Comparison of Train Resistances of TRANSRAPID and MLX01

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Abstract

Today the most important question for Maglev systems is their successful commercial application. One of the criteria determining the technical and economic parameters of high-speed railway systems is the train resistance. Correct methods of determination of the resistance forces and a comparative analysis between the existing Maglev systems TRANSRAPID (Germany) and MLX01 (Japan) show areas of effective applications for both systems and allow an optimization for the conditions of the future operation.

1 Introduction

The design and the construction of a railway system as well as its operational parameters are influenced by the characteristics of the train resistances in many respects. But there are not only technical aspects; the economic parameters of a railway or Maglev system depend on the train resistances, too. For this reason the determination and the comparison of the train resistances of the two existing Maglev systems TRANSRAPID (Germany) and MLX01 (Japan) is an important fact for the system's analysis.

The purpose of the present work is the structural definition of the different train resistance forces for the Maglev systems and the derivation of universal calculation methods. These methods are the basis for the following calculations, the comparative analysis and the conclusions.

2 Determination of the calculation methods

2.1 Train resistance of TRANSRAPID

The total train resistance F^{em} of the TRANSRAPID system with electromagnetic (em) levitation technology is the sum total of all resistance forces on the train's movement. It is defined according to the following expression:

$$\boldsymbol{F}^{em} = \boldsymbol{F}^{em}_{aero} + \boldsymbol{F}^{em}_{add} + \boldsymbol{F}^{em}_{grad} + \boldsymbol{F}^{em}_{a} \quad [\text{kN}]$$

with

F_{aero}^{em} - aerodynamic train resistance

F_{add}^{em} - additional train resistance (representing linear generator train resistance and eddy-current train resistance)

F_{grad}^{em} - train resistance in gradient

F_{ac}^{em} - train resistance due to acceleration

2.1.1 Aerodynamic train resistance

Based on measurement data from the TRANSRAPID Test Facility Emsland (TVE) and theoretical researches [2] [3] the formula for the aerodynamic train resistance was determined as followed:

$$F_{aero}^{em} = f_{Tu}^{em} * 10^{-3} * \frac{2{,}8}{3{,}6^2} * \left(0{,}53 * \frac{n_w^{em}}{2} + 0{,}3\right) * \left(V^{em} + \Delta V\right)^2 \quad \text{[kN]}$$

with

f_{Tu}^{em} - tunnel factor, depending on the length of the tunnel and the train's configuration

n_w^{em} - number of train sections (cars)

V^{em} - speed of the train [km/h]

ΔV - speed of headwind [km/h]

2.1.2 Additional train resistance

The expression for the additional train resistance was determined based on experimental data received from test results [1], too:

$$F_{add}^{em} = F_{LG} + F_{EM} \quad \text{[kN]}$$

with

$$F_{LG} = n_w^{em} * \left(\frac{P_{LG} * 3{,}6}{V^{em}} - 0{,}2\right) \quad \text{[kN]}$$

F_{LG} - linear generator resistance, F_{LG} is equal to zero if the speed is less than 100 km/h

P_{LG} - power of linear generator per train section [kW]

and

$$F_{EM} = n_w^{em} * \left[0{,}1 * \sqrt{\frac{V^{em}}{3{,}6}} + 0{,}02 * \left(\frac{V^{em}}{3{,}6}\right)^{0{,}7}\right] \quad \text{[kN]}$$

F_{EM} - eddy-current train resistance (due to eddy-currents in the guiding rail)

2.2 Train resistance of MLX01

The total train resistance of the MLX01 with electrodynamic (ed) levitation technology is the sum total of all resistance forces on the train's movement. It is defined according to the following expression:

$$F^{ed} = F^{ed}_{aero} + F^{ed}_{d} + F^{ed}_{grad} + F^{ed}_{a} \quad [\text{kN}]$$

where

F^{ed}_{aero} - aerodynamic train resistance

F^{ed}_{d} - electro-dynamic train resistance

F^{em}_{grad} - train resistance in gradient

F^{em}_{ac} - train resistance due to acceleration

2.2.1 Aerodynamic train resistance

The formula for the aerodynamic train resistance was determined by an analytical method using test data of MLX01 on the Yamanashi Maglev Test Line [4] and by theoretical researches [5], too. Hereby the aerodynamic resistance of the car body and the magnetic air gap [6] are taken into account.

$$F^{ed}_{aero} = f^{ed}_{Tu} * \left[W_X^{zug^{2endsek}} + \left(1 + L^{ed}_{endsek} * k_{1m}\right) * * \frac{\lambda_p * W^{ed}_{car} * h^{ed}_{air}}{98{,}0602} + \frac{\left(L^{ed}_{zug} - 2 * L^{ed}_{endsek}\right) * \left(tg\alpha_{zug} + tg\alpha_{air}\right)}{1000} \right] * \left(V^{ed} + \Delta V\right)^2 \quad [\text{kN}]$$

with

f^{ed}_{Tu} - tunnel factor, depending on the length of the tunnel and the train's configuration

$W_X^{zug^{2endsek}}$ - aerodynamic coefficient of the train's end sections $\left[\frac{kN}{(km/h)^2}\right]$

k_{1m} - specific coefficient, describing the change of the aerodynamic train resistance depending on the train's length (related on 1 m)

λ_p - coefficient, considering the aerodynamic resistance in the magnetic air gap

W^{ed}_{car} - breadth of the train [m]

h^{ed}_{air} - width of the magnetic air gap [m]

L^{ed}_{zug} - length of the train [m]

L^{ed}_{endsek} - length of one end section [m]

$\alpha_{zug}, \alpha_{air}$ - specific angular coefficients [grad]

V^{ed} - speed of the MLX train [km/h]

2.2.2 Electro-dynamic resistance

Based on experimental data received from test results with MLX01 [7] and theoretical researches carried out for zero-flow systems with super-conducting solenoids [8] the analytical method supplied the formula for the calculation of the electro-dynamic train resistance considering the train's configuration and the design of the super-conducting magnets [9].

$$F^{ed}_{d} = 8 * K^{korr}_{coil} * K_{coil} * \frac{3{,}6 * V^{ed} * v_{c1}}{V^{ed^2} + \left(3{,}6 * v_{c1}\right)^2} * \left(n^{ed}_{w} + 1\right) \quad [\text{kN}]$$

with

K_{coil}^{korr} - specific coil coefficient, taking into account interference of solenoids, located consecutively in a super-conducting magnet of a train

K_{coil} - coil coefficient, independent from train's speed;

n_w^{ed} - number of train sections (cars)

v_{c1} - specific speed coefficient [m/s]

2.3 Train resistance due to acceleration

As a result of simulation calculations and experimental researches carried out for TRANSRAPID trains [10], diagrams of the maximum acceleration dependent on the train's speed (from 0 km/h up to 450 km/h) and longitudinal track gradients (0, 20, 40 ‰) have been received. A mathematical analysis of these diagrams supplied a universal function of the maximum longitudinal acceleration, considering the present power rating of the TRANSRAPID propulsion system.

Fig. **1** shows the results of the acceleration calculations by means of the received universal function in the speed range from 0 km/h up to 500 km/h and for longitudinal gradients from 0 ‰ up to 60 ‰. In the 3-D diagram the typical decrease of acceleration in dependence of growing speed and gradient is recognizable.

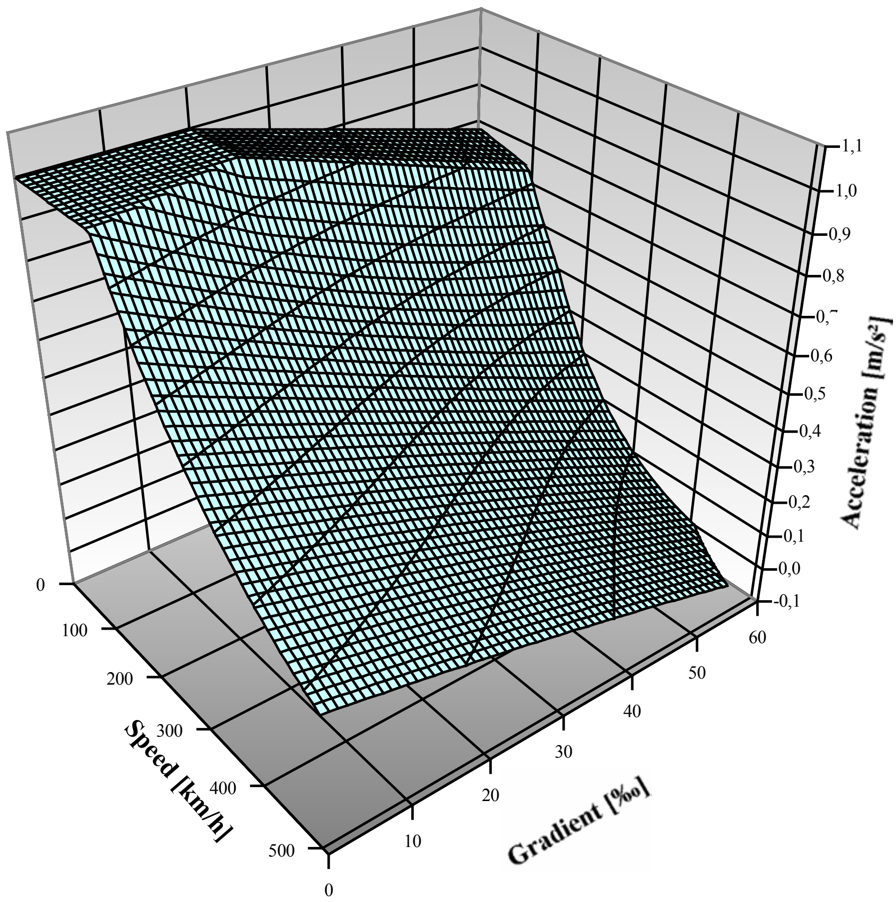


Fig. 1 Maximum acceleration of TRANSRAPID

Thus, the above-stated function considering the uneven change of acceleration of the TRANSRAPID was used for the calculation of the train resistance due to acceleration.

A similar tendency of decrease of the maximum acceleration dependent on speed and gradient is characteristic for the synchronous linear drive of MLX01, too. To ensure equal requirements for the comparison of both Maglev systems, the given acceleration function of the TRANSRAPID has also been used for the train resistance calculations of the MLX01.

3 Calculation variants

Based on the received formulas for the train resistances of both systems TRANSRAPID and MLX01 a number of calculation variants were carried out. The initial data for the calculations are specified in Table 1.

Table 1 Calculation data

PARAMETERS	Input data	
	MLX 01	TRANSRAPID
Number of sections	2 / 3 / 5	
Weight of sections [t] - middle section - front section	 22,0[*)] 33,0	 53,0 53,0
Lenght of sections [m] - middle section - front section	 24,3 28,0	 24,8 27,0
Payload per seat (including baggage) [kg]	125	125
Gradient [‰]	0 / 20 / 40	
Speed range [km/h]	0 - 500	
Maximum acceleration [m/s²]	dependent on speed and longitudinal gradient (see Fig. **1**)	

4 Calculation results

As a result of the calculations the characteristics of the train resistances of TRANSRAPID and MLX01 (total train resistance and its components) were determined in dependence on the vehicle's speed, the train configuration, the longitudinal gradient and the acceleration.

4.1 Characteristics of aerodynamic train resistances

As shown in Fig. **2** the aerodynamic train resistances of TRANSRAPID and MLX01 have similar characteristics. The aerodynamic resistance of TRANSRAPID is a bit higher than the resistance of MLX01 with equal number of sections. The absolute difference is growing with increasing speed and the number of sections.

4.2 Characteristics of additional train resistances

The comparison of the electro-dynamic resistance of MLX01 with the additional resistance of TRANSRAPID is shown in Fig. **3**. It is to establish, that at low and medium speeds the additional train resistance of TRANSRAPID is much lower than of MLX01 in spite of the

[*)] long car version

comparatively high linear generator resistance of the TRANSRAPID. The great difference is caused by the characteristic high eddy-current resistance of the MLX system at low speed. Because of the priority application of Maglev systems in the high-speed area the following investigations will exclude the speed range up to 100 km/h for the conclusions of the system's comparison. In the high speed range the electro-dynamic train resistance of MLX01 is reduced and becomes less than the additional resistance of TRANSRAPID. The reason why is the resistance force of the TRANSRAPID's linear generator for the contactless onboard power supply (MLX01 uses gas turbines). With increasing length of the trains this effect is shifted to lower speed.

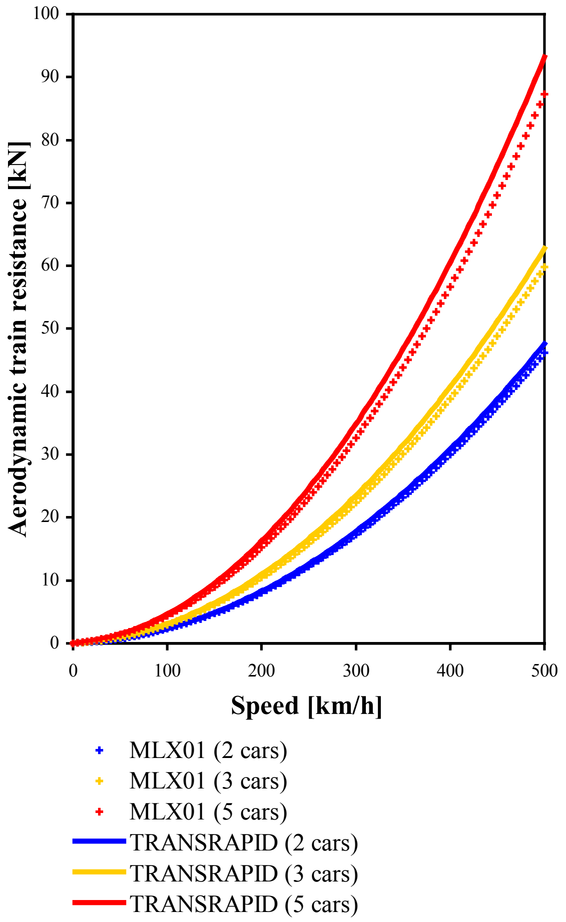


Fig. 2 Aerodynamic train resistances

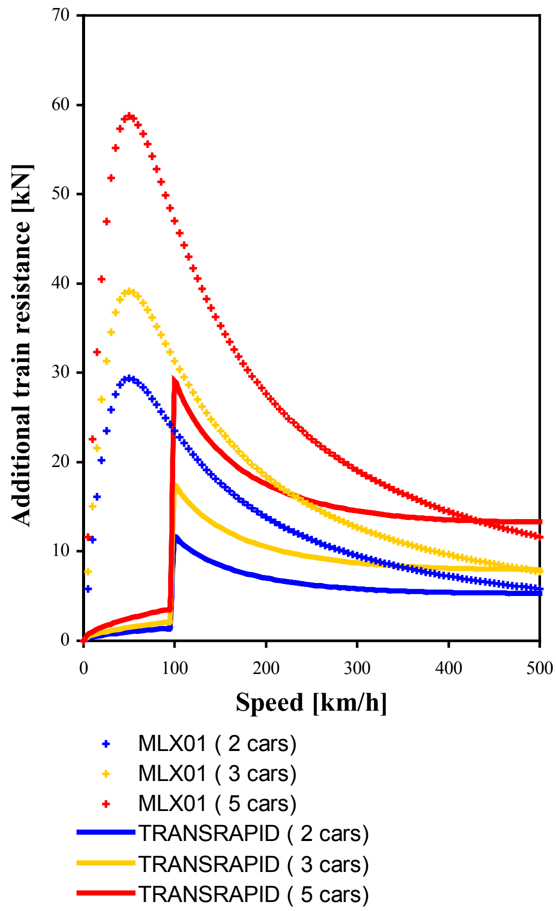


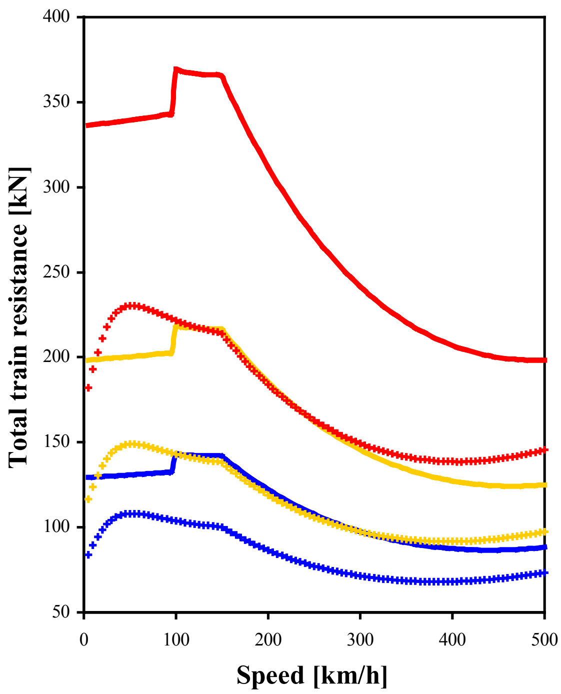
Fig. 3 Additional train resistances

4.3 Train resistances on maximum acceleration

Assuming that a train is accelerated from the standstill up to 500 km/h with the maximum longitudinal acceleration it will have its maximum train resistance characteristic. The following calculations were carried out for both systems to investigate these processes. The discussion of the results considers the total resistance forces as well as the specific values.

4.3.1 Total train resistance

As shown in Fig. **4** and Fig. **5** the total train resistance of TRANSRAPID system is higher than of MLX01 in all cases. This is mainly caused by the greater section mass of the TRANSRAPID cars (see Table 1). As to be expected the absolute difference between the two compared systems is growing with an increasing number of sections per train. Likewise the total train resistance increases proportionally with a rising track gradient.



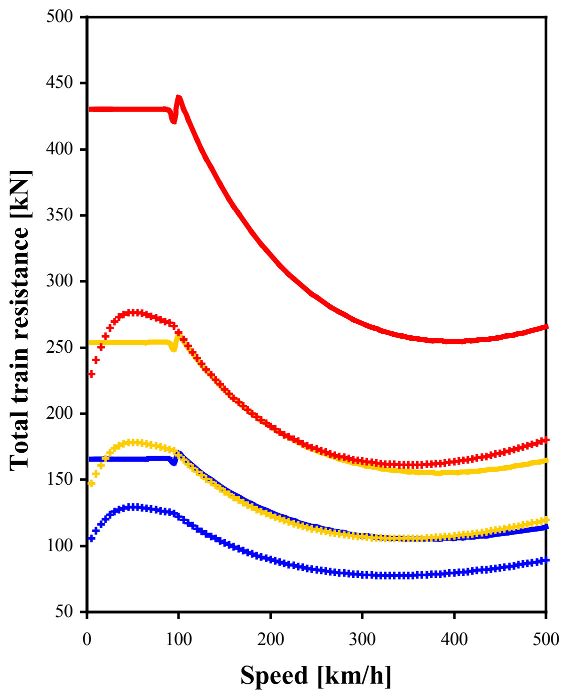


Fig. 4 **Total train resistance on maximum acceleration and longitudinal gradient 0 ‰**

Fig. 5 **Total train resistance on maximum acceleration and longitudinal gradient 40 ‰**

4.3.2 Specific train resistance

For a simple economic comparison of the train resistances of TRANSRAPID and MLX01 the specific values of the train resistance (sum total per one passenger) have to be taken into account.

The characteristics of the specific train resistances (Fig. **6** and Fig. **7**) show the fundamental advantage of the TRANSRAPID system due to the greater passenger capacity of its sections. But with an increasing number of sections in a train composition the established advantage gradually decreases. The presented diagrams only show the calculation results for a maximum train composition of 5 sections. By means of further calculations with longer trains it was realized, that the specific train resistance of the TRANSRAPID is gradually equalized by MLX01.

A train configuration with 10 sections of the MLX01 has nearly the same specific train resistance like the TRANSRAPID in the speed range from 100 km/h up to 250 km/h. Beginning with a configuration of 12 sections or more the specific train resistance of TRANSRAPID exceeds the values of MLX01 already at speeds up to 250 km/h. The given tendency was established especially for lines with flat gradients.

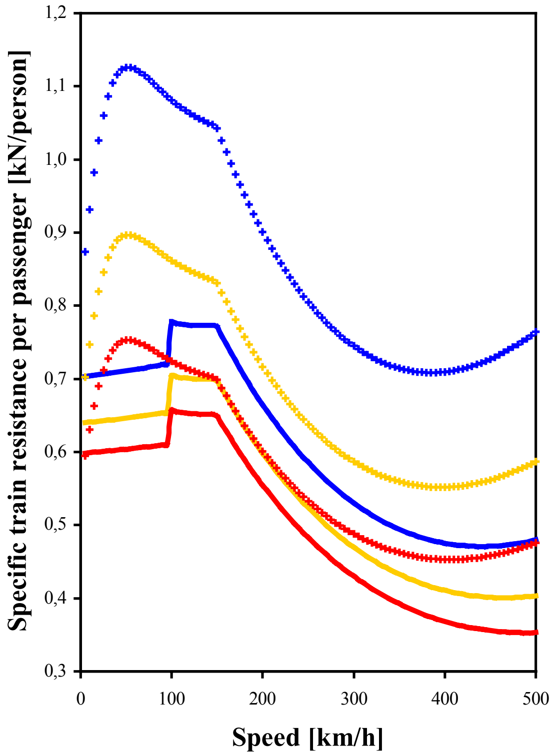


Fig. 6 Specific train resistance on maximum acceleration and longitudinal gradient 0 ‰

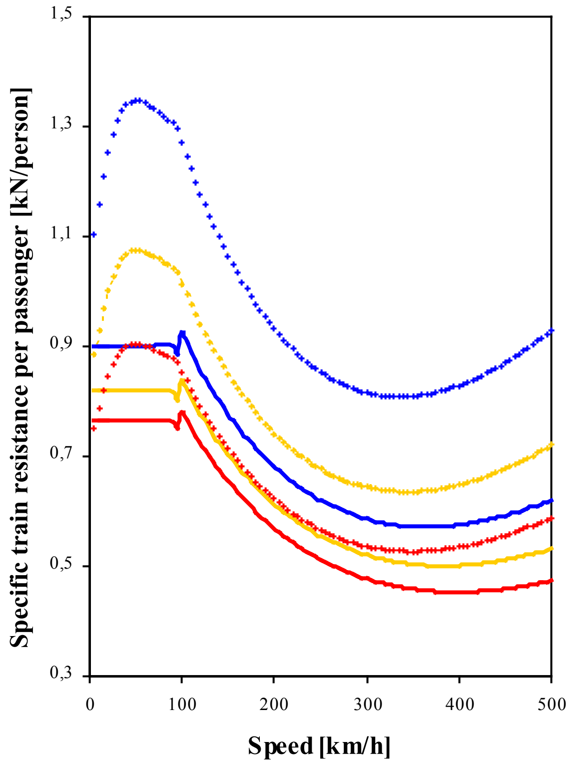


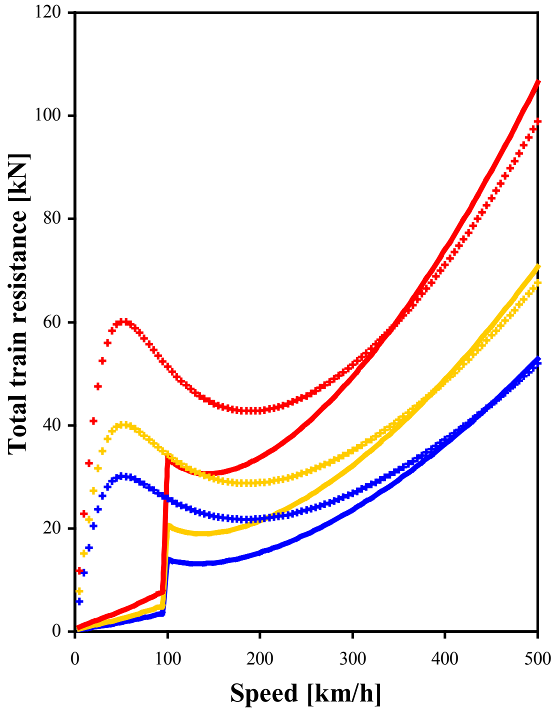
Fig. 7 Specific train resistance on maximum acceleration and longitudinal gradient 40 ‰

4.4 Train resistance at constant speed

For high speed systems long distance applications are characteristicly. On typical lines with stopping intervals of 50 km up to 100 km a train should pass the main part of its way with nearly constant speed. The periods of acceleration and deceleration are only small parts of the runtime. For this reason the comparison of train resistances at constant speed is the most interesting fact.

4.4.1 Total train resistance

Due to the characteristic of the aerodynamic train resistance the calculation results show increasing curves for both compared systems (Fig. **8** and Fig. **9**). At lower speed the typical influences of the linear generator train resistance (TRANSRAPID) and the eddy-current train resistance (MLX01) are evident. For low gradients and short trains the TRANSRAPD has lower train resistances. This advantage turns round with increasing gradients because of the higher train mass. It is to establish, that in the typical high-speed area (≥ 400 km/h, gradient 0 ‰) the absolute train resistances of both systems are nearly equal.



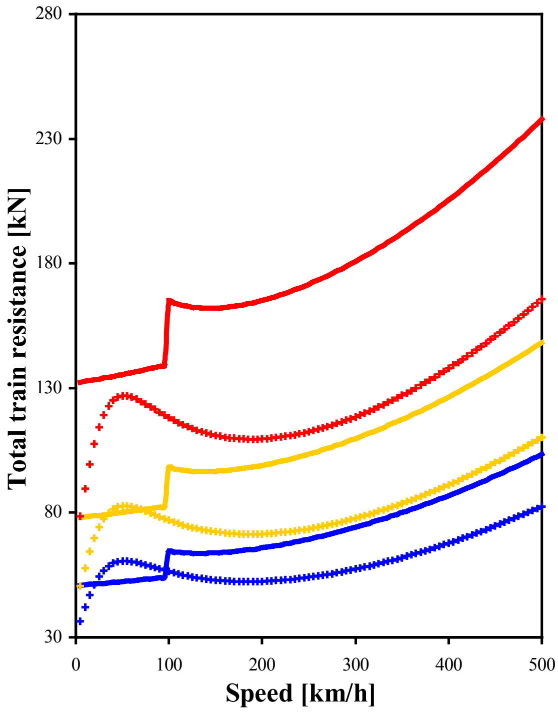


Fig. 8 Total train resistance at constant speed and longitudinal gradient 0 ‰

Fig. 9 Total train resistance at constant speed and longitudinal gradient 40 ‰

4.4.2 Specific train resistance

The most important characteristic for the economic comparison of the train resistances of both Maglev systems is the specific train resistance per one passenger (Fig. **10** and Fig. **11**).

The calculations on maximum acceleration as well as at constant speed show that the specific train resistance of TRANSRAPID is distinctly lower. For short trains of 3 or 4 sections the specific train resistance of MLX01 is nearly twice as big.

Because of the different passenger capacities of one train section the comparison of the specific resistance of trains with the same total passenger capacity is relevant. This comparison is possible for TRANSRAPID with 3 sections and MLX01 with 5 sections. As shown in Fig. **10** and Fig. **11** the specific train resistance of TRANSRAPID is about 15 ... 25 % lower. This advantage decreases with increasing longitudinal gradients.

These results are valid for the typical application scenario with trains consisting of maximum 5 sections. Further calculations has determined, that if the train length increases over 10 sections per train and the longitudinal track gradient is greater the 40 ‰ the specific train resistances of MLX01 becomes equal to TRANSRAPID.

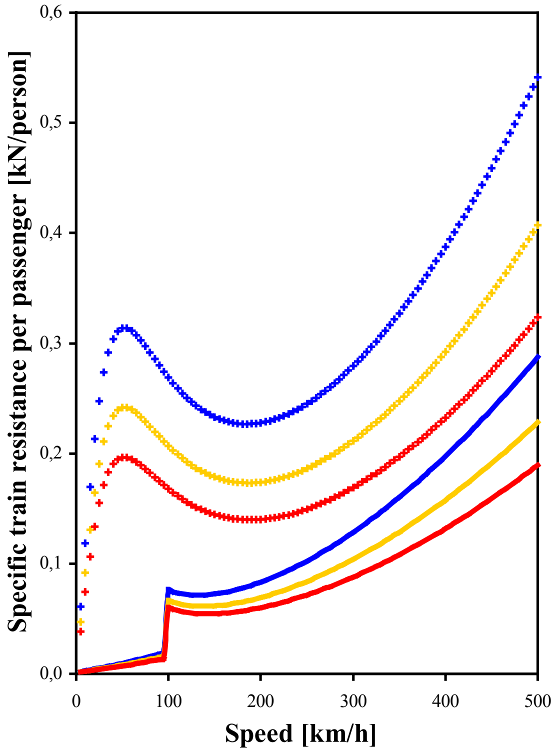


Fig. 10 Specific train resistance at constant speed and longitudinal gradient 0 ‰

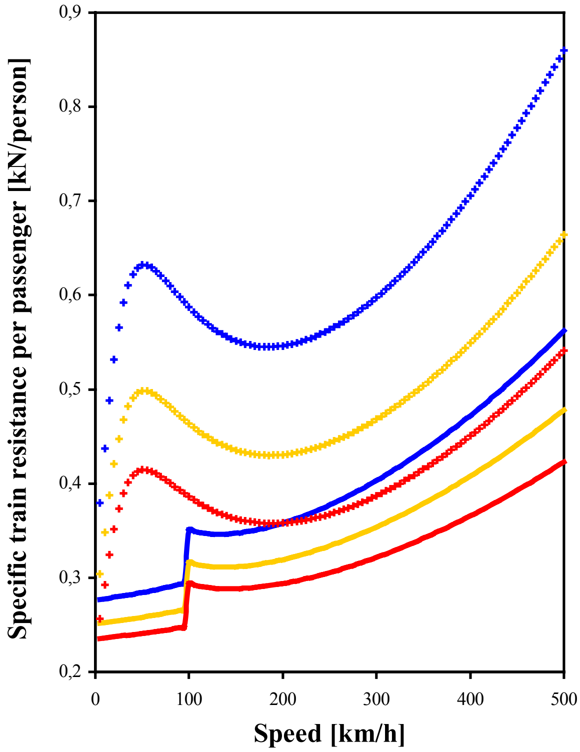


Fig. 11 Specific train resistance at constant speed and longitudinal gradient 40 ‰

5 Conclusions

As a result of the calculations the characteristics of the train resistances of TRANSRAPID and MLX01 were determined in dependence on the vehicle's speed, the train configuration, the longitudinal gradient and the acceleration. The results allow a technical comparison of the two systems and show the ranges of technical advantages and disadvantages of the respective technology.

The absolute train resistance force is the main parameter determining the power rating of the linear propulsion system. It also plays a decisive role for the absolute energy consumption of the system.

From the economic point of view it means, that the rated power of the propulsion system influences the amount of capital investments during the construction phase of the line, the quantity of the consumed energy determines a substantial part of the operational costs.

Both cost components are parts of the system's life cycle costs, which must be re-financed by the fare. Thus the train resistance indirectctly influences the quantity of the fare.

For a simple economic comparison the specific values of the train resistance (sum total per one passenger) were taken into account. As the specific train resistance influences the economic efficiency of the Maglev system, by the given criteria areas of efficient application of the compared systems TRANSRAPID and MLX01 can be determined.

So the TRANSRAPID seems to be the more efficient application for lower and medium-sized volumes of passenger traffic. For very large volumes of passenger traffic without further possibilities of decreasing the system's headway an essential expansion of the number of sections in the train could be required. In this case the application of MLX01 could be the more efficient solution. And, the application of MLX01 seems to be advantageous for routes with higher gradients and short distances between stops.

The present estimation of effective application fields for TRANSRAPID and MLX01 has only been given from the point of view of train resistances. Of course there are a lot of further parameters and preconditions for an extensive technical and economic comparison of both Maglev systems. The authors will continue their work intensively to extend the assessment basis to other parameters and also to the comparison with conventional high-speed railway systems [11].

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