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LOAD ANALYSIS OF A MULTI-MOTOR PROPULSION SYSTEM

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Abstract. The management of the load from several electric motors that integrate a propulsion system on a vehicle is a complex problem, primarily involving the stability of the vehicle, especially if the electric motors are independently distributed on vehicle axles or wheels. The management of the participation of each motor in achieving the traction torque, on the other hand, leads to energy efficiency and performance. It is necessary to manage the behavior of each motor for the entire operational area, since it contributes to the energy efficiency of the electric powertrain. In this context, the paper aims to present a synthesis of some research carried out by the author in this field.

1. INTRODUCTION

Electric vehicles are not a novelty, having been known for more than a century [1]. The last evolution in motor development and power electronics has led to a better understanding of electric motor usage in propulsion systems and opened perspectives for continuous improvement in searching for better efficiency in the transformation from electric to mechanical energy. There is a question regarding the usage of electric multiple motors in a powertrain. Several answers support the idea of electric multi-motor systems. It is easier to implement such powertrains with electric motors because of their dimensions, the possibility of control and power transmission by wires, and consequently, the physical distribution of such systems in a vehicle, without the constraint to place all components in a given volume. It leads to approaching the mechanical power production to the wheels, reducing the mechanical transmissions, and power losses in such transmissions, and creating possibilities for an improved efficiency of a multi-motor powertrain than a single motor powertrain [2].

It is important to manage the involvement of each powertrain motor in the torque production, as it also contributes to the performance [3-5] of the powertrain. The load allocation for the powertrain efficiency perspective is based on the knowledge of the system components in each operating point in order to decide the involvement of each motor in the torque production. Analytic calculation [6] and simulation [7] are the first steps in the preparation of further analysis. The simplest case for the study is represented by a powertrain with two motors [8]. The motors can be identical [9] or different [10], and the result is not the same in each case. Furthermore, the analysis can be extended to more than two motors [11]. The control methodology [12] of each motor is also an important factor in searching for efficiency improvement [13], but under real vehicle constraints as for example, in the case of motors powering directive wheels [14]. Experimental platforms [15] certify the results before going to physical implementation.

In the multi-motor propulsion system, at least theoretically, several possibilities of load allocation can be adopted. Firstly, the paper describes the methods proposed and used in the research, as well as in the didactic process, exemplifying their impact on the energy efficiency of the assembly. Knowing the behavior of each motor over the entire operational area, from the point of view of energy efficiency, is necessary to determine the energy efficiency of the whole system and to optimize based on the load allocation methods for each motor. From this perspective, an analysis of internal losses as a function of the motor load and its speed is presented with results obtained on permanent magnet motors. Such methods are complementary to motor conception and motor control techniques. A comparative analysis is further presented

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on the performances that can be obtained by continuously applying a single method of allocating the load between the motors, as well as the successive application of several different methods, aiming to optimize both the efficiency of the propulsion system and achieve high performances. If in a parallel connection of electrical transformers, the load is carried out until the first of them reaches the nominal load, the individual control of each electric motor in a propulsion system allows motors with different constructive data to be driven simultaneously at nominal or maximum load, for a certain period. The research follows the transfer of load from one motor to another as a process that requires time and control, especially in the case of in-wheel motors, or motors that individually control each axle of a vehicle.

2. REFLECTIONS ON LOAD ALLOCATION IN A MULTI-MOTOR PROPULSION SYSTEM

2.1 Static, dynamic, and mixed load allocations

Considering a powertrain with a torque request $\boldsymbol{T_t}$, each electric motor can satisfy at least a part of this torque

$$T_m = \boldsymbol{\lambda_m} \cdot \boldsymbol{T_t}, \tag{1}$$

where $\boldsymbol{\lambda_m}$ is a load distribution coefficient for motor *m*. If $\boldsymbol{\lambda_m}$=1, the motor *m* covers the whole torque. At each moment of the powertrain operation

$$\sum_i \boldsymbol{\lambda_i} = \mathbf{1}. \tag{2}$$

The load allocation represents the process, or the method, establishing the load distribution coefficient for each motor of the powertrain in each operating point of the powertrain. An operating point can be defined as a couple of physical sizes torque and speed, requested at a certain moment. The operational area is determined by all operating points.

In this context, the load allocation between motors can be defined in several ways:
- static load allocation,
- dynamic load allocation,
- mixed load allocation.

In the first case, the load allocation rule is the same for each operating point. It is defined once and applied to the whole operational area of the powertrain. As it doesn't change during the powertrain operation, it is called **static**.

The second case concerns at least a new calculation of the load allocation coefficients in each operating point. It can be based on the previous request from the powertrain, the actual situation, and the request for the next operating point. The rule can also change from one operating point to another. For that, it is called **dynamic**.

Finally, the third case represents a combination of the previous ones. For certain operating points, a static load allocation can be used, and for others, a dynamic load allocation. So, it is a **mixed** load allocation.

2.2 Particular cases for load allocations

For each load allocation, particular cases can be defined. They are called load distributions for the respective load allocation.

Static load allocation cases:

- **complementary load distribution** – the motors of the powertrain are involved one by one following an established activation rule, a motor being activated when the previous one attempts its maximum capabilities, Fig. 1;

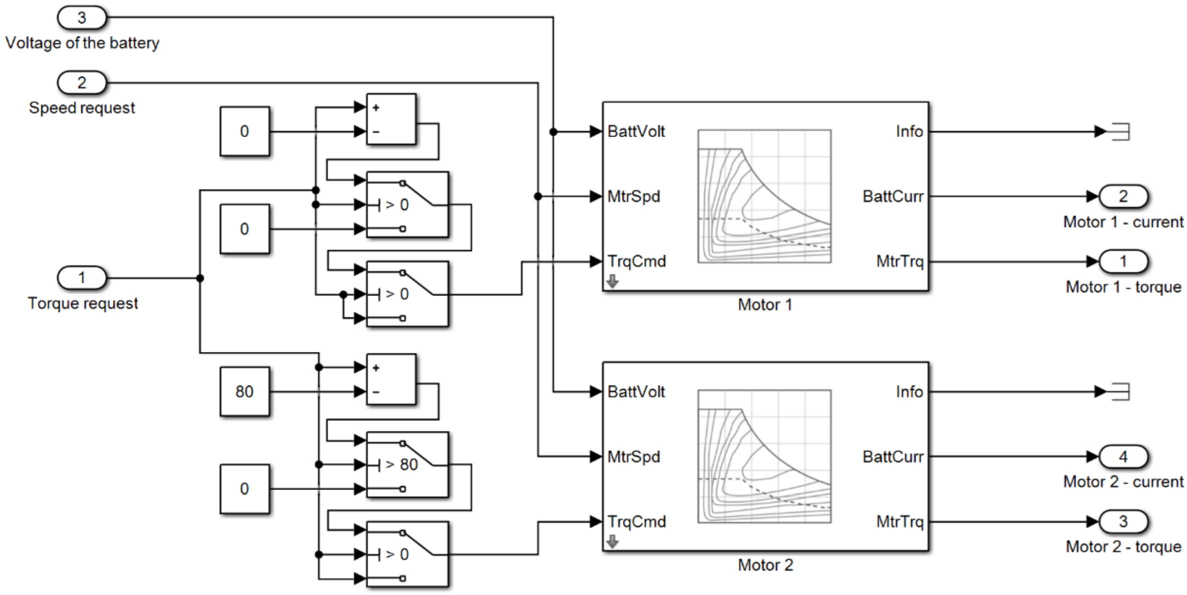

Fig. 1 – Example of complementary load distribution – MATLAB/Simulink implementation.

- **percentual load distribution** – each motor contributes with a fixed percentage form the total torque request, the percentage being the same for each operating point;

- **proportional load distribution** – is a particular case of the percentual load distribution, the percentage being calculated using the ratio between the maximum mechanical power of the respective motor and the total mechanical power of the propulsion system

$$\boldsymbol{\lambda_m = \frac{P_{Max_m}}{P_{tMax}}}. \tag{3}$$

- **optimal load distribution** – is a result of an analytic calculation of load distribution coefficients which maximize the powertrain efficiency for each operating point.

It appears that the optimal load distribution is more a part of the dynamic load allocation family than the static one. But it can be demonstrated, for example, in the case of a powertrain with two motors, that the optimal load distribution represents in fact a percentual load distribution. So, the load distribution coefficient for each motor remains the same for the whole operational area of the powertrain.

Let's consider the power losses for each motor *m* as the sum of:

- the copper losses (dependent on internal electric resistance of motor windings *R*, and motor current squared - so dependent on motor torque T_m and motor torque constant $\boldsymbol{k_T}$ - so dependent on the total torque of the powertrain and motor load distribution coefficient by $\boldsymbol{R_m(\lambda_m T/k_{Tm})^2}$,

- and iron and friction power losses (depending on motor speed $\boldsymbol{\Omega}$ and motor speed squared by two coefficients, $\boldsymbol{C_{Hm}\Omega + C_{Fm}\Omega^2}$).

The yield of the powertrain represents the ratio between the mechanical power and the total power consumed (mechanical power produced plus power losses, as explained before).

If one motor has the load distribution coefficient $\boldsymbol{\lambda_1 = \alpha}$, the other has $\boldsymbol{\lambda_2 = (1-\alpha)}$. Under the condition $\boldsymbol{d\eta(\alpha, T, \Omega)/d\alpha = 0}$ results:

$$\boldsymbol{\alpha = \frac{R_2 k_{T1}^2}{R_2 k_{T1}^2 + R_1 k_{T2}^2}}. \tag{4}$$

So, the coefficients for the optimal load distribution are in this particular case of two motors, two constant values for the whole operational area.

For the dynamic load allocation cases, examples can be given by the load distribution coefficients which minimize the copper losses (Joule losses), or hysteresis and eddy currents losses for each operating point.

As in real cases, the load distribution between the electric motors of a vehicle must follow not only efficiency criteria, but also vehicle stability and performance issues, a static load allocation is, in most cases, applicable for short periods of time, and it is combined with dynamic load allocation, ensuring also the transition between periods with static load allocation.

3. STUDIES ON LOAD ALLOCATION APPLICATIONS

A vehicle with an electric multi-motor powertrain is considered for each study. Resistant forces acting on the vehicle are presented in [7]. For each study, there is a dynamic situation for the vehicle, the powertrain receiving fluctuating requests as the vehicle must respect a testing cycle (in the analysis, it is used the Worldwide Harmonized Light Vehicles Test Cycle - WLTC). The transformation of the speed testing cycle in request for the powertrain is described in [8]. The vehicle is running on a flat surface as well as an inclined surface, thus adding additional resistant force. It is equivalent to an increased energy request for the powertrain when the slope angle increases (increased values for the electric current passing through the motors).

3.1 Entry data for a study of a powertrain with two electric motors

The vehicle data are presented in Table 1. The data for the two-motor powertrain are presented in Table 2.

Table 1
Vehicle Data

Characteristics	Values
Gross weight	250 kg
Wind velocity	0 m/s
Frontal area	0.95 m^2
Wheel radius	0.275 m
Slope capabilities	maximum possible
Aerodynamic drag coefficient	0.46

Table 2
Powertrain Data

Characteristics	Motor One (M1)	Motor Two (M2)
Nominal / Max Power	4 / 8 kW	3 / 6 kW
Torque constant	1.655 Nm/A	1.800 Nm/A
Nominal Voltage	72 V	72 V
Pair poles number	16	16
Phase internal resistance	0.128 Ω	0.130 Ω
Maximum torque	182 Nm	180 Nm
Maximum speed	880 rpm	880 rpm
Hysteresis losses coefficient	0.0938 W/rpm	0.0651 W/rpm
Eddy currents losses coefficient	0.0001 W/rpm2	0.00009 W/rpm2

3.2 Operational area for powertrain

Based on the previous data, for each second of the WLTC the requested torque for the powertrain is calculated. The respective operating points are represented in the next two figures.

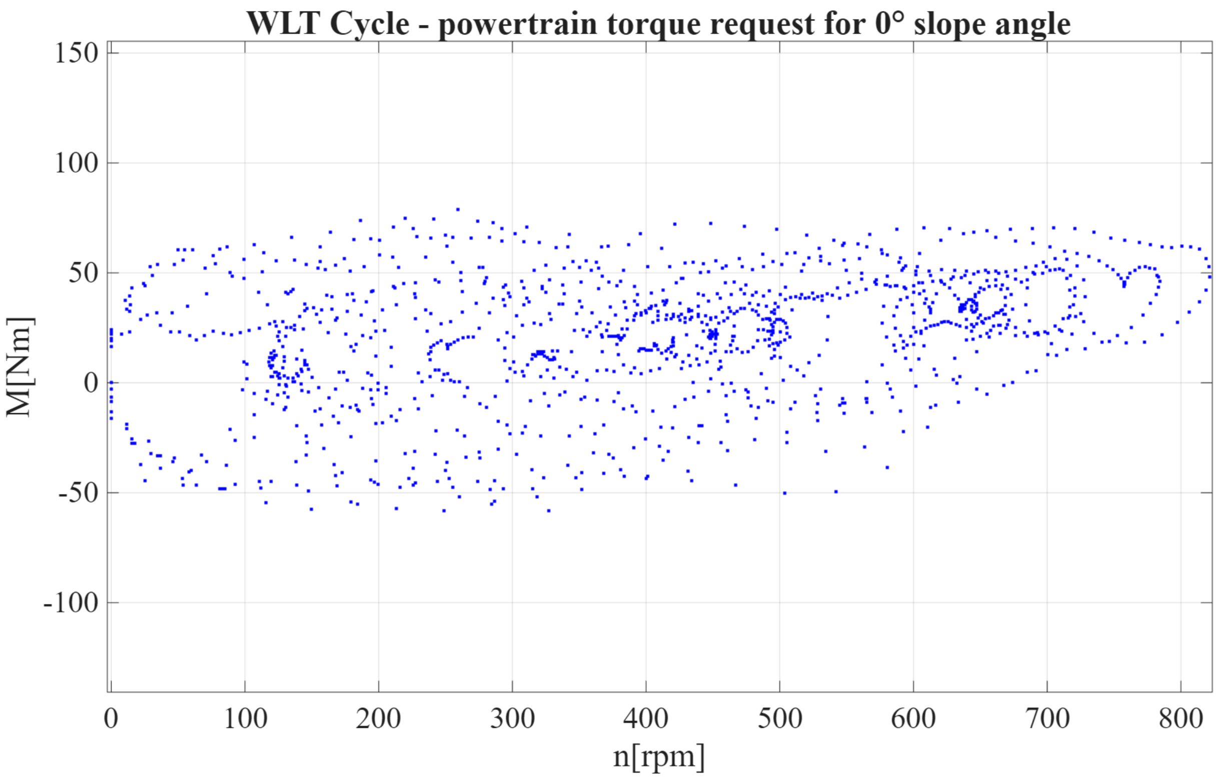

Fig. 2 – Operating points for a testing cycle WLTC on a flat surface.

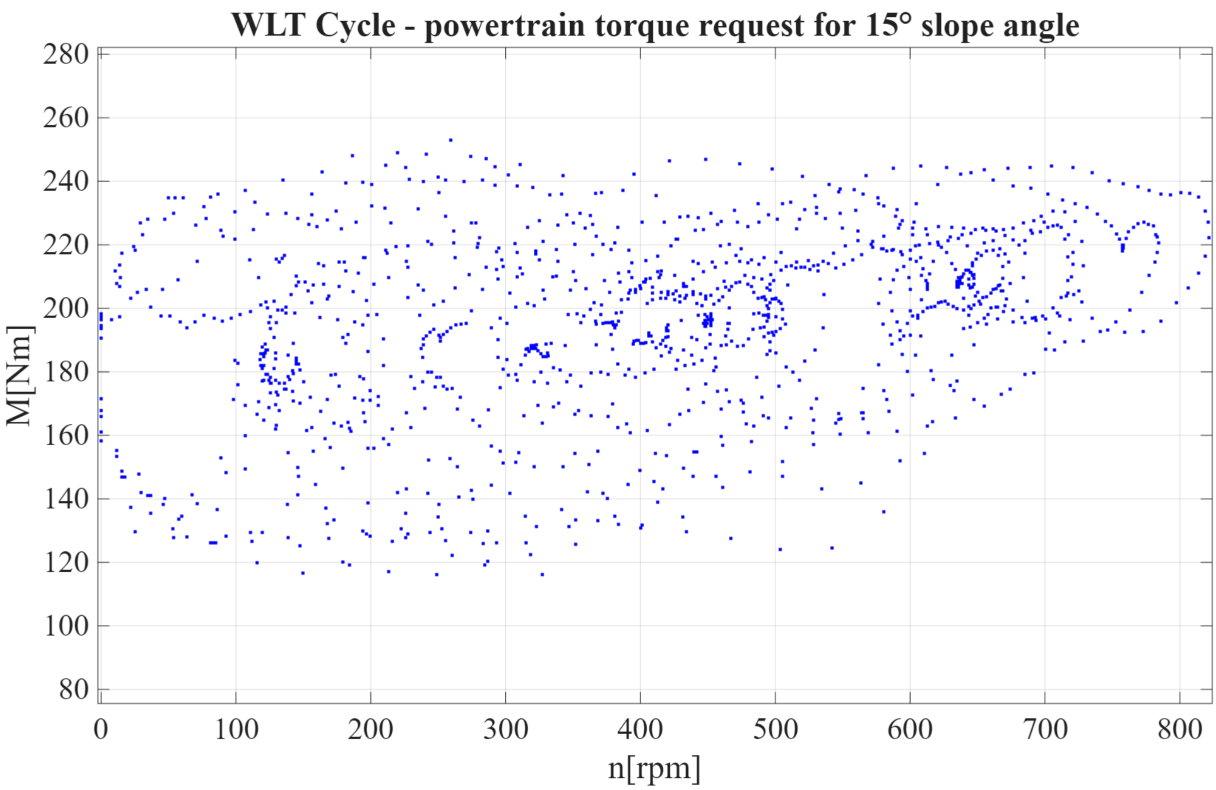

Fig. 3 – Operating points for a testing cycle WLTC at 15º slope angle.

Increasing the slope angle from 0 to 15 degrees, the maximum torque request increases more than three times (3.2 times). This is important in the analysis of the load distributions between motors in conditions approaching the maximum capabilities of the motors.

3.3 Motor internal losses analysis

In [8] an analysis of the internal motor losses has been performed. These losses, as described in section 2, depend on the motor torque request. In the next two figures, they are presented when the vehicle runs at 0 degrees slope angle and at 15 degrees.

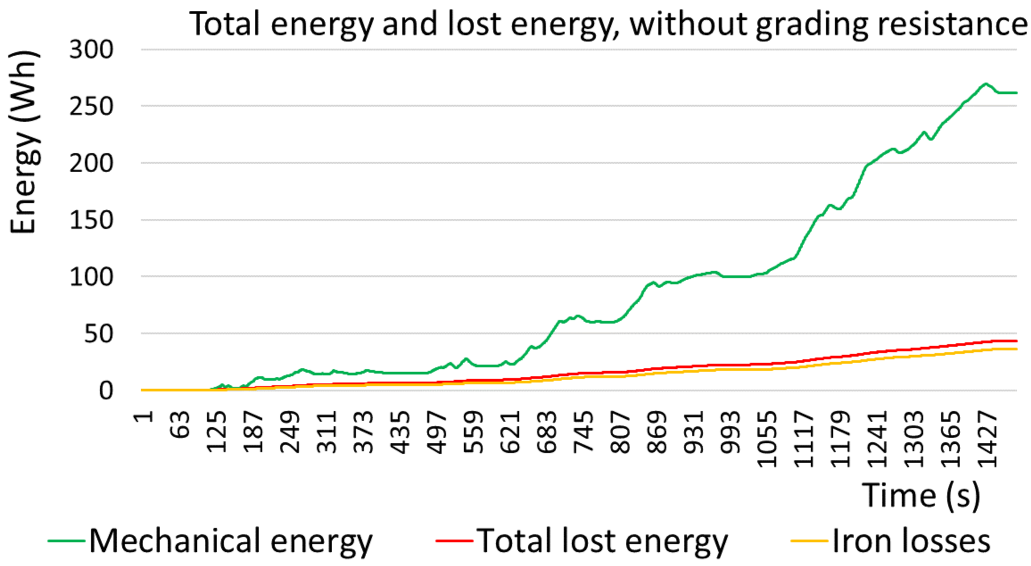

Fig. 4 – Energy needed to perform the WLTC cycle at 0º slope angle.

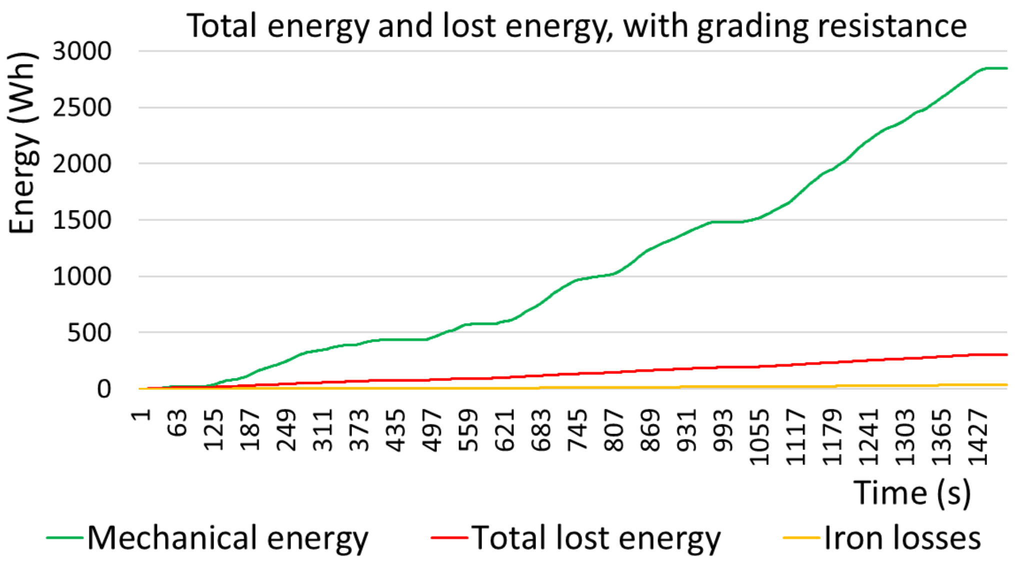

Fig. 5 – Energy needed to perform the WLTC cycle at 15º slope angle.

At small solicitation, the current passing through the electric motors is small, and the losses are given principally by the iron losses. In the case of permanent magnet motors, the presence of the magnets in a moving position relative to the iron core of the machine generates the iron losses. The Joule losses and other friction losses are small. So, in such a situation, if there is a possibility of affecting the load based on a dynamic load allocation approach, the minimization of total iron losses (including all the powertrain motors) can be used. But, even if there is no torque request for a motor, if its rotor turns, the motor generates such losses. It is better to mechanically disengage the rotor of each motor that is not used. Of course, physical implementation is more complex. At high solicitation, the Joule losses are predominant, and iron losses could even be neglected in the decision process. It is possible to affect the load based on Joule losses minimization. In the case of identical motors, applying the Joule losses minimization is equivalent to distributing the load equally to each motor.

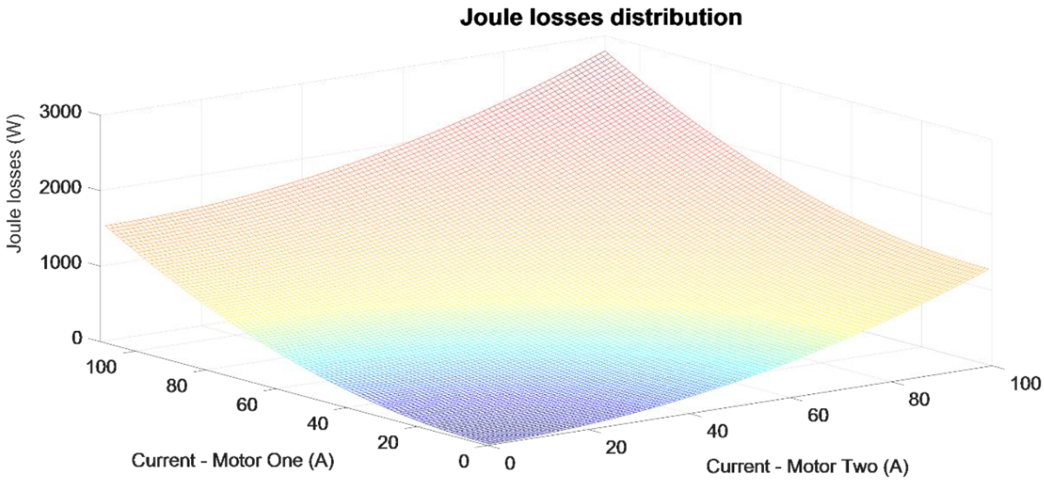

Fig. 6 – Copper losses (Joule losses) for the powertrain depending on the current passing each electric motor.

It means that in fact a percentual load distribution is used and the load distribution coefficient for each motor is 50%. If the motors are different, the Joule losses minimization respects, in fact, a dynamic load allocation when a first relation between the currents passing through each motor is established, from the total torque request being the sum of the torque produced by each motor. A second relation between currents comes from the condition for finding the current pair giving minimum Joule losses.

3.4 Comparative analysis of static load allocations and opportunities to extend the operational area using mixed load allocations

For the assembly vehicle plus powertrain with the characteristics from Tables 1 and 2 the next figure presents the powertrain efficiency for several load allocations.

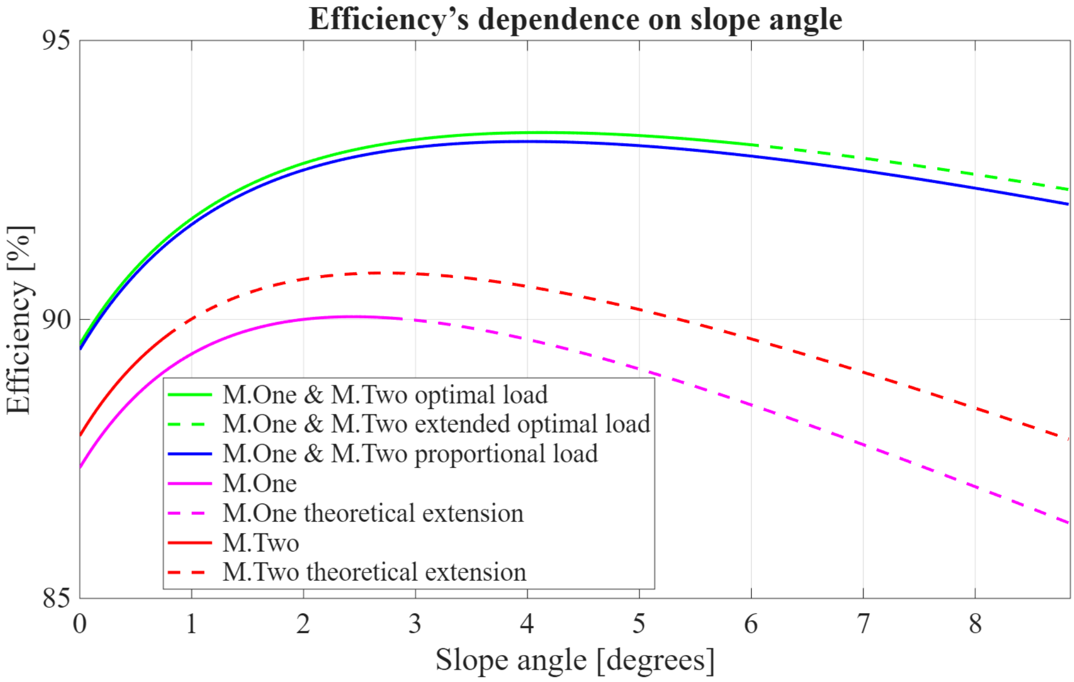

Fig. 7 – Efficiency for different static load allocations.

Each curve of efficiency stops when one of the motors attempts the maximum capabilities (maximum torque, power, or speed). As expected, the maximum efficiency is given by the optimal load distribution, but the maximum slope angle is obtained for the proportional load distribution. It allows the motors to be charged proportionally to their maximum power, and both motors attempt this maximum power simultaneously at approximatively 9-degree slope - the **maximum slope angle** for the vehicle with the actual powertrain. What happens when applying the optimal load is explained using the next three figures.

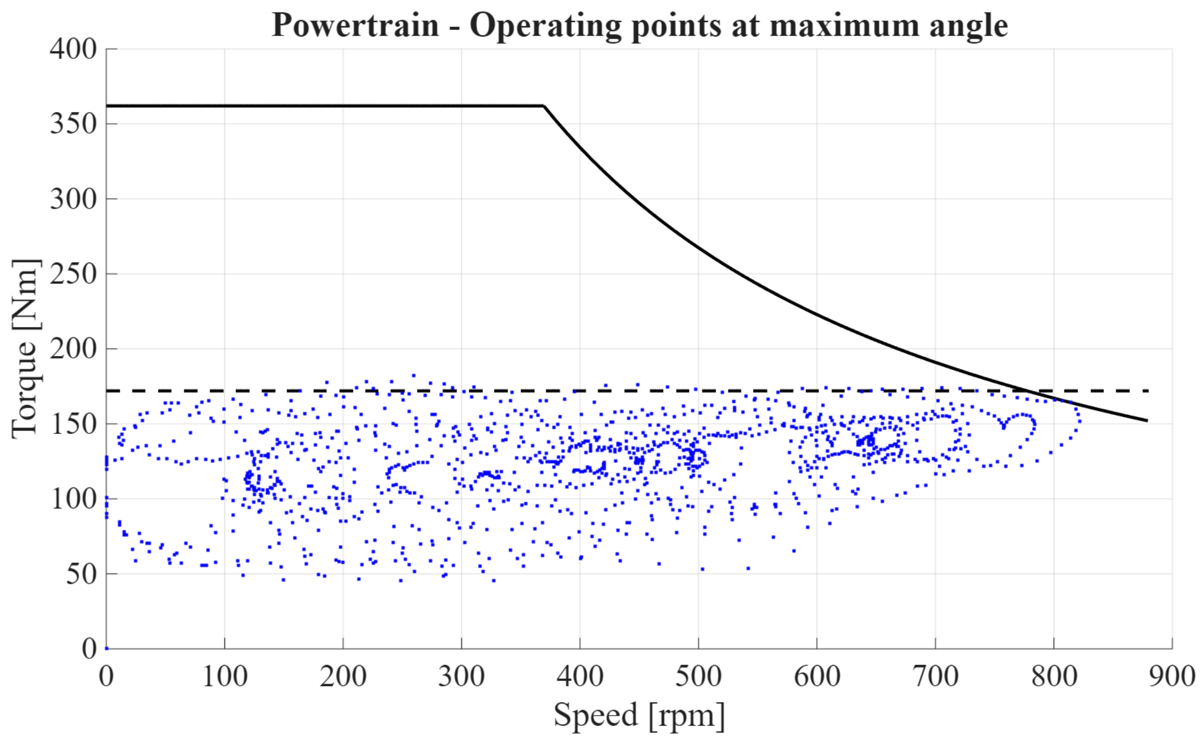

Fig. 8 – Operating points for the powertrain at maximum slope angle.

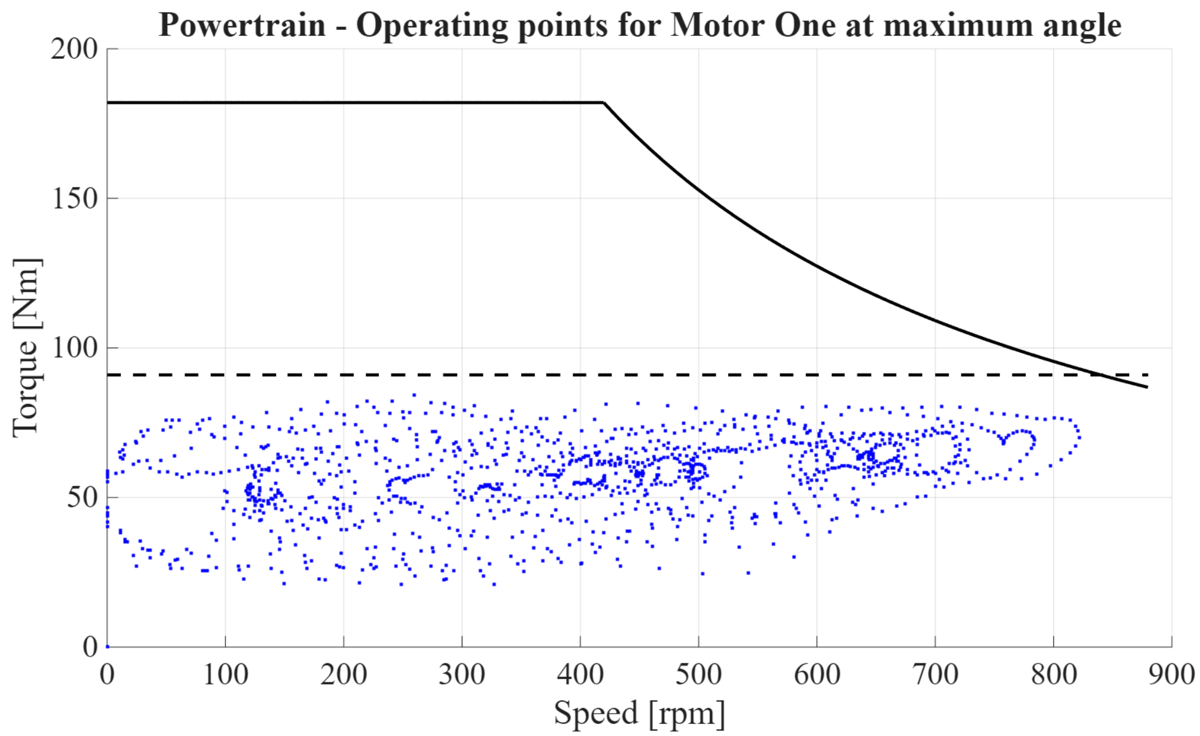

Fig. 9 – Operating points for Motor One using the optimal load at the maximum slope angle.

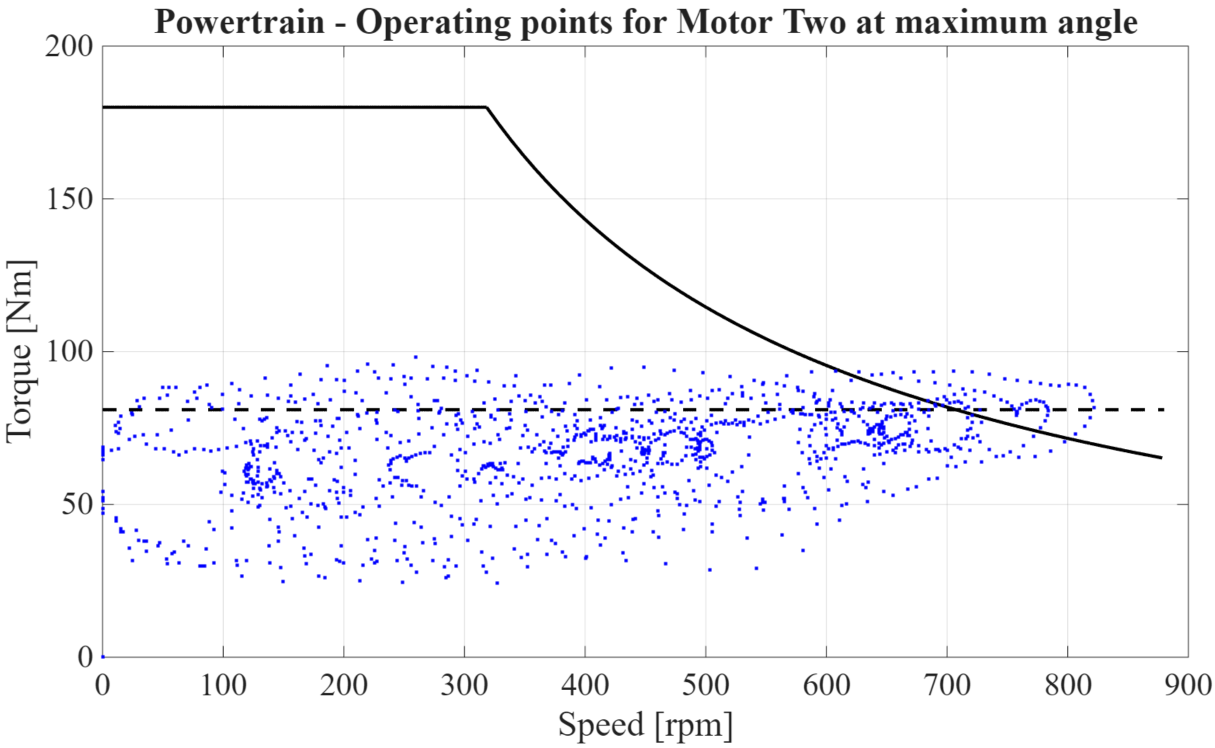

Fig. 10 – Operating points for Motor Two using the optimal load at the maximum slope angle.

At the maximum slope angle, the optimal load distribution would ask Motor Two to provide more than its maximum power. So, the efficiency curve for the optimal load distribution must stop at a slope angle when Motor Two attempts its maximum power. In Fig. 7, it represents approximately 6 degrees. From this point, motor two cannot receive any additional charge; the condition for load allocation for this motor will be to charge it at its maximum power. The maximum torque provided by this motor will decrease with speed, under the previous constraint of maximum power. The difference up to the total torque requested by the vehicle can be obtained from the other motor, using a complementary load distribution. Like that it is possible to extend the curve of the optimal load distribution by the green dashed line as shown in Fig. 7.

Two other curves in Fig. 7 correspond to the percentual load distribution with 100% for one motor and 0 % for the other (only one motor in use). The extensions of the curves by the dashed lines are more theoretical, asking for the motor to exceed the maximum power. It could be possible, for example, by increasing the voltage of the electric power source.

3.5 Application of vehicle constraints on load allocation

Additional constraints appear when vehicle stability can be affected by the load distribution between the motors of the powertrain. It is the case when the powertrain offers a dedicated motor for each vehicle wheel. In [14], a specific analysis is made regarding the steering angle impact on the torque distribution on in-wheel motors and electric energy consumption. In this case the motors of the powertrain are identical.

The next two figures provide the steering angle profile and the MATLAB/Simulink computing model for load distribution between the motors studied in [14].

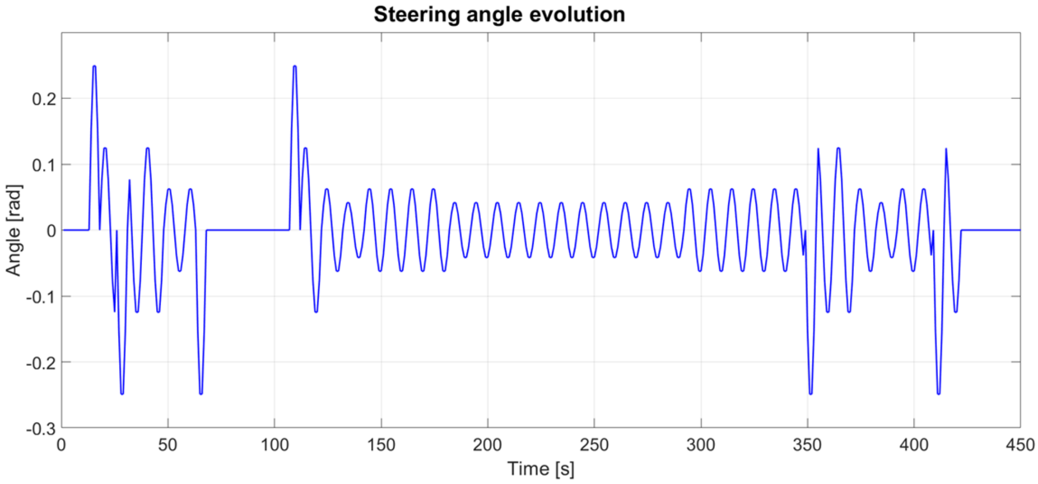

Fig. 11 – Steering angle profile studied in [14].

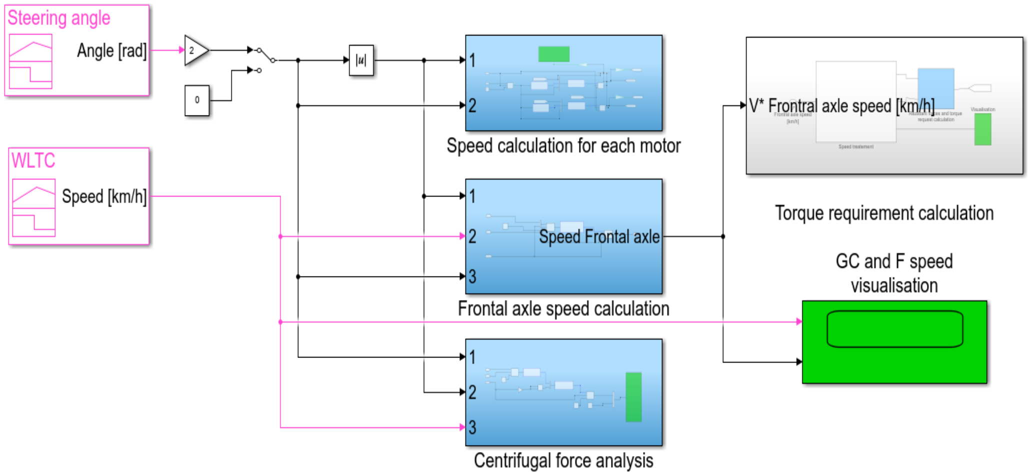

Fig. 12 – Simulink model for motor torque calculation in [14].

3.5 Torque transfer between the motors of the same powertrain

In real vehicle life, another aspect of load allocation in a multi-motor powertrain regards the management of torque transfer between motors. An example of such a study is given in [9].

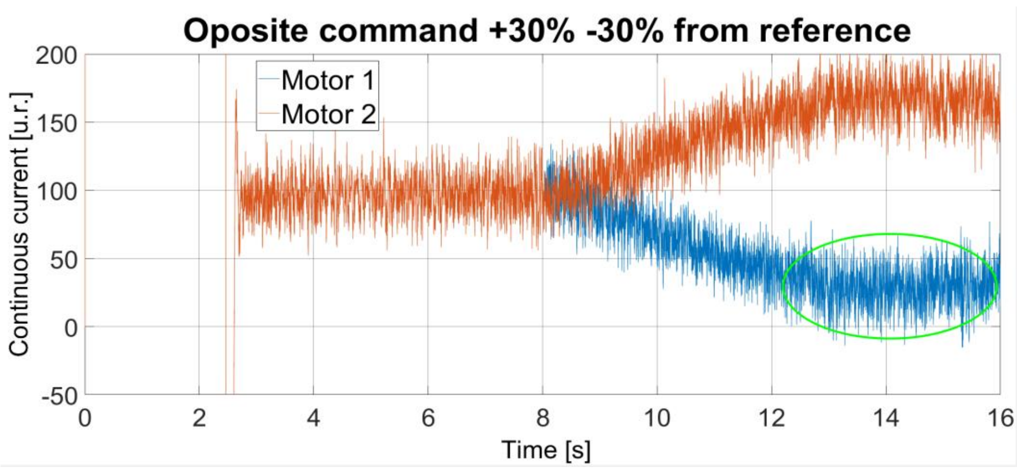

Fig. 13 – Motor currents during torque transfer between two motors in [9].

A transition phase must be managed when changing the load distribution between the motors of the powertrain in order to avoid chocs and vehicle instability.

3.6 Efficiency maps usage in the load allocation for multi-motor powertrain

An example of efficiency maps realization for a given motor is presented in [11]. It is also the case studying a powertrain with three motors.

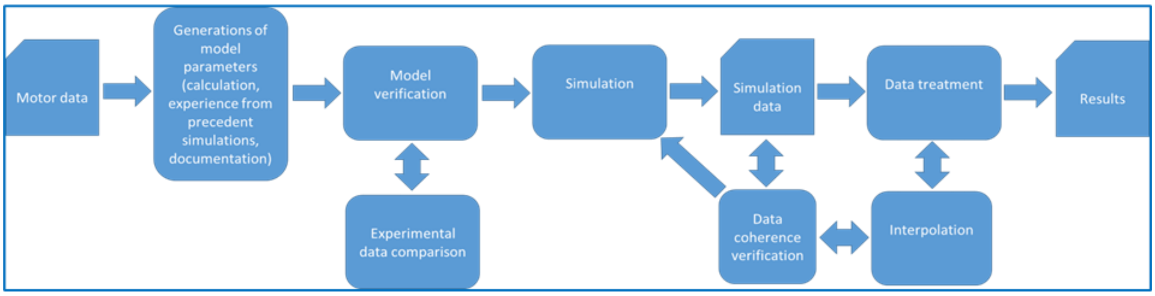

Fig. 14 – Process of efficiency maps construction used in [11].

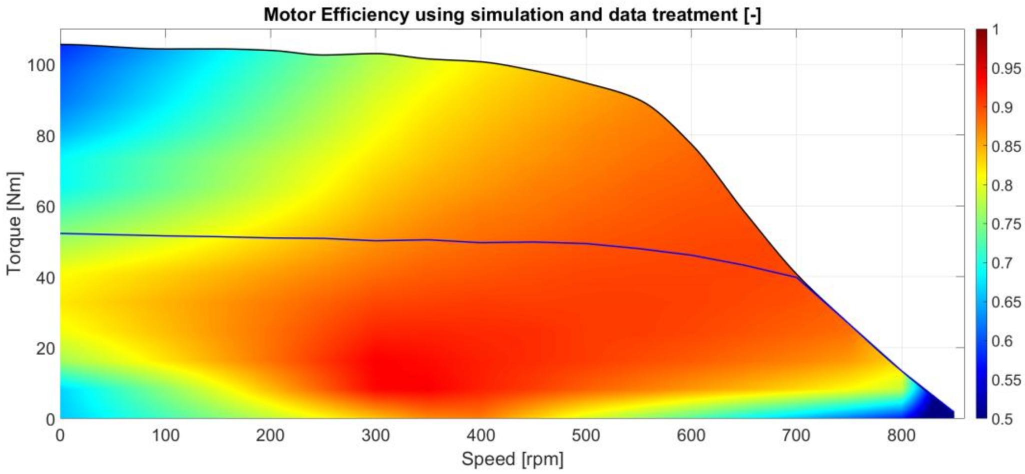

Fig. 15 – Example of efficiency maps realization in [11].

For real vehicles, the knowledge of the motor's efficiency maps can be another source for a load distribution strategy between the motors of the powertrain. As presented previously, the optimal load distribution can be easily implemented but presents some limitations coming from analytical calculation and approximations in mathematical models. The knowledge of the motors' yield in each operating point can be used to affect the load for each motor, giving a maximum yield for the powertrain in the respective operating point. The results are expected to be better than the ones obtained by the optimal load distribution.

3.7 Preoccupations for physical implementation and next steps

For previous analysis, the calculation and the simulation were important steps in the analysis. Furthermore, the expected results can be verified on physical platforms [15] or a real vehicle [16]. There are preoccupations for physical implementation on real vehicles. Simultaneously, the research in methodology needs to be continued in order to offer new opportunities for analysis and improvement in multi-motors powertrains.

4. CONCLUSIONS

The present paper has presented research of the author in multi-motor powertrains regarding the involvement of each motor in torque production. The load distribution possibilities are defined following the modality of distribution coefficients calculation and the fact to keep them for all operational area, or not.

An analysis between the presented methods has been performed following efficiency constraints. As in real cases, the vehicle safety comes first, issues regarding the torque transfer, forces calculation and additional impacts have been referred.

Finally, the work has continued with concerns related to the physical implementation of multi-motor propulsion systems.

CONFIRMATION

The work was presented at *Electric machines, materials and drives* Symposium SME'XXI, edition 2025.

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