

## HYBRID PROPULSION UNIT

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### ABSTRACT

The authors presented a conceptual idea of a high-speed mainline with a maximum speed of 400–450 km/h. The use of rotary engines requires more energy at high speeds, there are difficulties with current collection, wheel-rail adhesion, etc. At the

same time, the use of a linear traction motor at low speeds is not justified from an economic point of view, but efficient at high speed in terms of operation. In this regard, an option of a combined or hybrid traction propulsion unit is offered, in which the positive aspects of previous models interfit.

**Keywords:** transport, high-speed trains, high-speed lines, linear synchronous motor, asynchronous traction electric motor, resistance to motion, wheel-rail adhesion force, hybrid propulsion unit, conceptual idea.

**Background.** Today, in the world a large number of high-speed mainlines is in operation, the maximum speed at which is 250–350 km/h [1]. To achieve high speed with conventional wheel-rail system with a classical arrangement of traction motors on the rolling stock (from a motor shaft on a wheel set axle via a gear) it is necessary to solve several problems. Such as for example the problem of wheel-rail adhesion, current collection, electric train power.

Adhesion of wheel sets with rail is one of the limitations of traction characteristics of the rolling stock, and on the basis of physical processes with increasing speed adhesion coefficient reduces, and this reduces traction. Unconventional systems, especially on the rolling stock with linear synchronous motors (hereinafter – LSM), deprived of these issues, traction force is transmitted here not through the wheel-rail, but due to interaction of primary and secondary elements, arranged on the rolling stock and tracks. But such a design has a flaw – the need for resettlement throughout the track of one of the parts of the linear traction motor.

Current collection problem comes to the fore with increasing speed over 200 km/h, where we can speak about probability of arcing between the runner and the current wires due to vibration and a small detachment of the runners from the wire, increasing aerodynamic effects, etc. [2]. Electric trains with linear synchronous motor do not have current collection problems in principle, since electric power is supplied to the stator, located directly on the railway bed. However, the use of LSM results in a significant increase in the cost of track structure and rolling stock.

An alternative is offered: a double or hybrid traction propulsion unit, i.e. in areas with relatively low speed (up to 300 km/h) rotating traction motors may be used, and in areas with a speed higher than 300 km/h linear motors may be used.

**Objective.** The objective of the authors is to consider a hybrid propulsion unit, which can be used on electric trains.

**Methods.** The authors use general scientific and engineering methods, simulation, comparative analysis, mathematical calculations.

### Results.

#### 1. Calculation of motion resistance force

When substantiating the alleged change it is necessary to calculate motion resistance forces and rail adhesion forces. As an example, eight-car train was taken, which included four motor and four trailing cars with a load of 160 and 150 kN / axis on each. For this version with the formula  $MH + T + M + T + T + M + T + MH$  (where  $M$  – motor car,  $T$  – trailing car,  $MH$  – motor head car) motion resistance force can be calculated as follows.

The resistance to motion is dependent on the design and the technical condition of the rolling stock, track superstructure, profile and plan of the track, on the train speed, as well as wind speed and direction. It is due to the presence of friction in nodes of rolling stock, wheel friction on the rails, deformation of track and rolling stock elements, air resistance, as well as the nature of gravity on slopes. The resistance to motion is conventionally divided into two main components.

The first is called main resistance to motion  $W'_m$ , it is resistance to motion of rolling stock of this type on a straight horizontal open section of the track at any speed (including when  $v = 0$ ). This component is caused by internal friction in nodes of the rolling stock, resistance arising in interaction of the rolling stock and tracks, as well as air resistance (when there is no wind). [3]

The second component is called additional resistance to motion  $W'_a$ , it is derived from slopes and curves. It is believed that additional resistance is independent on speed and is determined only by the plan and profile of the track. Next, the calculation is carried out without taking into account the effect of additional resistance forces.

The main resistance to motion is calculated as the sum of two components:  $W'_{mech}$  – mechanical resistance to motion and  $W'_{air}$  – resistance of air ambient. Specific resistance to motion of the entire train  $w'_m$  is calculated as the sum of specific forces [3].

$$w'_m = w'_{mech} + w'_{air} \quad (1)$$

where  $w'_m$  is main specific resistance to motion,  $\frac{N}{kN}$ ;

$w'_{mech}$  is mechanical specific resistance to motion,  $\frac{N}{kN}$ ;

$w'_{air}$  is specific air resistance,  $\frac{N}{kN}$ .

Specific mechanical resistance to motion:

$$w'_{mech} = 0,45 + \frac{7 + 0,12 \cdot V}{q_0}, \quad (2)$$

where  $V$  is train speed, km/h;

$q_0$  is weight per axis of a wheel set, kN/axis.

Specific air resistance:

$$w'_{air} = \frac{C_x \cdot \Omega \cdot \rho \cdot V^2}{2 \cdot 3,6^2 \cdot q_{0av}}, \quad (3)$$

where  $C_x$  is coefficient of air resistance of a train;

$\Omega$  is calculated mid-section area,  $10,7 \text{ m}^2$ ;

$\rho$  is density of ambient air,  $0,125 \frac{\text{kg} \cdot \text{s}^2}{\text{m}^4}$ ;



Table 1

Main and specific motion resistance forces

v, km/h	0	50	100	150	200	250	300	350	400
w'mech, N/kN	0,90	1,29	1,68	2,06	2,45	2,84	3,22	3,61	4,00
w'air, N/kN	0	0,50	2,01	4,53	8,05	12,58	18,12	24,66	32,21
w'a/w'm,	0	0,39	1,20	2,20	3,29	4,43	5,62	6,83	8,05
w'm, N/kN	0,90	1,79	3,69	6,59	10,50	15,42	21,34	28,27	36,20
Wm, N	4472	8888	18296	32696	52088	76472	105848	140216	179576
Wm, kN	4	9	18	33	52	76	106	140	180

Table 2

Adhesion force of the train with four motor and four trailing cars

v, km/h	0	50	100	150	200	250	300	350	400
$\psi_{cad}$	0,25	0,17	0,13	0,10	0,08	0,07	0,06	0,06	0,05
$F_{adaxis}$ , N	4000	2670	2000	1600	1330	1140	1000	890	800
$F_{ad}$ , N	640000	426666	320000	256000	213333	182857	160000	142222	128000
$F_{adaxis}$ , kN	640	427	320	256	213	183	160	142	128

$q_{0av}$  is average weight per axis of a wheel set, kN/axis.

The coefficient of air resistance of the train [3].

$C_x = C_0 + C_a \cdot (N - 1)$ ,  
where  $C_0$  is coefficient of air resistance of a conditional single car, 0,55;

$C_a$  is coefficient of air resistance of a car in the middle of the train, 0,21;

$N$  is a number of cars in the train.

Weight per axis of motor and trailing cars is different, so the calculations use the average value  $q_{0av}$ :

$$q_{0av} = \frac{q_{0m} \cdot N_{cm} + q_{0t} \cdot N_{ct}}{N_{cm} + N_{ct}}, \quad (5)$$

where  $q_{0m}$ ,  $q_{0t}$  is weight per axis of a wheel set of a motor and trailing car respectively, kN/axis;

$N_{cm}$ ,  $N_{ct}$  is a number of motor and trailing cars.

Average weight per axle of a car for this arrangement is 155 kN / axis.

All calculations are summarized in Table 1.

Calculations show that at low speeds mechanical resistance to motion prevails, and at speeds above 100 km / h air resistance forces are more significant.

## 2. Limitation of adhesion

One of the main criteria of train movement is a restriction on wheel-rail adhesion forces  $F_{ad}$ . External to the wheel is a force, thanks to which the torque of the traction motor is realized in the form of traction, transmitting the forward movement of the wheel, and with it the entire train. From this it follows that for conventional design of the rolling stock with rotary traction motors motion resistance force should be smaller in magnitude than wheel-rail adhesion force.

In reality it is difficult to calculate the coefficient of adhesion, therefore the formula for each type of rolling stock is determined experimentally, for example, for the selected rolling stock the coefficient is determined by [4].

$$\psi_{cad} = \frac{25}{100 + v}, \quad (6)$$

where  $v$  is train speed, km/h.

Adhesion force per one motor axis:

$$F_{adaxis} = \psi_{cad} \cdot q_{0m}, \quad (7)$$

where  $F_{adaxis}$  is adhesion force, N.

Adhesion force of the entire train:

$$F_{ad} = F_{adaxis} \cdot N_{am}, \quad (8)$$

where  $N_{am}$  is a number of axes with traction motors in the entire train.

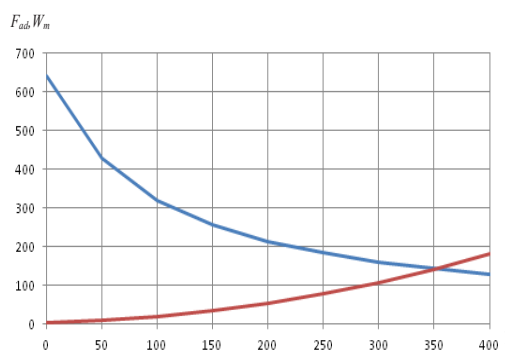
Calculations of wheel-rail adhesion force depending on speed are shown in Table 2. According to tables 1 and 2 built in Pic. 1 dependences  $F_{ad}(V)$  and  $Wm(V)$  are shown for convenience in dimensions [kN].

With the adopted configuration of the electric train adhesion restriction does not allow moving at speeds above 350 km/h. To increase it, it is necessary either to decrease motion resistance force, which seems quite difficult and requires significant changes in the design of the train, or to increase adhesion force. In the traditional system of wheel-rail wheel-rail adhesion coefficient cannot be enlarged; adhesion forces can be extended by a simple mechanical increase in the number of motor axes (capacity multiplication), but this would increase the weight of rolling stock, which in turn will adversely affect the dynamic action on the track from the high-speed electric train [5].

## 3. Hybrid propulsion unit

For the movement of high-speed electric trains at speeds at which wheel-rail adhesion force be lower than motion resistance force and traction force cannot be implemented with the help of its own rotating traction motors, LSM will be used. That is, to give the rolling stock double or hybrid propulsion unit: traction motors and LSM.

The primary element of the linear motor, what kind of some permanent magnets can be, is located on the rolling stock, and the motor winding or the secondary element is arranged on the track, for example, between the rails. Movement on high-speed lines in the presence of LSM will be with the use of control of windings' frequency regardless of the train, centrally. Wheel-rail adhesion force in this case does not play a big role, because the rails are used only as a guide for movement. There is also no problem of current



**Pic. 1. Dependencies  $F_{ad}(V)$  and  $W/m(V)$ .**

collection, since on the electric train a primary element of LSM is set, which does not require power supply. Example of location of primary and secondary windings of such a motor is shown in Pic. 2.

As for the order of testing of the hybrid propulsion unit, it is possible to take a high-speed mainline and divide it into several sections (Pic. 3). Start and end sections (№ 1) of the line are used for acceleration and deceleration of high-speed electric trains to a speed of 200 km/h, in the following areas (№ 2) the train accelerates to a speed of 300–350 km/h, to date, it is the marginal commercial rate of exploitation of such trains in the world [6] using the traditional wheel-rail system and rotating traction motors.

On a site № 3 the train moves with the help of LSM, speed can reach 400–450 km/h and above, control, signaling, centralization and blocking occur centrally in the control center without a driver. On this site natively on ballastless track secondary element of LSM will be installed. Since supply of primary element is not required (connected elements on the railway bed), then at such high speeds there is no problem of current collection, wheel-rail adhesion and the system of electrification and signaling.

Location of the primary element on the rolling stock does not require complex modifications, these are elements with permanent magnets that must be installed under the car bottom at a certain height (linear synchronous motor allows to have a significant air gap between the primary and secondary elements).

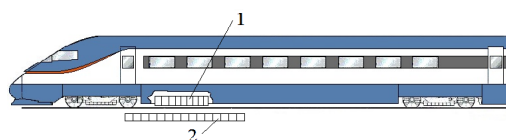
**Conclusion.** The use of a hybrid propulsion unit will increase speed on the railway line, including high-speed mainlines that are in operation or are being prepared for operation, for example, a high-speed mainline VDE8 in Germany, Madrid – region of Galicia in Spain, the second phase of the line TGV Est [7, 8]. The new rolling stock, for example, trains ICx, have a maximum speed of 250 km/h [9], with the use of a hybrid propulsion unit (installation of the primary section of LSM on the train) increase in speed without any change in rotating traction motors becomes real. Relatively traffic on new high-speed mainlines can be arranged according to the scheme, as shown in Pic. 3.

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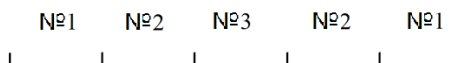
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**Pic. 2. Location of primary and secondary elements of LSM on the high-speed electric train: 1 – primary part of LSM mounted on the rolling stock; 2 – secondary part of LSM, mounted on the railway bed.**



**Pic. 3. Example of a high-speed mainline: 1 – areas of acceleration and deceleration of the electric train from beginning of movement to a speed of 200 km/h; 2 – areas of movement of electric trains with a maximum speed of up to 300–350 km/h; 3 – area of the mainline equipped with LSM, with speed of 400–450 km/h.**

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