THE ELECTRIC TRACTION MOTORS BALANCING FOR LOAD TRANSFER EFFECTS COMPENSATION
/
ECHILIBRAREA MOTOARELOR ELECTRICE DE TRACȚIUNE PENTRU COMPENSAREA EFECTELOR TRANSFERULUI DE SARCINĂ

Mihail ANDREI [1], Gabriel POPA[2], Emil TUDOR [3*], Paula ANGHELIȚA[3], Mihai-Gabriel MATACHE[4*]

[1] Doctoral School of FIMM, National University of Science and Technology POLITEHNICA of Bucharest / Romania;
[2] Railway Vehicles Department, National University of Science and Technology POLITEHNICA of Bucharest / Romania;
[3] Renewable Sources and Energy Efficiency Department, National Institute for Research and Development in Electrical Engineering ICPE-CA, Bucharest / Romania;
[4] National Institute for Research and Development in Machines and Installations Designed for Agriculture and Food Industry, INMA Bucharest / Romania;
Tel: +40755015614; E-mail: emil.tudor@icpe-ca.ro
DOI: https://doi.org/10.35633/inmateh-71-25

***Keywords:** load transfer, traction characteristic, adhesion coefficient*

ABSTRACT
The individual drive of the axles of a vehicle produces a reduction of the axle adhesion, implicitly reducing the total traction force of the vehicle. The paper proposes eliminating load transfer effects by using an algorithm to redistribute the traction effort between the tractive axles equipped with electric traction motors. A case study is presented, using the balancing of the electric traction torque for an electric locomotive, using the load transfer effects compensation. The conclusions can be used to maximise the traction of all types of vehicles, such as trailers, hybrid tractors, large harvesters, and Diesel-electric locomotives.

REZUMAT
Acționarea individuală a axelor unui vehicul produce o reducere a aderenței axei, reducând implicit forța totală de tracțiune a vehiculului. Lucrarea propune eliminarea efectelor transferului de sarcină prin utilizarea unui algoritm de redistribuire a efortului de tracțiune între axele de tracțiune echipate cu motoare electrice de tracțiune. Este prezentat un studiu de caz, folosind echilibrarea cuplului de tracțiune electrică pentru o locomotivă electrică, folosind compensarea efectelor transferului de sarcină. Concluziile pot fi utilizate pentru a maximiza tracțiunea tuturor tipurilor de vehicule, cum ar fi autocamioane, tractoare hibride, utilaje agricole mari și locomotive diesel-electrice.

INTRODUCTION
Producing tractive torque at large vehicles implies the use of multiple tractive axles as a solution to overcome the limitations of the tractive effort due to the lack of adherence. Multiple tractive axles are used in trailers, hybrid tractors, large harvesters, and Diesel-electric locomotives. Because of the ease of control, for multiple traction, there is a preferred solution, consisting of independent electric motors for traction connected using a fixed single-gear transmission. A review regarding Electric Traction Motors for Battery Electric and Hybrid Vehicles presented the latest developments in electric traction motors and provided an efficient overview of the state-of-the-art motor designs, performances, technical limitations, as well as future concepts and trends (*Krings and Monissen, 2020*). The main topologies of the electric motors used for traction are the Direct-Current machines and the Alternative-current machines (*Nategh et al., 2020*). The AC machines are asynchronous machines and synchronous machines. Synchronous machines use permanent magnets PMSM or variable reluctance motors SRM (*Widmer et al., 2015*).

Regarding the independent tractive axle drive, a practical active traction control system is proposed, according to the wheel slip state of the front and rear axles, and the dynamic transfer of torque between axles is realised to maintain the vehicle propulsion power (*Wang et al., 2023*). From the papers involved in independent axle driving, it can be mentioned the analysis of *Nussupbek et al., (2023*), regarding a proposed phenomenon of redistribution of a 4x4 vehicle traction forces, by considering front and rear drive wheels separately as modular ones with reduction of all parameters to equation for each wheel separately.
The hydraulic system of the tractor hitch has the characteristics of a large load and complex working environment. A differential and integral sliding mode adaptive controller is designed for the hydraulic transmission system (*Liu et al, 2023*).

The dependence of the force of draft force on the square of the working speed is found in most of the literature (*Cardei et al., 2019*). The modelling of the running system pressure on the soil depending on the structural parameters of the tractors according to *Golub et al., (2023*) is important for the characterisation of the traction system of the vehicle, especially during the normal operation of agricultural vehicles while sliding on the soil.

When assessing the adherence of the tractive wheels to the ground (soil, road, rail), the adherence coefficient is a very important figure, which characterises the maximum possible torque which can be applied to the tractive axle. A new approach to estimating vehicle tire forces and road maximum adherence is presented by *Villagra et al., (2010*). A fast method for the computation of the wheel-rail forces, suitable for the investigations of problems regarding traction control and axle drive dynamics and their interaction with a vehicle's dynamic behaviour is presented in *Polach, (2001*). It is well-known that the adhesion coefficient between wheel and rail is widely variable, which has an influence on the running stability of vehicles, particularly the performance of driving and braking of the rail vehicles (*Zhao et al., 2018*). Prevention measures against adherence loss are necessary, and a new anti-slip control approach for four-wheel independent-drive electric vehicles based on the energy method is proposed, making full use of the distribution of motor energy between the body and the wheels during vehicle turning, being able to adjust the driving torque of each wheel (*Ci et al., 2023*).

Load transfer between tractive axles during traction is described in the comprehensive review of the current technologies in practice and future research trends in traction motors developed for high-speed railways, starting with Multiphysics design, including electromagnetic, mechanical, and thermal perspectives, with a special focus on understanding the use of the distributed traction system for high-speed railway system and related motor technology (*Paul et al., 2022*). The drive torque for each motor can be performed independently for the distributed drive, and the torque distribution can be optimised according to the axle load (*Gao et al., 2021*).

When speaking of multiplying the tractive force of a vehicle, the best example can be found in railway traction, where, based on the limited adherence of the wheel-to-rail system, multiple tractive axles must be used. A typical traction system consists of one or more locomotives and a train formed with several wagons. For locomotives, a two-bogie tractive solution with a total of 4 or 6 tractive axles is used. The Diesel-electric locomotives use the 4-tractive axle system and the all-electric locomotives use both 4-axle and 6-axle solutions. For large freight trains towing, multiple locomotives can be used according to *Sun et al., (2017*), in tandem operation, in independent operations and in "push-pull" operation. The experience was used, lately, in the Electric Multiple Units (EMU) passenger trains, where the traction system developed is located in the tractive coaches, similar to the underground trains. An example of improving the energy efficiency of rail vehicles equipped with multi-motor electrical traction when operating with partial load is shown in *Zarifyan et al., (2019*). Electronic control of multiple traction units used in modern AC high adhesion locomotives are very complex mechatronic systems and can be designed with two alternative traction topologies of either bogie or individual axle controls (*Spiryagin et al., 2017*). For proper acceleration or braking of the wheel, the driving torque should be kept near the adhesive level for the desired anti-slip control *(Isharat et al., 2016*). Depending on the type of drive system used, the distribution of the forces and moments generated by the drive equipment at the axles is different (*Arsene et al., 2018*).

The present paper will perform a case study for the two-axle bogie locomotive traction system, starting with an in-depth analysis of the axle load distribution, a study of the influence of load transfer on the traction characteristics of locomotives, pointing out the mechanical characteristics with limited grip for axle depending on the position of each axle. The original contribution of the authors is underlined by the presented algorithm of redistribution of the prescribed tractive force among the tractive axles for maximising the tractive force, applied for the case of torsion of the locomotive which generated a 15% unbalance between tractive axles.

MATERIALS AND METHODS

Calculation of axle load redistribution in the case of two-axle bogie vehicles

The case of a locomotive on two independent bogies having the *B0-B0* formula of axles will be analysed. Each of the two bogies transmits the traction forces to the box through a pivot. The calculation of the axle load redistribution is done in the following simplifying hypotheses:

- the bogie frame and the locomotive chassis are rigid assemblies that do not deform when the traction forces are applied or under their weight;
- traction motors generate equal traction forces;
- the forces of gravity and traction are evenly distributed on the bogies and the axles of the locomotive;

- the rolling resistance forces of the two bogies are neglected;

Symbol $F0$ represents the traction force at the locomotive hook and F represents the traction force corresponding to each axle.

In traction mode, two horizontal forces act on the locomotive:

- Traction force applied to the knuckle $F0$, to each driving axle having a force $F=F0/n$, $n = 4$ (number of driving axles);
- Resistant force T applied by the train to the traction hook.

These two forces form a torque that tends to unload the front axles and load the rear axles. In the absence of traction force, the axle load is $G/4$, and G is the total weight of the locomotive (equal in this case to the adherent weight).

In traction mode, due to the effect of the wiring torque, the loads on the four axles change, the values being denoted by: $G1$, $G2$, G_3 and $G4$. The variations of the axle loads will be equal to:

$$\Delta G_1 = \frac{G}{4} - G_1;\ \ \Delta G_2 = \frac{G}{4} - G_2;\ \ \Delta G_3 = \frac{G}{4} - G_3\,;\ \ \Delta G_4 = \frac{G}{4} - G_4 \tag{1}$$

In the case of axle unloading, the ΔG values are positive, and in the case of overloading, the ΔG values are negative. The evaluation of the effect of the wiring torque is done by calculating separately the wiring of the box and the wiring of the bogies and then the total effect will be the sum of these two cumulative effects (superposition).

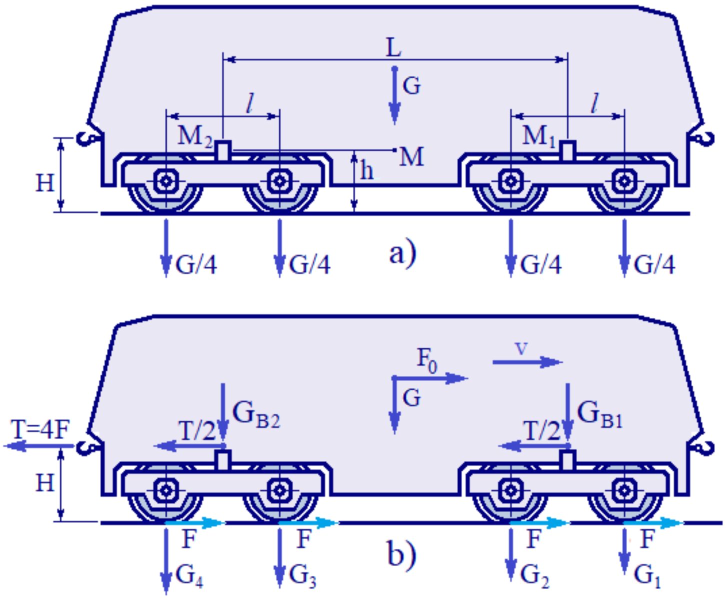

Fig. 1 - Forces acting on the motor vehicle in bogies

a) without traction; b) in traction mode

Two pairs of forces acting in equilibrium act on the locomotive box:

- The torque generated by the resistant force T (applied to the hook at height H above the upper rail level) and the two traction forces $T/2$ applied by bogies to the two pivots of the locomotive (forces applied at height h above the upper level of the rail). The torque generated by these forces tends to rotate the locomotive box in a counterclockwise direction;
- The torque generated by the two reactions at components G_{B1} and G_{B2} of the gravitational force G of the locomotive box applied to the supports of the pivots at a distance L. This torque tends to rotate the locomotive box in a clockwise direction;

Equating the moments of these two torques acting on the box, torques calculated concerning the point M located in the middle of the distance between the two pivots at the height h from the upper level of the rail, the equation is obtained:

$$T(H-h) = (G_{B2} - G_{B1}) \cdot \frac{L}{2} \tag{2}$$

This equation establishes the equality of the modules of the couples of those two moments of opposite directions. In the absence of traction, the two components of the weight force G are equal, the weight of the locomotive being evenly distributed over the two bogies.

In traction, a redistribution of the weight force occurs on the two bogies with the value ΔG_C.

$$G_{B1} = \frac{G}{2} - \Delta G_C \quad and \quad G_{B2} = \frac{G}{2} + \Delta G_C \tag{3}$$

Result:

$$\Delta G_C = \frac{G_{B2} - G_{B1}}{2} \tag{4}$$

From the equal relation of the moments of the couples acting on the box is obtained:

$$\Delta G_C = \frac{G_{B2} - G_{B1}}{2} = T \cdot \frac{H-h}{L} \tag{5}$$

The amount ΔG_C represents the effect of the box load transfer in the redistribution of loads on axles and bogies. By replacing the ΔG_C the expressions for the load of the box on the two bogies are obtained:

$$G_{B1} = \frac{G}{2} - T \cdot \frac{H-h}{L} \tag{6}$$

$$G_{B2} = \frac{G}{2} + T \cdot \frac{H-h}{L} \tag{7}$$

The evaluation of the load redistribution on the two axles of a bogie is made considering the two bogies loaded by the box with the loads G_{B1} and G_{B2} respectively. In traction mode, the loads on the four axles are G_{B1}, G_{B2}, G_{B3} and G_{B4}. For each bogie, the moment generated by the traction forces of the two axles is equal to the moment generated by the redistribution of the loads on the two axles:

$$\frac{T}{2}h = (G_2 - G_1)\frac{l}{2} \quad and \quad \frac{T}{2}h = (G_4 - G_3)\frac{l}{2} \tag{8}$$

Substituting in the equilibrium relation of the moments for each of the two bogies results:

$$\Delta G_{OB} = \frac{G_2 - G_1}{2} = \frac{G_4 - G_3}{2} = \frac{T}{2} \cdot \frac{h}{l} \tag{9}$$

Using G_B as the bogie's weight, in the absence of traction effort, the static load on the axle is:

$$G_0 = \frac{G}{4} + \frac{G_B}{2} \tag{10}$$

After applying the traction force T, the loads on the four axles will be:

$$G_1 = \frac{G_B + G_{B1}}{2} - \Delta G_{OB} \tag{11}$$

$$G_2 = \frac{G_B + G_{B1}}{2} + \Delta G_{OB} \tag{12}$$

$$G_3 = \frac{G_B + G_{B2}}{2} - \Delta G_{OB} \tag{13}$$

$$G_4 = \frac{G_B + G_{B2}}{2} + \Delta G_{OB} \tag{14}$$

Replacing expressions for ΔG_{OB}, G_{B1} and G_{B2} is obtained:

$$G_1 = \frac{G}{4} + \frac{G_B}{2} + \frac{T}{2} \cdot \left(-\frac{H-h}{L} - \frac{h}{l}\right) \tag{15}$$

$$G_2 = \frac{G}{4} + \frac{G_B}{2} + \frac{T}{2} \cdot \left(-\frac{H-h}{L} + \frac{h}{l}\right) \tag{16}$$

$$G_3 = \frac{G}{4} + \frac{G_B}{2} + \frac{T}{2} \cdot \left(+\frac{H-h}{L} - \frac{h}{l}\right) \tag{17}$$

$$G_4 = \frac{G}{4} + \frac{G_B}{2} + \frac{T}{2} \cdot \left(+\frac{H-h}{L} + \frac{h}{l}\right) \tag{18}$$

Unloading the 4 axles ΔG_i the index i representing the axle number ($i=1...4$) is equal to:

$$\Delta G_i = G_0 - G_i \ (where\, i = 1 \ldots 4) \tag{19}$$

$$\Delta G_1 = \frac{T}{2} \cdot \left(+\frac{H-h}{L} + \frac{h}{l}\right) \tag{20}$$

$$\Delta G_2 = \frac{T}{2} \cdot \left(+\frac{H-h}{L} - \frac{h}{l}\right) \tag{21}$$

$$\Delta G_3 = \frac{T}{2} \cdot \left(-\frac{H-h}{L} + \frac{h}{l}\right) \tag{22}$$

$$\Delta G_4 = \frac{T}{2} \cdot \left(-\frac{H-h}{L} - \frac{h}{l}\right) \tag{23}$$

The forces generated by the motor-transmission system also contribute to the redistribution of axle loads and apply vertical forces Z on the drive axle, the values of which are given by the relations (24)-(26):

$$Z = F \cdot \frac{D}{2b} \quad \text{for the semi-suspended motor;} \tag{24}$$

$$Z = F \cdot \frac{D}{2b}\left(1 + \frac{1}{i}\right) \quad \text{for the suspended motor with the semi-suspended gear;} \tag{25}$$

$$Z = 0 \quad \text{for fully suspended motor and gear.} \tag{26}$$

where D is the diameter of the drive wheels, b is the distance in the horizontal direction between the axle axis and the point of support of the motor on the bogie frame and *i* is the gear ratio of the gear. These vertical forces produce a variation of the axle load due to the motor-reduction gear system equal to:

$$\Delta G_{OM} = Z \tag{27}$$

Expression of ΔG_{OM} can be written as:

$$\Delta G_{OM} = \pm F \cdot \frac{D}{2b} \cdot \lambda \tag{28}$$

where the coefficient λ depends on the type of motor suspension and gearbox:

$\lambda = 1$ for the semi-suspended motor; (29)

$\lambda = 1 + \frac{1}{i}$ for the suspended motor with the semi-suspended gear; (30)

$\lambda = 0$ for fully suspended motor and gear. (31)

The general expression of the load on the drive axles can be given in the form:

$$\Delta G_i = \frac{T}{2} \cdot \left(\pm \frac{H-h}{L} \pm \frac{h}{l} \pm \frac{D}{4b} \cdot \lambda\right) \quad (32)$$

This relationship highlights the three components that unload the axles of the locomotive in traction mode:

- the component represented by the term *+/-(H-h)/L* is the component given by the locking of the locomotive box. This term appears with the plus sign for the front bogie axles (bogie no.1) and with the minus sign for the rear bogie axles (bogie no.2);
- the component represented by the term *+/- h/l* represents the component given by the load transfer of the bogie under which the axle is mounted. This term appears with the plus sign if the axle is mounted in the front of the bogie (axles no.1 and no.3 respectively) and with the minus sign if the axle is mounted in the back of the bogie (axles no.2 respectively no.4).
- the component represented by the term *+/- D λ/4b* represents the component given by the force generated by the motor-reduction system. This term appears with the plus sign if the traction motor is placed in front of the axle (the axle is unloaded) and with the minus sign if the traction motor is behind the axle it drives (the axle is overloaded). In electric braking mode, the signs are reversed.

The influence of load transfer on the traction characteristics of locomotives

The redistribution of loads on the locomotive axles under the action of the coupling torques and the forces exerted on the drive axle by the traction gear have negative effects on the traction force that can be developed by the unloaded axles.

In the case of locomotives that have bogies in which the axles are operated in groups, (single-motor bogies) the traction force is automatically redistributed only between the axles of the same bogie. In this case, only the box wiring is manifested, which has a relatively low effect (max. 4% of the load on the bogies).

Locomotives with individual drive axles cannot make full use of the weight due to the tendency of the unloaded axles to skid.

The relationship gives the maximum traction force that a drive axle can develop:

$$F_{max} = \psi(v) \cdot (G_0 - \Delta G) \quad (33)$$

Where $\psi(v)$ is the speed-dependent axle adhesion coefficient.

The dependence of the velocity adhesion coefficient is approximated by parabola or hyperbola arcs, one of the commonly used formulas being:

$$\psi(v) = \frac{7.5}{v+44} + 0{,}161 \quad (34)$$

As previously shown, the unloading of an axle in traction or electric braking mode is given by the relation:

$$\Delta G = 2 \cdot F \cdot \left(\pm \frac{H-h}{L} \pm \frac{h}{l} \pm \frac{D}{4b} \cdot \lambda\right) = F \cdot \varphi \quad (35)$$

where:

$$\varphi = 2 \cdot \left(\pm \frac{H-h}{L} \pm \frac{h}{l} \pm \frac{D}{4b} \cdot \lambda\right) \quad (36)$$

For $\varphi>0$ the axle is unloaded and $\varphi<0$ the axle is overloaded.

By replacing the Φ result:

$$F_{max} = \psi(v) \cdot (G_0 - F_{max} \cdot \varphi) \quad (37)$$

$$F_{max} = \frac{\psi(v)}{1+\psi(v)\cdot\varphi} \cdot G_0 = \eta(v) \cdot G_0 \quad (38)$$

where:

$$\eta(v) = \frac{\psi(v)}{1+\psi(v)\cdot\varphi} \quad (39)$$

It is obvious that:

$\eta(v) < \psi(v)$ if $\varphi > 0$ (unloaded axle) (40)

$\eta(v) > \psi(v)$ if $\varphi < 0$ (overloaded axle); (41)

$\eta(v) = \psi(v)$ if $\varphi = 0$. (42)

The drive axle subjected to unloading behaves as if it were running with a low grip, and the overloaded axles behave as if they were running with an increased grip. In the graph in Figure 2, the family of curves was drawn $\eta(v)$ for the usual values of axle loads $(-0.20 \leq \varphi \leq 0.20)$.

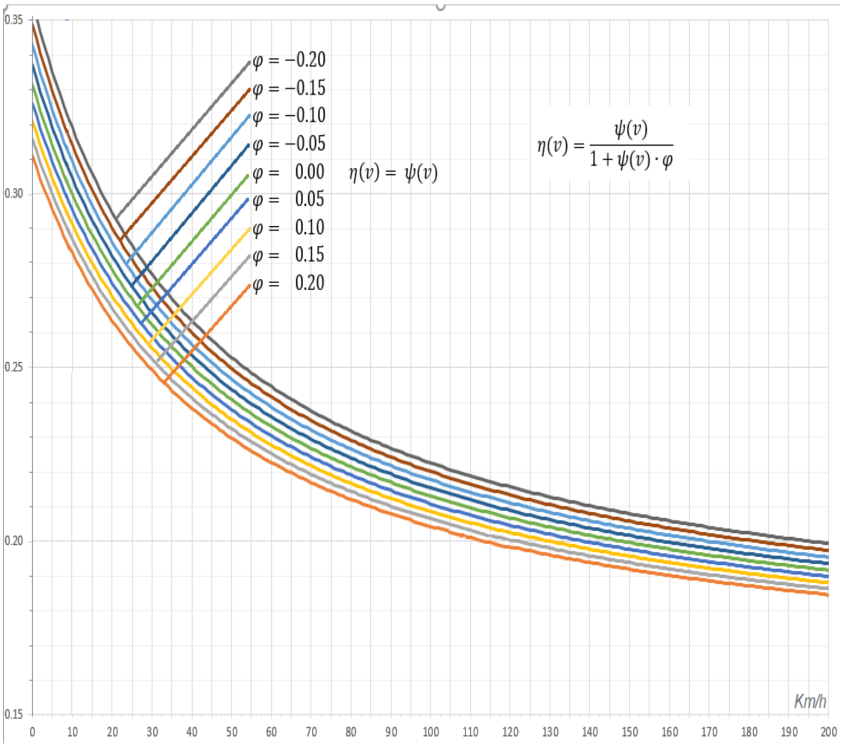

Fig. 2 - Calculation of adhesion limits according to the degree of unloading or loading the drive axle

In Figure 2 it can be observed that, in the absence of load transfer limitation measures, the limit of adhesion of the unloaded axles is considerably reduced, significantly diminishing the performance of the locomotive.

F(v) limited grip characteristics for drive axles depending on the position of each axle

Next, the traction characteristics $F(v)$ will be constructed for each drive axle affected by the wiring, depending on the position of the axle under the locomotives. For clarity, it will be exemplified on a locomotive with two bogies, each bogie having two axles, the example can be easily generalized for other types of locomotives.

Subsequently, based on the characteristics of each axle affected by the load transfer, the actual characteristic $F(v)$ of the locomotive will be constructed under the influence of the load transfer for different traction motor control systems.

The traction characteristic $F(v)$ for a single-drive axle has the following limits:

- On the right side it is limited by the maximum speed of the locomotive. This speed is mainly due to the maximum speed allowed by the rotors of the traction motors but also by a multitude of other factors such as suspension type, brake type, etc.
- The central part is limited by the maximum power that the traction motor can provide to the crankshaft;
- In the upper part the characteristic is limited by the adhesion and the adhesion is influenced by the load transfer ΔG_i.
- Taking into account the relations expressing the axle discharges ΔG_i calculated in the previous chapter and the fact that the values of the discharges given by the box load transfer are lower compared to the discharges given by the bogie load transfer, there is the following order of amplitude of these discharges:

$$\Delta G_4 < \Delta G_2 < 0 < \Delta G_3 < \Delta G_1 \tag{43}$$

Axles 1 and 3 will be unloaded and axles 2 and 4 will be overloaded. There will be the same order for the coefficients φ_i.

$$\varphi_4 < \varphi_2 < 0 < \varphi_3 < \varphi_1 \tag{44}$$

When constructing characteristic *F(v)*, the appearance of the adhesion limit curves in Figure 2 shall also be taken into account for the various values and signs of φ_i.

Using this demonstration, the characteristics *F(v)* for each axle will have the appearance of Figure 3.

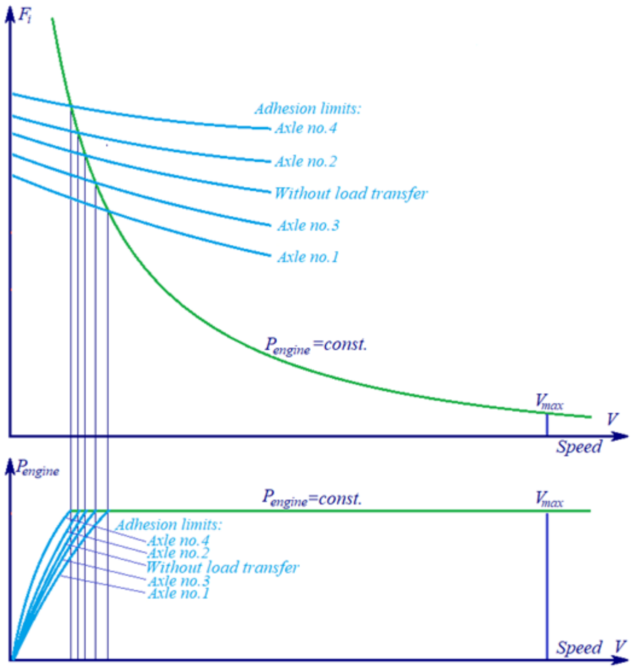

Fig. 3 - Characteristics F (v) and P (v) for each axle with the adhesion limits given by the wiring

In the case of locomotives for which the individual adjustment of the traction motors is performed, an algorithm of integral use of the adhesion will be proposed, even in the presence of load redistributions between the motor axles. The algorithm aims to compensate for the limitations caused by the unloading of the axles with the additional traction force available on the axles loaded as a result of the load transfer.

This is how the algorithm works:

- An order is given to increase the traction force of the locomotive. If no motor has slipped, it is further ordered to increase the traction effort.
- If a starting slip is detected on one of the motors, then that motor will enter the force limit at the grip limit. To compensate for the limitation of the traction force on the traction motor, the traction force is increased in the same way as for the other three motors which will uniformly take over the traction force deficit caused by the limitation produced by the traction motor.
- The traction force is further increased for non-slip axle.
- If another motor with a tendency to skid is detected, then it will also enter the force limitation and the traction force will be uniformly increased for non-slip axle.

The logic diagram for the implementation of this algorithm is shown in Figure 4.

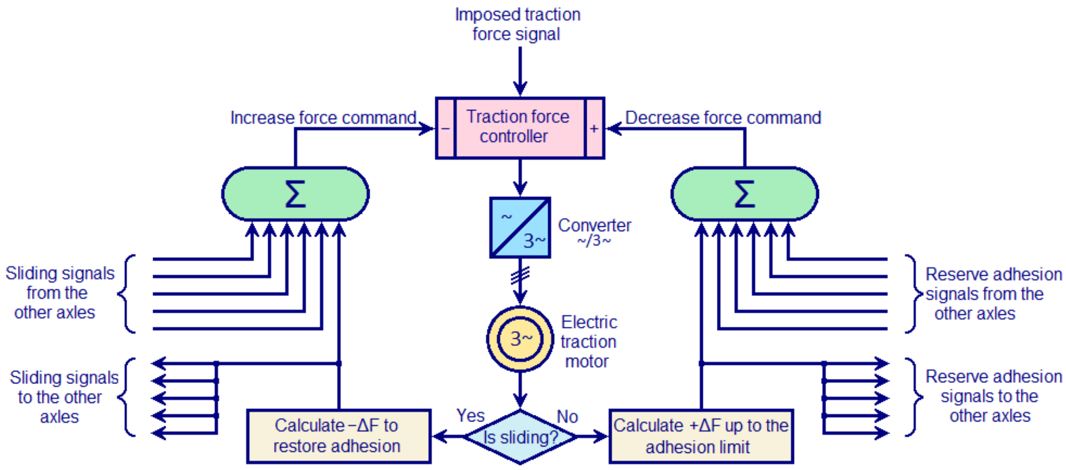

Fig. 4 - Scheme for the implementation of the algorithm for redistribution of traction forces on the loaded axles

For the efficient operation of this method in compensating the effects of load transfer, the redistribution of traction forces must be done equally on all non-slip axles. Any overloads to which the traction motors and the electric power equipment are subjected during this redistribution of traction forces will have minimum, tolerable values. Otherwise, there will be a risk of overcurrent or overvoltage protection coming into action, which will nullify these measures for the efficient use of locomotive adhesion.

RESULTS

Traction simulation software program under the influence of load transfer on locomotives

To visualize the traction characteristics under the influence of load transfer and how the load transfer influences the performance of the locomotive, a software code was written (named Sim Cabraj.exe) that simulates the behaviour of the drive axles and the locomotive as a whole, taking into account the negative effects of load transfer. The presented program calculates and represents graphically the traction characteristics of the locomotives taking into account the effect of the load transfer on the adhesion and the different solutions adopted to limit it.

The graphical representation of the traction characteristics starts from the calculation of the characteristics *F(v)* for each axle. The calculation of the characteristics *F(v)* of each axle is made according to the effects of the load transfer on each axle.

From the traction characteristics calculated for each axle, the traction characteristics of the locomotive are obtained by calculating the sum of the traction forces of the axles for a given speed. The calculation of these sums of the traction forces of the axles is made taking into account the limitations given by the constructive variant of the locomotive: the electrical diagram and the measures taken to reduce the load transfer and its effects.

The traction characteristics for the most used variants of locomotives were calculated and plotted:

- Locomotives with group adjustment of traction motors with anti-slip that act simultaneously on all axles;
- Locomotives with independent adjustment of traction motors, each axle having its anti-slip system;
- The variant proposed by the locomotive with independent adjustment of the traction motors, in which, in case of a slip, it achieves the automatic redistribution of the traction force on the other axles that have the adhesion ensured due to the load transfer (overloaded axles).

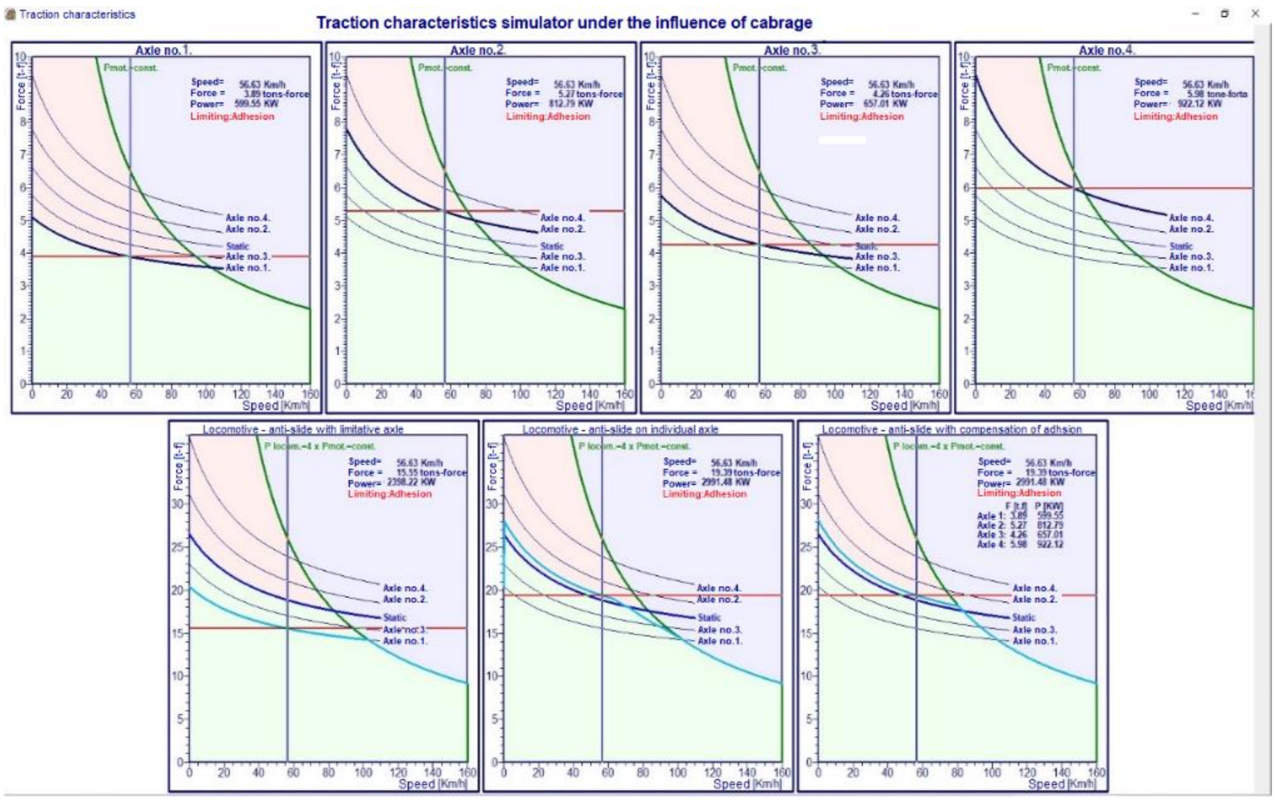

Fig. 5 - The main SimCabraj.exe application window.

After launching the program, two rows of diagrams are displayed in the main application window. The diagrams on the top row represent the traction characteristics for each driving axle of the locomotive. At the bottom row are three diagrams of traction characteristics for each of the three types of studied locomotives. The three variants of locomotives analysed can thus be easily compared, concluding their advantages and disadvantages. The following curves are drawn on each diagram:

- Constant power curve - green colour.
- Adhesion limit curve - dark blue, corresponding to the axle.

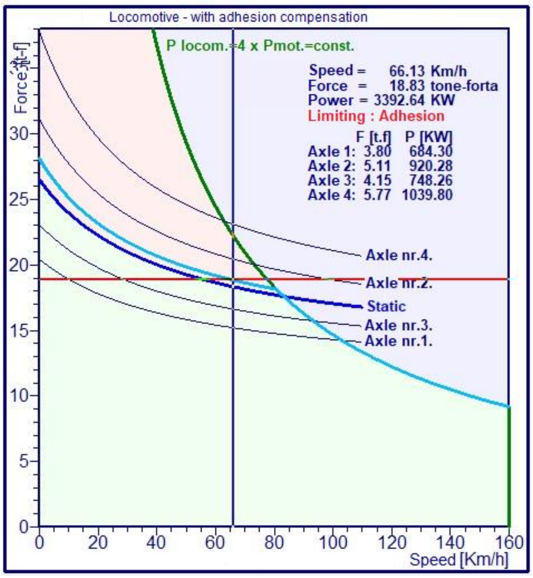

Fig. 6 - The Force-Speed characteristic after redistribution of traction efforts according to the algorithm

For comparison, the adhesion limits for all other axles were drawn with a thin line. With a thin blue line, the adhesion limit was represented in the absence of load transfer. For locomotives, (lower row) in light blue is the actual traction characteristic of the locomotive. The first two curves delimit three differently coloured areas:

- The light green area under these two curves is the area where the locomotive can operate normally;
- The red area above the grip curve is the slipping area;
- The blue area above the constant power curve is the overload operating area.

The values characteristic of the indicated cursor point (speed, traction force, power) are displayed in the upper right part of each diagram. By moving the cursors on different areas of the diagrams, following the way the traction characteristics are constructed and the implications of the three constructive variants on the performance of the locomotive can be evaluated.

CONCLUSIONS

The diagrams generated by the presented software show that this algorithm manages to avoid slipping the locomotive axles as a result of the balanced load transfer while keeping the traction characteristics of the locomotive unaltered. By applying this algorithm, the harmful effects of axle slipping are avoided and the power of the locomotive can be used in full. Using the proposed algorithm in controlling the torque commands for each independent drive, the unloaded axle motors will gradually enter the force limitation regime, and with the other motors, it will be possible to go beyond the normal adhesion limit, these being overloaded as a result of the load transfer. By doing so, it is theoretically possible to fully compensate for the load transfer, thus the locomotive operates practically with maximum adhesion.

ACKNOWLEDGEMENT

This work has been funded by the European Social Fund from the Sectorial Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Training of PhD students and postdoctoral researchers to acquire applied research skills - SMART", Contract no. 13530/16.06.2022 - SMIS code: 153734. Part of the work was supported by MCID within Nucleu Program 42N / 2023, project number PN23140101, and by contract 25PFE/2021.

REFERENCES

[1] Arsene, S., Sebesan, I., Popa, G., Gheti, M.A., (2018), Considerations on studying the loads on the motor bogie frame, *IOP Conference Series: Materials Science and Engineering,* Volume 400, Issue 4, doi:10.1088/1757-899X/400/4/042003;

[2] Cardei P., Muraru S.L., Sfiru R., Muraru V, (2019) General structure of tillage draft force. Consequences in experimental and applicative researches, *INMATEH – Agricultural Engineering*, Vol. 59, No. 3 / 2019, ISSN 2068 – 2239, DOI:/10.35633/inmateh-59-28;

[3] Guangzong Gao; Jixin Wang; Tao Ma; Yunwu Han; Xihao Yang; Xuefei Li; (2021). Optimisation strategy of torque distribution for the distributed drive electric wheel loader based on the estimated shovelling load, *Vehicle System Dynamics*, Volume 60, 2022, Issue 6, Pages 2036-2054, DOI:10.1080/00423114.2021.1890153;

[4] Golub, G., Chuba, V., Achkevych, V., Krushelnytskyi, V., Tsyvenkova, N., (2023), Modelling of the running system pressure on the soil depending on the structural parameters of the tractors, *INMATEH - Agricultural Engineering*, Vol. 69, No.1 / 2023, https://doi.org/10.35633/inmateh-69-34;

[5] Ishrat, T., Ledwich, G., Vilathgamuwa, M., Borghesani, P., (2016), Wheel slip control based on traction force estimation of electric locomotives, *2016 Australasian Universities Power Engineering Conference (AUPEC)*, Brisbane, QLD, Australia, pp. 1-6, doi: 10.1109/AUPEC.2016.7749331;

[6] Krings, A., Monissen, C., (2020) Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles, *2020 International Conference on Electrical Machines (ICEM)*, Gothenburg, Sweden, pp. 1807-1813, DOI: 10.1109/ICEM49940.2020.9270946;

[7] Changing LIU, Jinheng GU, Xin DU, Chengwen LIU, Yuefeng DU, Enrong MAO, Differential and integral sliding mode adaptive control algorithm for draft and position integrated control of electro-hydraulic hitch in agricultural tractor, *INMATEH – Agricultural Engineering*, Volume 70, No. 2 / 2023, ISSN 2068 – 2239, DOI:/10.35633/inmateh-70-36;

[8] Ci Longtao, Yan Zhou, and Dejun Yin, (2023) An Anti-Skid Control System Based on the Energy Method for Decentralized Electric Vehicles, *World Electric Vehicle Journal*, vol 14, no. 2: 49. DOI:10.3390/wevj14020049;

[9] Nategh, S., Boglietti, A., Liu, Yujing, Barber, D., Brammer, R., Lindberg, D., Aglen, O., (2020) A Review on Different Aspects of Traction Motor Design for Railway Applications, *IEEE Transactions on Industry Applications*, vol. 56, no. 3, pp. 2148-2157, DOI: 10.1109/TIA.2020.2968414;

[10] Nussupbek, Zh.T., Bekenov, T.N., Sattinova, Z.K., Beisenbi, M.A., Tassybekov, Zh.T., (2023) Substantiation of methods for calculation of traction forces redistribution indicators on modular front and rear wheels of the vehicle (4X4), *Transportation Engineering* Volume 13, September 2023, 100193, DOI:10.1016/j.treng.2023.100193;

[11] Paul S., Pil-Wan Han, Junghwan Chang, Yon-Do Chun, Jae-Gil Lee, (2022), State-of-the-art review of railway traction motors for distributed traction considering South Korean high-speed railway, *Energy Reports* 8 (2022) 14623–14642, DOI: 10.1016/j.egyr.2022.10.411

[12] Polach O., (2001), Influence of Locomotive Tractive Effort on the Forces Between Wheel and Rail, *Vehicle System Dynamics* Supplement 35, pp. 7-22, Zwets & Zeitlinger

[13] Spiryagin, M., Wolfs, P., Cole, C., Stichel, S., Mats B, Plöchl M., (2017), Influence of AC system design on the realisation of tractive efforts by high adhesion locomotives, *Vehicle System Dynamics*, DOI: 10.1080/00423114.2017.1308522

[14] Yannan Sun; Tong Zhang; Changxian Li, (2017), Study and construction of traction control system of EMUs, *36th Chinese Control Conference (CCC)*, Dalian, China, pp. 9972-9976, ISSN: 1934-1768, DOI: 10.23919/ChiCC.2017.8028948.

[15] Villagra J, d'Andréa-Novel B, Fliess M, Mounier H., (2010) A diagnosis-based approach for tire–road forces and maximum friction estimation, *Control Engineering Practice* Volume 19, Issue 2, Pages 174-184, ISSN: 0967-0661, https://doi.org/10.1016/j.conengprac.2010.11.005

[16] Zarifyan, A. Zarifyan, N. Grebennikov, T. Talakhadze, N. Romanchenko and A. Shapshal, (2019), Increasing the Energy Efficiency of Rail Vehicles Equipped with a Multi-Motor Electrical Traction Drive, *26th International Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED)*, Moscow, Russia, 2019, pp. 1-5, DOI: 10.1109/IWED.2019.8664283

[17] Kaihui Zhao, Peng Li, Changfan Zhang, Jing He, Yanfei Li, Tonghuan Yin, (2018), Online Accurate Estimation of the Wheel-Rail Adhesion Coefficient and Optimal Adhesion Antiskid Control of Heavy-

Haul Electric Locomotives Based on Asymmetric Barrier Lyapunov Function, *Journal of Sensors*, vol. 2018, Article ID 2740679, 12 pages. https://doi.org/10.1155/2018/2740679;
[18] Wang, Junnian, Gao, Shoulin, Lv, Siwen, Sun, Jie, Sun, Wen, Yang, Zhihua, (2023), Practical active traction control for independent-wheel-drive electric vehicle based on slip-ratio threshold determination, *Asian J Control* 25, pp. 3524–3540, ISSN1561-8625, DOI: 10.1002/asjc.3034;
[19] Widmer, J., Martin, R., Kimiabeigi, M., (2015) Electric vehicle traction motors without rare earth magnets, *Sustainable Materials and Technologies* 3, pp. 7–13, ISSN: 2214-9937, DOI: 10.1016/j.susmat.2015.02.001;