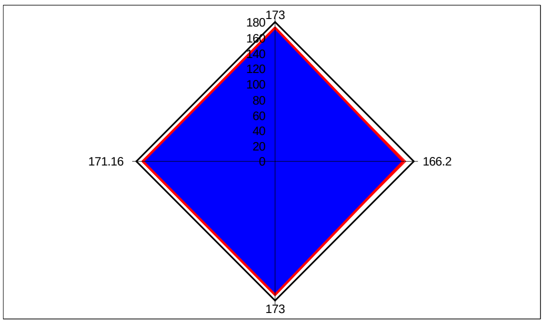
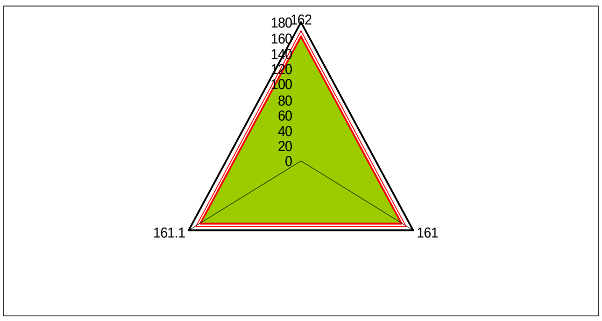


Fig. 17. *Evolution of effective specific fuel consumption values for different states of the propulsion system*

On the other hand, the evolution of specific fuel consumption values for different states of the propulsion system is highlighted in **Fig. 17**. It can thus be noted that increased stability during operation of the propulsion system, values of these inputs are reduced, which is very advantageous. Using the **Fig. 18 a, b, c** shown the variation of these inputs for the three states of the system, and that each state consumption values are very close together, being practically constant regardless of equipment and characteristics of propulsion system that obtains the condition of its.





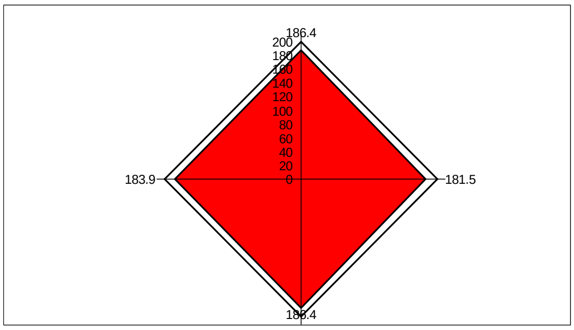


Fig. 18. a, b, c. *The range of values of effective specific fuel consumption corresponding of the three states of propulsion system*

Based on ***MATCEL-PROP*** **simulation**, design using ***CATIA V5R16*** environment has created a ***virtual model of transmission***, as a complex part of the propulsion system for the most stable operating situation highlighted. It was also considered the modeling of dynamic phenomena mainly in order to validate ***the equivalent mechanical model of the propulsion system.***

Since the equivalent model substitute the presence of trees, gears and other rotating masses, specific to propulsion system, also was considered useful an evaluation of a discrete model of the propulsion system, encompassing such elements assimilated in mechanical model.

3. Conclusions

In this work a model study was performed, which allows to define more completely stabilized operating modes of propulsion systems and their dynamic, economic and pollution parameters. This provides early-phase design, construction and functional definition of criteria additional to those present, to ensure stable operation and economic, in an area as extensive, contributing to an integrated management of automotive propulsion systems and the environment.

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