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ALGORITHM FOR PLOTTING THE POWER AND TRACTION CHARACTERISTICS OF THE MOTOR VEHICLES

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Abstract: *The knowing of the resistance to advance is needed to assess the vehicle performance. The size of the drag forces and the powers necessary for their overcoming is influenced by their movement conditions and by the constructive parameters of the vehicles. The resistance to advance of the vehicles, the powers and forces at the driving wheels, for various situations of exploitation considered are evaluated by developing of a numerically MathCad model that gives the results with graphic interpretation and that takes into account of the various travel regimes, the gear, geometry, nature and the state of the road, etc. Thus, it can be identified the gear ratios that can be used in different operating situations of the the motor vehicle.*

Key words: vehicle, drag resistance, self propelled, dynamic performance, modeling

1. INTRODUCTION

The obtaining of some tangential forces at the driving wheels of the vehicle, required to overcoming the drag forces (force of the rolling resistance, resistance forces due to the longitudinal inclination of the road (gradient resistance force), force of air resistance, resistance forces at the vehicle startup, resistance forces due to the traction of trailers or semi-trailers) directly depends on the moment and on the power that reaches at the driving wheels [1-15].

The power that reaches to the driving wheels of the vehicle is reduced compared to the effective power developed by the engine, with the power required to overcoming the friction resistance that occurring between the parts of the vehicle transmission components. Due to the resistance from the transmission, the active torque transmitted to the driving wheels is reduced compared to one developed by the engine, but is much increased by the total transmission gear ratio [1-15].

The powers reach at the driving wheels and also the tangential forces to the the driving wheels is dependent on the vehicle speed and the gear used.

By plotting the dynamic balance between power at the wheel and the amount of power required to overcoming the resistance to advance, depending on the vehicle speed for all the gears, is obtained the *powers characteristic* and by plotting the dynamic balance of the force to the wheel and the sum of the drag forces, depending on the speed of the vehicle at all gears, it obtain the *traction characteristic* or the *force characteristic at the wheel*.

Based on the powers characteristic and on the traction characteristic it can be determine the availability of acceleration, as power and force capable to defeat the start-up resistance in each gear may also be identified the maximum speed of the vehicle that can be obtained in the considered driving conditions. Also, with these characteristics it may be analyzed which of the gears may be used in full vehicle exploitation [1-3, 5, 9, 10, 13, 14].

To assess the ability of the self propelled motor vehicles, it has been developed a numerical calculation model which take into account the different movement regimes, their constructive parameters, the gear ratios used, geometry, nature and condition of the road and that allows the user to achieve desired results with graphic interpretations.

2. NUMERICAL EVALUATION METHOD

2.1. Notations used in the numerical computation model

Numerical computation algorithm, developed in MathCAD software, take into account the constructive parameters of the vehicle, the various driving conditions - geometry, nature and condition of the road, etc.

The main notations used in the calculation model are found in Table 1.

Table 1

The main notations used in the calculation model

Dimension	Notations	M.U.
❑ engine power	P_e	kW
❑ power at the wheel	P_R	kW
❑ torque at the wheel	M_R	daN·m
❑ force at the wheel	F_R	daN
❑ the rolling resistance force and the power required to overcome it	R_r, P_r	daN, kW
❑ gradient resistance force due to the longitudinal inclination of the road and the power required to overcome it	R_p, P_p	daN, kW
❑ total force of the road resistance and the power required to overcome it	R_ψ, P_ψ	daN, kW
❑ total air resistance force and the power required to overcome it	R_a, P_a	daN, kW
❑ the sum of resistance and external powers, which do not depend on the movement character	ΣR_{ext}, ΣP_{ext}	daN, kW
❑ resistance force to starting (the force available for acceleration) and the necessary power to overcome it (power available for acceleration)	R_d, P_d	daN, kW
❑ vehicle weight	G_a	daN
❑ dynamic radius of wheels	r_d	m
❑ acceleration of gravity	g	m/s^2
❑ track of the vehicle	E	m
❑ vehicle height	H	m
❑ cross-sectional area of the vehicle	S_f	m^2
❑ the vehicle speed	v	km/h
❑ relative speed of the vehicle on the longitudinal axis direction as against to air	v_r	km/h
❑ wind speed	v_w	km/h
❑ aerodynamic coefficient	k_a	$daN \cdot s^2/m^4$
❑ the weighting cross-sectional area of the vehicle	k_s	-
❑ number of gears in the gearbox	k	-
❑ a certain gear (j = 1...k)	j	-
❑ minimum speed for gear I	v_{min_1}	km/h
❑ minimum speed for gear j	v_{min_j}	km/h
❑ maximum speed for gear j	v_{max_j}	km/h
❑ maximum speed for gear k	v_{max_k}	km/h
❑ maximum speed possible	v_{max_c}	km/h
❑ idling engine speed	n_{min}	rot/min
❑ engine speed corresponding to the effective maximum torque (M_{max})	n_M	rot/min
❑ engine speed corresponding to the effective maximum power (P_{max})	n_P	rot/min
❑ maximum engine speed	n_{max}	rot/min
❑ longitudinal inclination of the road	α	deg
❑ rolling resistance coefficient	f	-
❑ grip coefficient	φ	-
❑ total resistance coefficient of the road or the specific total resistance of the road	ψ	-
❑ transmission ratio gearbox, in the gear j	i_{cv_j}	-
❑ the main transmission gear ratio	i_o	-
❑ total gear ratio transmission, the gearbox is coupled gear j	i_{t_j}	-
❑ total mechanical efficiency of the transmission	η_t	-

To the development of the numerical calculation, are taken into consideration different longitudinal inclination of the road (p_u = 0…9%), captured by using the variable *u = 1...4* (p_1 = 0%, p_2 = 4%, p_3 = 8%, p_4 = 12%), and various natures and states of the road, while using the variable c = 1...3 (1 - concrete-asphalt dry: $\varphi_1 = \varphi_{med_1} = 0.75$, $f_1 = f_{med_1} = 0.0165$; 2 - dry ground: $\varphi_2 = \varphi_{med_2} = 0.55$, $f_2 = f_{med_2} = 0.03$; 3 - trodden snow: $\varphi_3 = \varphi_{med_3} = 0.225$, $f_3 = f_{med_3} = 0.04$ [1-3, 14, 15]).

For evaluating the powers necessary to overcoming the drag forces is used too the variable $v = 0 \ldots v_{max_c}$ that characterizes the variation of the vehicle speed.

Longitudinal inclination angle of the road will be considered according to:

$$\alpha_u = \deg^{-1} \cdot a\tan\left(\frac{p_u[\%]}{100}\right). \quad (1)$$

For example, in the numerical computation model, a motor vehicle is taken into the study, about which there are the following: spark ignition engine; G_a = 1536 daN; P_{max} = 64 kW at n_P = 5500 rot/min; M_{max} = 12.8 daN·m at n_M = 3000 rot/min; front driving axle; k_a = 0.022 daN·s^2/m^4; inflation pressure of the tire 0.22 MPa; marking tires 185/65 R 15; k = 5, with the direct gear in the (k-1); v_{max_c} = 174 km/h; wheelbase, 2.589 m; front track, 1.480 m; rear track, 1.470 m; height, 1.534 m; total length, 4.020 m.

2.2. Evaluation of the resistance forces at the advance and the power required to overcome it [1-15]

In the development of the numerical calculation for determining the resistance at the advance of the vehicle, is used some assumptions [1, 5, 9, 13, 14]:

- the rolling rays are the same for all wheels;
- the coefficient of rolling resistance and the grip are the same for all wheels;
- the loading of the vehicle is considered symmetrical as against the symmetry longitudinal plane of the vehicle.

Considering the car under study, the numerical calculation model is developed for a situation where the engine is on the front axle (Fig. 1).

The total rolling resistance force of the vehicle is the sum of the rolling resistance forces for all wheels in the form:

$$R_{r_{c,u}} = f_u \cdot G_a \cdot \cos\alpha_u \text{, in daN.} \quad (2)$$

The power required to overcoming the rolling resistance force of a singular vehicle, moving with speed v is given by:

$$P_{r_{c,u,v}} = \frac{v \cdot R_{r_{c,u}}}{360} \text{, in kW.} \quad (3)$$

The force of resistance due to the inclination of the longitudinal road R_p of the vehicle occurs due to the weight component ($G_a \cdot \sin\alpha$) parallel with the road surface (see Fig. 1):

$$R_{p_u} = G_a \sin\alpha_u \text{, in daN,} \quad (4)$$

this is a force of gradient resistance and an active force at the descent of the slope.

Power consumed or received of motor vehicle when driving on ramp/slope with the speed v, is given by:

$$P_{p_{u,v}} = \frac{v \cdot R_{p_u}}{360} \text{, in kW.} \quad (5)$$

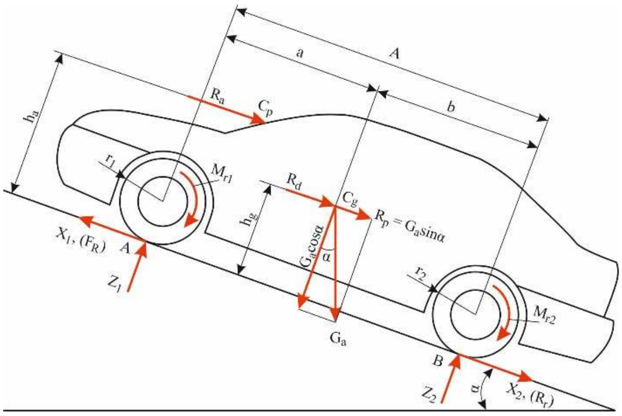

Fig. 1. The scheme of the forces, moments and the reaction forces acting on the vehicle in motion.

The symbols used in Figure 1 refer to: r_1, r_2 - the rolling radius (dynamic radius - r_d) of the wheels at front axle and rear axle; M_{r1}, M_{r2} - resistance of the rolling moments, at the front and at the rear axle; Z_1, Z_2 - normal reaction of the road at the wheels/axles (front and rear); X_1, X_2 - tangential reactions of the road at the front and rear axle; a, b - distance from center of gravity to the front axle respectivelly rear axle; A - wheelbase; h_g - the height of gravity center; h_a - the height of the pressure center where is considered the air resistance force.

The total force of the road resistance R_ψ has the components: the force of rolling resistance R_r and the resistance force due to the longitudinal inclination of the road R_p,

$$R_{\psi_{c,u}} = R_{r_{c,u}} \pm R_{p_u} = G_a \cdot \psi_{c,u} \text{, in daN,} \quad (6)$$

in which $\psi_{c,u} = f_c \cdot \cos\alpha_u \pm \sin\alpha_u$, (+) is used for climbing and (–) descending.

The power required to overcome the total force of the road resistance is given by:

$$P_{\psi_{c,u,v}} = \frac{v \cdot R_{\psi_{c,u}}}{360}, \text{ in kW.} \quad (7)$$

The force of air resistance R_a is given by:

$$R_{a_v} = k_a \cdot S_f \cdot \left(\frac{v_r}{3.6}\right)^2, \text{ in daN,} \quad (8)$$

in which: $S_f \cong k_s \cdot H \cdot E$, where the correction factor k_s is in the range between 0.90...0.95 in the case of passenger cars and 1.05...1.10 in the case of trucks [1, 10, 13, 14]; at the calculation of the speed v_r it take into account the speed v of the vehicle and the wind speed v_w so: if the wind blows in the opposite movement of the vehicle; $v_r = v - v_w$ if the wind blows in the same direction as the movement of the vehicle; $v_r = \sqrt{v^2 + v_w^2 + 2 \cdot v \cdot v_w \cdot \cos\alpha_w}$ if the wind blows at an angle to the longitudinal axis of the vehicle.

The power required to overcoming the air resistance force is given by:

$$P_{a_v} = \frac{v \cdot R_{a_v}}{360}, \text{ in kW.} \quad (9)$$

The force available for acceleration, able to overcome the starting resistance is determined according to:

$$R_{d_{i,j,c,u,v}} = F_{R_{i,j}} - \Sigma R_{ext_{c,u,v}}, \text{ in daN} \quad (10)$$

in which: $\Sigma R_{ext_{c,u,v}} = R_{r_{c,u}} + R_{p_u} + R_{a_{c,u,v}}$.

Depending on the direction and the sense of the wind are to be used different notations $\Sigma R_{ext_{c,u,v}}$, as follows:

- from the front, along the longitudinal axis of the vehicle:
  $\Sigma R_{ext\text{-}f_{c,u,v}} = R_{r_{c,u}} + R_{p_u} + R_{a\text{-}f_{c,u,v}}$;
- from the rear, along the longitudinal axis of the vehicle:
  $\Sigma R_{ext\text{-}r_{c,u,v}} = R_{r_{c,u}} + R_{p_u} + R_{a\text{-}r_{c,u,v}}$;
- lateral, perpendicular to the longitudinal axis of the vehicle:
  $\Sigma R_{ext\text{-}p_{c,u,v}} = R_{r_{c,u}} + R_{p_u} + R_{a\text{-}p_{c,u,v}}$.

The power available for acceleration in certain operating conditions of the vehicle, is given by:

$$P_{d_{i,j,c,u,v}} = P_{R_{i,j}} - \Sigma P_{ext_{c,u,v}}, \text{ in kW} \quad (11)$$

in which: $\Sigma P_{ext_{c,u,v}} = P_{r_{c,u}} + P_{p_u} + P_{a_{c,u,v}}$.

Also are to be used different notations, $\Sigma P_{ext_{c,u,v}}$ depending on the direction and the sense of beating the wind, as follows:

- from the front, along the longitudinal axis of the vehicle: $\Sigma P_{ext\text{-}f_{c,u,v}} = P_{r_{c,u}} + P_{p_u} + P_{a\text{-}f_{c,u,v}}$;
- from the rear, along the longitudinal axis of the vehicle: $\Sigma P_{ext\text{-}r_{c,u,v}} = P_{r_{c,u}} + P_{p_u} + P_{a\text{-}r_{c,u,v}}$;
- lateral, perpendicular to the longitudinal axis of the vehicle:
  $\Sigma P_{ext\text{-}p_{c,u,v}} = P_{r_{c,u}} + P_{p_u} + P_{a\text{-}p_{c,u,v}}$.

2.3. Evaluation of the forces and powers at the the driving wheels, depending on the corresponding gear shifting [1-15]

Taking into account the gear in which the vehicle operate, the force at the driving wheels is determined using the relation [12]:

$$F_{Rvn_{i,j}} = \frac{M_{Rvn_{i,j}}}{r_d}, \text{ in daN,} \quad (12)$$

where in r_d is determined according to the marking of the tires, taking into account the inflation pressure of the wheels according to [1, 5, 9, 10, 13, 14].

The active torque $M_{Rvn_{i,j}}$ at the the driving wheels is determined according to the relationship [12]:

$$M_{Rvn_{i,j}} = 954.92 \cdot 0.377 \cdot \frac{P_{Rvn_{i,j}} \cdot r_d}{vn_{i,j}}, \text{ in daN·m,} \quad (13)$$

in which the power at the the driving wheels $P_{R_{i,j}}$ is given by [1, 5, 9, 10, 12-14]:

$$P_{Rvn_{i,j}} = \eta_t \cdot P_{evn_{i,j}} = \\ = \eta_t \cdot P_{max} \cdot \left[\begin{pmatrix} \alpha_m \\ \alpha'_m \end{pmatrix} \cdot \frac{\frac{vn_{i,j} \cdot i_{t_j}}{0.377 \cdot r_d}}{n_P} + \\ + \begin{pmatrix} \beta_m \\ \beta'_m \end{pmatrix} \cdot \left(\frac{\frac{vn_{i,j} \cdot i_{t_j}}{0.377 \cdot r_d}}{n_P}\right)^2 - \\ - \begin{pmatrix} \gamma_m \\ \gamma'_m \end{pmatrix} \cdot \left(\frac{\frac{vn_{i,j} \cdot i_{t_j}}{0.377 \cdot r_d}}{n_P}\right)^3 \right], \text{ in kW,} \quad (14)$$

in which: the coefficients $\begin{pmatrix}\alpha_m\\ \alpha_m'\end{pmatrix},\begin{pmatrix}\beta_m\\ \beta_m'\end{pmatrix},\begin{pmatrix}\gamma_m\\ \gamma_m'\end{pmatrix}$ depend on the flexibility of the engine and has been determined according to [1, 3, 5, 9, 10, 12-14], between these there are the relationship:

$$\begin{pmatrix}\alpha_m\\ \alpha_m'\end{pmatrix}+\begin{pmatrix}\beta_m\\ \beta_m'\end{pmatrix}-\begin{pmatrix}\gamma_m\\ \gamma_m'\end{pmatrix}=\begin{pmatrix}1\\ 1\end{pmatrix}, \quad (15)$$

The dimensionless coefficients $\alpha_m,\beta_m,\gamma_m$ is used for $vn_{i,j}\le v_{med_j}$, and $\alpha_m',\beta_m',\gamma_m'$ for $vn_{i,j}>v_{med_j}$, where v_{med_j} it is given by the formula [1]:

$$v_{med_j}=0.377\cdot\frac{r_d\cdot n_{med}}{i_{t_j}}, \text{ in km/h}, \quad (16)$$

with $n_{med}=\frac{n_M+n_P}{2}$.

The speed $vn_{i,j}$, corresponding to the gears at various engine speeds n_i, is given by [1, 5, 9, 10, 12-14]

$$vn_{i,j}=0.377\cdot\frac{r_d\cdot n_i}{i_{t_j}}, \text{ in km/h}, \quad (17)$$

where: $i_{t_j}=i_0\cdot i_{cv_j}$, were determined according to [1, 3, 5, 9, 10, 12-14], and the different speeds of the engine n_i are captured between $n_{min}\cong 0.2\cdot n_P$ and $n_{max}\cong 1.1\cdot n_P$, with the relationship:

$$n_i=n_{min}-\frac{n_{max}-n_{min}}{99}\cdot i, \text{ if } i=0...99. \quad (18)$$

The forces at the driving wheels it can be obtained depending on the $vs_{j,s}$ speed, corresponding to the gear shifting:

$$vs_{j,s}=v_{min_j}-\frac{v_{max_j}-v_{min_j}}{88}\cdot s, \text{ if } s=0...88. \quad (19)$$

The minimum and maximum speeds for each gear is determined for a situation where the gear shifting is optimal, the engine operated in the engine speed range between [n_M, n_p], thereby [1, 10, 11, 13, 14]:

$$v_{min_j}=\begin{cases}0.377\cdot\dfrac{n_{min}\cdot r_d}{i_{t_j}}, \text{ if } j=1\\[2ex] 0.377\cdot\dfrac{n_M\cdot r_d}{i_{t_j}}, \text{ if } j\ge 2\end{cases}, \text{ in km/h}, \quad (20)$$

$$v_{max_j}=\begin{cases}0.377\cdot\dfrac{n_p\cdot r_d}{i_{t_j}}, \text{ if } j\le(k-2)\\[2ex] 0.377\cdot\dfrac{n_{max}\cdot r_d}{i_{t_j}}, \text{ if } j=(k-1)\\[2ex] 0.377\cdot\dfrac{n_{lim}\cdot r_d}{i_{t_j}}, \text{ if } j=k\end{cases}, \text{ in km/h}, \quad (21)$$

in which:

$$n_{lim}=\frac{v_{max_e}\cdot i_{t_k}}{0.377\cdot r_d}, \text{ in rot/min}. \quad (22)$$

In this case, expressions (12), (13) and (14) are adapted to the speed $vs_{j,s}$, and thereby:

$$F_{Rvs_{j,s}}=\frac{M_{Rvs_{j,s}}}{r_d}, \text{ in daN}, \quad (23)$$

$$M_{Rvs_{j,s}}=954.92\cdot 0.377\cdot\frac{P_{Rvs_{j,s}}\cdot r_d}{vs_{j,s}}, \text{ in daN·m}, \quad (24)$$

$$P_{Rvs_{j,s}}=\eta_t\cdot P_{evs_{j,s}}=$$

$$=\eta_t\cdot P_{max}\cdot\left[\begin{pmatrix}\alpha_m\\ \alpha_m'\end{pmatrix}\cdot\frac{\dfrac{vs_{j,s}\cdot i_{t_j}}{0.377\cdot r_d}}{n_P}+\begin{pmatrix}\beta_m\\ \beta_m'\end{pmatrix}\cdot\left(\frac{\dfrac{vs_{j,s}\cdot i_{t_j}}{0.377\cdot r_d}}{n_P}\right)^2-\begin{pmatrix}\gamma_m\\ \gamma_m'\end{pmatrix}\cdot\left(\frac{\dfrac{vs_{j,s}\cdot i_{t_j}}{0.377\cdot r_d}}{n_P}\right)^3\right]. \text{ in kW}, \quad (25)$$

where the coefficients $\alpha_m,\beta_m,\gamma_m$ are used for $vs_{j,s}\le v_{med_j}$, and $\alpha_m',\beta_m',\gamma_m'$ for $vs_{j,s}>v_{med_j}$.

3. OBTAINED RESULTS

The intersection of the curves P_R and the absorbed power due to the external resistances ΣP_{ext} that do not depend on the movement character (Fig. 2, Fig. 3) determines the maximum speed of the vehicle that can be obtained in considered road conditions; at this intersection point of the curves (P_R and ΣP_{ext}) is the regime to which the vehicle move from one uniform accelerated motion and the power available for acceleration is zero. At one regime to which the vehicle is moving at a certain speed, the distance between those curves (P_R and ΣP_{ext}) represents the power available for acceleration ($P_d = P_R - \Sigma P_{ext}$) (Fig. 2, Fig. 3).

The curves of powers P_{R_j} which are below the curve ΣP_{ext} characterized that the gears can not be used in those conditions for the vehicle eploitation. In this way resulting acceleration powers P_{d_j} available for each gear (Fig.2,Fig. 3).

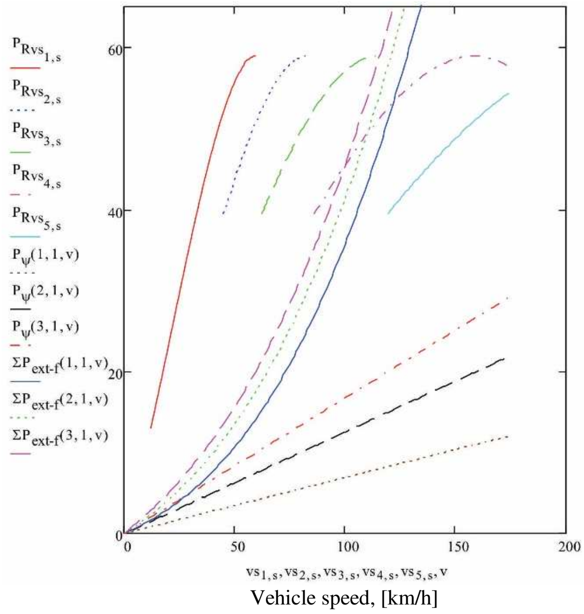

Fig. 2. The power characteristic for different nature and state of the road at a certain longitudinal inclination.

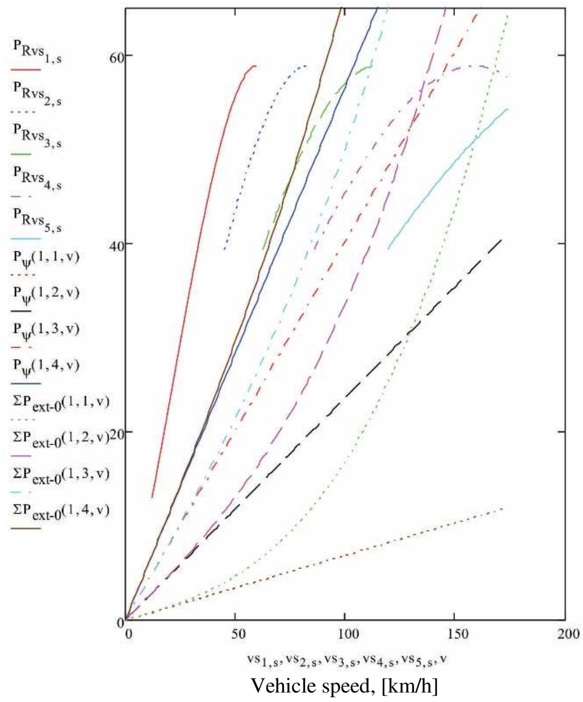

Fig. 3. The power characteristic for different longitudinal inclination of the road and a certain nature and state of it.

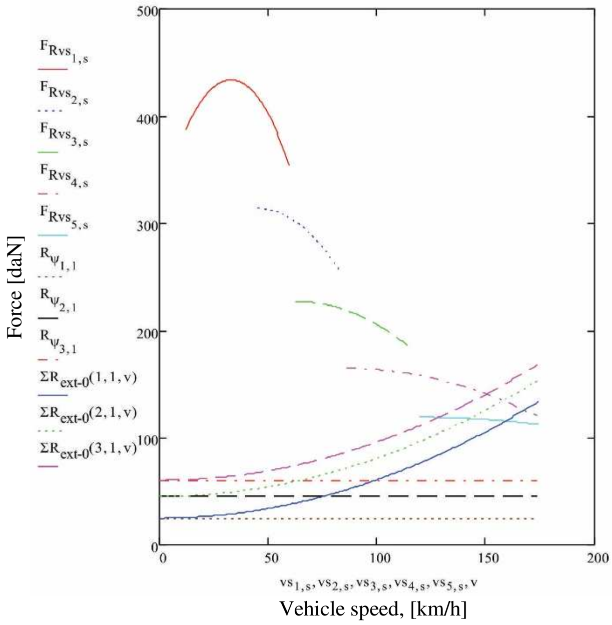

Fig. 4. The traction characteristic for the situation of different nature and state of the road at a certain longitudinal inclination.

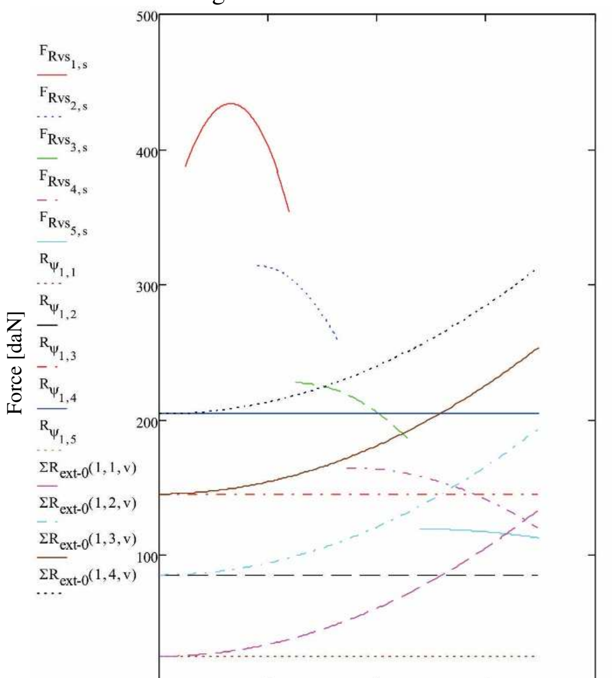

Fig. 5. The traction characteristic for different longitudinal inclination of the road and a certain nature and state of it.

Intersection between the curves F_R and the amount of the external resistances ΣR_{ext}, which do not depend on the movement character, determines the maximum vehicle speed that can be obtained in considered road conditions (Fig.

4, Fig. 5); this point represents the regime to which the vehicle passes from accelerated motion to a uniform one, and the force available for acceleration is zero.

At a certain travel speed of the vehicle, lower than that determined by the intersection of the curves F_R and ΣR_{ext}, the distance between the respective curves (F_R and ΣR_{ext}) represent the power available for acceleration ($R_d = F_R - \Sigma R_{ext}$), able to overcome the resistance at the vehicle starting (Fig. 4, Fig. 5).

The curves of the forces at the wheel F_{R_j} that are under the curve ΣR_{ext} characterizes that these gears may not be used in those operating conditions of the vehicle. In this way results the available forces for acceleration R_{d_j} in each gear (Fig. 4, Fig. 5).

4. CONCLUSIONS

The results obtained can be a support on the study of the vehicle performance, relating to the parameters and the characteristics indices of the vehicle movement with transient acceleration regime, the specific excess forces, dynamic characteristic, parameters start capacity, etc.

Depending on the selfpropelled conditions of the vehicle, taking into account the general equation of motion, which can be determined based on the obtained results, reference may be made to some particular form of it, namely: *moving at full speed* with which the vehicle can move on a horizontal rolling path; *moving on rolling path with maximum longitudinal inclination or on the rolling path with maximum specific resistance*, which is obtained when the full available force is used to overcome the resistance forces related to the type and characteristics road R_ψ; *starting the vehicle from a stop point with maximum acceleration*, which is obtained when the entire force available is used to increase the vehicle speed, situation corresponding to the vehicle starting on horizontal road.

The developed numerical computation model, can be adapted to any type of vehicle in the study and of any operating conditions that need to be captured (different operating conditions of the engine, different dynamic radius of the wheel - these being directly influenced by the pressures of tires inflation, etc.), allowing a comparative study between different vehicles. Also, in the numerical computation model, it can be captured also the different loading situations of the studied vehicles, identifying in this way the influence of the vehicle weight on their performance or on their self propelled ability.

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ALGORITM PENTRU TRASAREA CARACTERISTICILOR DE PUTERE ȘI DE TRACȚIUNE ALE AUTOVEHICULELOR

Rezumat: Cunoaşterea rezistențelor la înaintarea autovehiculelor este necesară pentru evaluarea performanțelor acestora. Mărimea forțelor de rezistență la înaintare și puterile necesare învingerii lor este influenţată de condiţiile de deplasare şi de parametrii constructivi ai autovehiculelor. Rezistențele la înaintarea autovehiculelor, puterile și forțele la roțile motoare, pentru diferitele situații de exploatare luate în considerare, se evaluează prin dezvoltarea unui model de calcul numeric în MathCad care să permită obținerea de rezultate cu interpretare grafică și care să țină seama de diferitele regimuri de deplasare, treapta de viteză utilizată, geometria, natura și starea drumului etc. Astfel, se pot identifica treptele de viteză care pot fi utilizate în diferite situații de exploatare ale autovehiculelor.

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