360.revista de alta velocidad
número 5 - junio - 2018. Pág 33 - 43

Technological, economic and sociological factors on the maximum design speed of high speed trains

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Abstract

The maximum design speed of high speed trains is the maximal speed the train is operating in regular traffic. Due to certification and testing purposes the real maximum speed is higher. Historically the maximum design speed was understood as a constant value, which is depending on factors like distance to be travelled between two stops, traffic volume, energy cost etc. The study to be presented here aims to show, that the maximum design speed is a variable value depending as well on factors as willingness to pay, which is again depending on variables like airplane ticket prices or even petrol prices.

Keywords: Very High Speed, Aerodynamics, Signalling

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1. Introduction and current discussion of high-speed mass transport systems

When Elon Musk published his Hyperloop-Alpha paper in 2013 [1], he explicitly referred to the California High-Speed Rail project, but ironically enclosed the term “high-speed” by quotation marks. This way he wanted to express his disappointment on the intended speed level, which is 350 km/h at most or 264 km/h on average between San Francisco and Los Angeles.

He even finally concluded: “How could it be that the home of Silicon Valley and JPL, doing incredible things like indexing all the world’s knowledge and putting rovers on Mars, would build a bullet train that is both one of the most expensive per mile and one of the slowest in the world?” With this background, the spectacular solution Mr. Musk is envisioning, is targeted to run at a maximum of 1220 km/h and is supposed to operate in sealed partial-vacuum tubes in order to substantially reduce the aerodynamic drag.

Surprisingly the discussion of the Hyperloop concept does not comment at all on the actual technology leader in terms of speed which is the MAGLEV system that initially was targeted on 500 km/h operational speed not being the end point of its technical potential [2], [3].

A lesson to be learned from the MAGLEV experiences is about the application of a customized track system elevated and supported by pylons that the Hyperloop-Alpha paper assumes to be a major item to save money compared to conventional rail track systems.

However, the incompatibility to existing rail infrastructure either requires to purchase premises for stations where they are in particular expensive if available at all, i.e. in downtown areas, or to accept access times similar to planes which in turn compromises optional travel time gains by higher running velocities.

In order to point out the significance of this drawback, opponents here may refer to the fact that several prominent plans to install long-distance MAGLEV lines have been abandoned in favor of wheel-rail technology in the past [4], although the MAGLEV technology has proven its technical maturity since the 1980’s. Examples are the connections from Beijing to Shanghai or from Hamburg to Berlin.

The potential counterexample is Chuo Shinkansen from Tokyo to Nagoya that, by the current state of knowledge, will be the first long-distance MAGLEV line and open in 2027 [3], [5]. However even there, the approval of the Japanese government to construct this new line was given under the condition, “it could be rebuilt to a conventional high-speed line later, if necessary” [6].

There is no doubt, the existing rail infrastructure, its pure construction value on a global economic scale, its availability in urban centers, defines the competitive edge of the traditional wheel-rail technology.

However in view of the challenges posed by the mobility megatrend very high speed is nevertheless an issue for the steel-on-steel technology.

In fact, the pure technical feasibility of classical trains is not limited to today’s maximums speeds of to say 350 km/h. The TGV world record of 2007, when 574.8 km/h maximum speed were reached, is surely the outstanding example to substantiate this statement. But actually it is only the leading one in a series of records of experimental or commercial train layouts since 1980, in which competing suppliers and operators showcase their capabilities, see Figure 1.

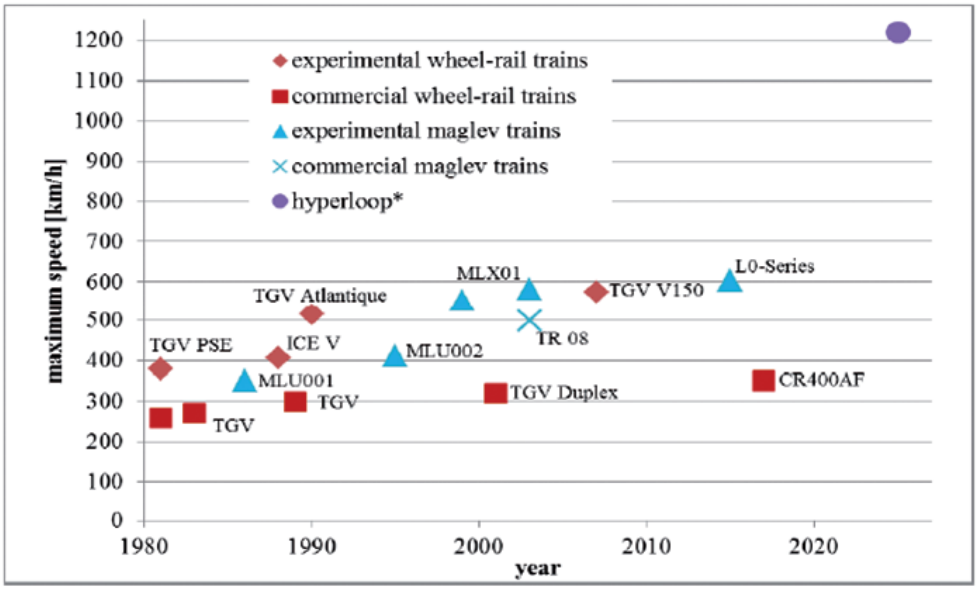

Figure 1. Maximum speed of passenger trains in the last 40 years,
**concept study experimental = technical modified or prototype vehicles commercial = vehicles are used in daily operation.*

Even though the record runs of experimental vehicles in Figure 1 each document a certain status of feasibility, which is still to come for the Hyperloop idea, their relevance for every-daypurposes is actually limited. The TGV world record for instance was conducted on a brand new high speed line exploiting downhill segments with increased catenary tension and voltage, the test vehicle was assembled with additional powered axles, larger wheels and deployed aerodynamic improvements. Since these circumstances cannot be transferred to regular operation, an interesting question in consideration of the summary in Figure 1 and in competition to the Hyperloop and the MAGLEV concept still remains unanswered, namely:

What is a reasonable upper speed limit for high speed wheel-rail systems in daily operation?

This question was adopted to be elaborated within the project to be introduced in the following section.

2. DLR’s Next Generation Train Project

In 2007, DLR initiated a long term research project on a future railway vehicle called Next Generation Train (NGT). Eight high level objectives were specified:

- Increase in the permitted speed in daily operation to 400 km/h and additionally explore the velocity range up to 600 km/h
- Halving the specific energy demand compared to the ICE 3 at 300 km/h
- Noise reduction
- Increase in comfort
- Improvement in vehicle safety
- Improved wear behaviour and life cycle costs
- Cost-efficient construction using modulisation and system integration
- Improvement in efficiency of development and approval processes

With this background, a concept for a train set of 202 m length consisting of eight coaches and two train heads was developed and named NGT HGV , see Figure 2.

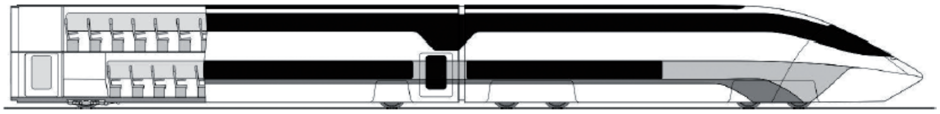

Figure 2: Side view of the NGT HGV with leading train head and first intermediate coach

Important features considered by this train concept may be summarized as follows:

- Double deck configuration in order to increase the number of seats per train length and in turn reduce energy consumption per seat
- Ambitious light weight design and streamlined construction of carbodies and running gears accordingly
- Use of running gears with independently rotating and driven wheels throughout the complete train set in order to distribute traction effort, actively control running stability and reduce wear and noise

Due to the organization of DLR, the NGT project could be organized as a joint effort of 11 institutes involving disciplines such as structural mechanics, vehicle dynamics, aerodynamics, electrical engineering as well as systems and operational engineering.

The same wide-range expertise could also be exploited to explore the speed range up to 600 km/h and elaborate on the “reasonable upper speed limit” question posed in the section above.

3. Technical Aspects related to higher train speed

3.1 Vehicle Dynamics

Modern high speed trains are complex systems and quantities such as forces, accelerations or wear result from the interaction of many components and environmental as well as operational influences. In order to master a fundamental question as given, it is helpful to subdivide the transportation task from the vehicle-dynamical point of view, which leads to three sub-tasks each focused on one specific direction of motion, cf. [7]:

a. load bearing, that is mainly related to the vertical dynamics of the vehicle,

b. guidance, which is associated to the lateral dynamics along curved and tangential track and

c. traction in order to transmit propulsion and braking forces in longitudinal direction.

As regards a., i.e. vertical dynamics, the comfort of the passengers is dominated by forced vibrations of the bounce and pitch motion of the vehicle, cf. [7, p. 14], which in turn are ruled by the quality of the track and the train speed. Due to human perception, comfort is in addition a function of the vibration frequency with the main emphasis on frequencies between 4 and 8 Hz [8].

On the one hand, measurements of non-ideal , real tracks expose a rise of irregularity amplitudes for increasing wavelengths. On the other hand the excitation frequency, the vehicle is exposed to, is a linear function of the train speed divided by the wavelength. These two relationships together constitute the following effect: as regards a specific frequency under consideration, the wheels are excited by larger amplitudes, if the train runs faster on the same, non-ideal track. In turn, the vibration comfort will be compromised and higher dynamic contact wheel -rail forces will stress wheels and rails for higher train speeds.

However, passenger railway vehicles use two levels of suspensions and it is a matter of concept and design tuning to organize a comfortable train ride and keep the dynamic forces at the wheel-rail interface within acceptable limits. There is a large, so far unexploited potential to deploy active or semi-active components which allow for online adaption of suspension characteristics to the train speed and the track quality is a tuning parameter as well. In summary, train speeds up to the range of the TGV record seem to be feasible even in daily operation concerning vertical dynamics.

As regards b., the lateral dynamics of railway vehicles is strongly related to the so-called hunting motion[1] : lateral track irregularities initiate lateral oscillations of the wheel-sets that are intended to be damped out in order to fulfill the guidance task. However, the stability of this hunting motion depends on the vehicle speed, which defines a requirement for vehicle design. Measures such as low equivalent conicities of the wheel-rail contact geometry [16], [9], adjusted stiffnesses of the primary suspensions [10], additional yaw dampers [11], [12], long wheel-bases [10] among others increase the stability region or the maximum speed a vehicle is capable of running safely, respectively. It can be concluded that a proper mechanical design provides a stable running of a railway running gear even at very high speeds. As Delfosse mentioned in [13], the simulation of the modified TGV unit, which set the former speed record of 515.3 km/h, showed that the critical speed of the train was above 700 km/h.

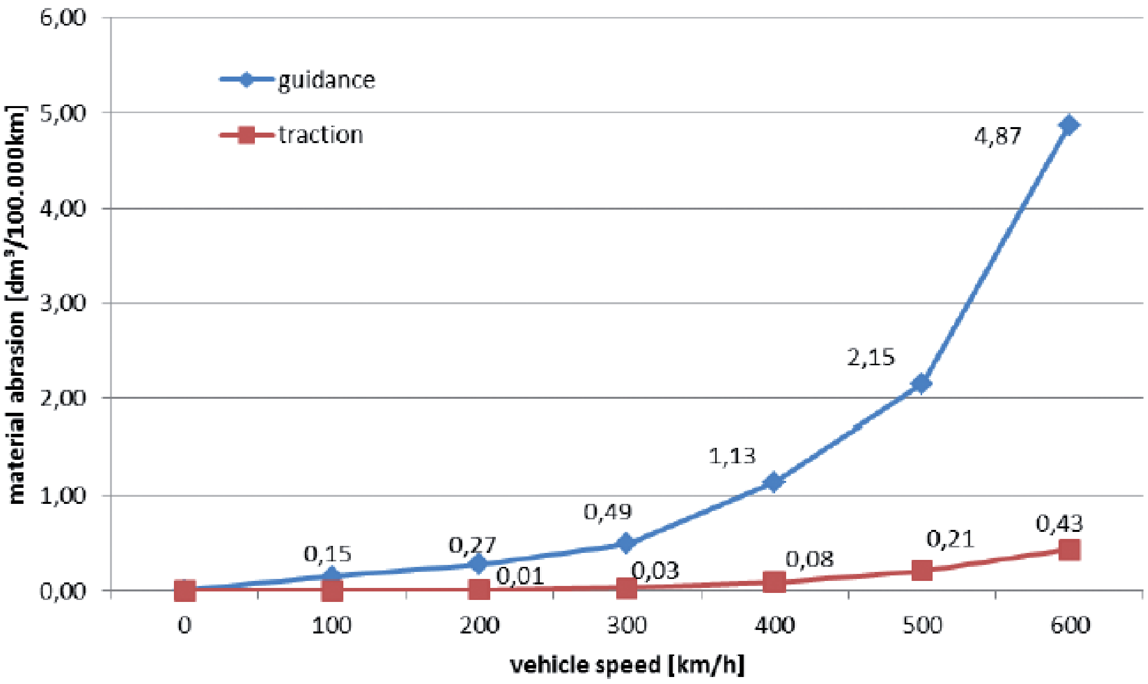

Figure 3: Exemplary estimation of wheel wear as a function of vehicle speed

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[1] *Streaktly speaking, this applies to the vast majority of railway vehicles that use wheel-sets, only.*

Wear is another aspect to be taken into account. In order to transmit tangential forces it is required to violate the ideal rolling condition at the wheel-rail interface, i.e. there is a small relative motion between the contact partners, which leads to sliding friction [14]. Wear or more precisely the volume of abrasive removed material is related to the associated frictional work [15]. However, wear and rail corrugation are very complex processes, so that a general statement how they depend on the train speed is difficult and out of reach in the given context. Just in order to get an idea, a multibody simulation of a today's articulated highspeed train with 6 cars, two bogies each car, 16*t* load per wheel-set, running on a straight track was performed considering track irregularities. The material abrasion at the wheels per traveling distance as a function of vehicle speed was evaluated on a trial basis. The exemplary results in Figure 3 expose a rough trend: wheel wear for guidance grows progressively with the train speed.

The wear partition associated to traction, i.e. longitudinal dynamics, grows less intense but still with the fourth power of the vehicle speed as shown in Figure 3. This characteristic is based on the fact that the longitudinal forces at the wheel-rail interface depend on the resistance forces which in turn are dominated by the aerodynamic drag at very high velocities.

The traction potential itself is as well a function of the running speed. According to the prominent historical survey by Curtius and Kniffler [16], the friction coefficient converges asymptotically against $\mu = 0.16$ on average for very high speeds, while the lower bound of the measurements indicates $\mu = 0.1$ to be a very reliable figure. The aerodynamic drag may approach values of approximately 200 kN at 600 km/h, which requires 13 wheel axles each loaded with 16 t be counterbalanced by traction with $\mu = 0.1$. This appears to be feasible but indicates the necessity to power as much wheels as possible in order to fully exploit the available traction potential. That's why one intermediate car of TGV 150 that set the world speed record of 574.8 km/h in 2007 was equipped with additional powered running gears [17].

3.2 Aerodynamics

Usually the aerodynamic forces like the drag scale with the stagnation pressure $\rho V^2/2$, where ρ is the density of the air and V is the incident flow velocity in the reference frame of the vehicle. In still air V corresponds directly to the driving speed U. It follows that the power which is required to equalize the aerodynamic drag is proportional to U^3, and at higher speeds the aerodynamic drag will exceed the effect of mechanical friction [18].

However, today's driving speeds up to 600 km/h correspond to a Mach number of $M \approx 0.5$, so that new aerodynamic effects associated to the compressibility of the fluid enter the picture. The critical Mach number specifies the lowest Mach number at which the airflow over some point of the train reaches the speed of sound. Above this critical Mach number the aerodynamic quality of the vehicle will degenerate rapidly. To push the critical Mach number above $M = 0.5$ a train requires a relatively long pointed nose similar to the Japanese Maglev train [19].

A highly safety relevant aerodynamic aspect concerns the crosswind stability in particular if lightweight design is under consideration. Although newer train head designs show elements to reduce the cross-wind forces [20], [21], the optimization potential is limited in general. Investigations with the NGT train concept support the assumption that operational train speeds beyond 400 km/h require a specific device to prevent the lift-off and overturning of the vehicle as it is proposed in [22] or as it is conceptually given by the MAGLEV guidance system. An alternative way to deal with the cross-wind issue at higher speeds is to protect the train from strong gusts using wind fences. Such fences could act as sound barrier at the same time and help to reduce noise emissions of high speed trains.

Another safety relevant aspect concerns the aerodynamic loads which the flow around the train induces on its surrounding. These loads typically as well scale with the square of the driving speed. Either the track-side objects like noise barriers or signal installation are placed at a larger distance from the track or the objects are designed more sturdily to withstand the higher loads.

In the range of 200 to 300 km/h the aeroacoustic emissions of a typical high-speed train are in the same order as the wheel-rail sound. At higher speeds above 300 km/h the aeroacoustic effects dominate [23]. The flow around structural elements like the parts of a pantograph cause a dipole type sound emission whose intensity scales with U^6 [24] [25]. This means a pantograph at 600 km/h radiates about 64 times more acoustic power to its surrounding than at 300 km/h. The measurements presented by Kurita [26] showed that a reasonable noise reduction can be achieved by using aerodynamically optimized pantograph geometries, acoustically absorbing surfaces, and so called noise insulation plates on the roof of the train (see also Yamada et al. [27] and Ikeda et al. [28]). The insulation plates shield the acoustic emissions from the pantograph in lateral direction. The experiments of Baldauf et al. [29] showed that by using an actively controlled single-arm pantograph it is possible to reduce the pantograph noise about 10dB compared to the standard pantograph installed at the German ICE trains. Combining new pantograph designs and noise insulation plates, it appears not unrealistic that the radiation intensity of the pantograph noise at 600 km/h can be reduced to today's standard level at 330 km/h. Thus the aeroacoustic emissions of pantographs do not constitute an insuperable obstacle for train speeds above 400 km/h.

3.3 Signaling and Train Control

In an approximation the braking distance grows quadratic with the speed, which means that the minimal braking distance increases from 2800m to estimated 11.2 km at 300km/h. Hence it is state of the art, that drivers cannot control the train by trackside signaling at speeds above 160 km/h. Nevertheless all the elements required for a suitable train control and signaling system are available today:

- Cab Signaling
- Safe and reliable radio connections
- Safe on-board Localization
- Train Integrity Supervision in multiple units
- Continuous control and supervision of speed
- Train separation by moving block
- Automatic Train Operation (ATO)

Most of the Elements are part of the European Rail Traffic Management System ERTMS and proven in use. Only two of the required technologies are currently objective of ongoing research activities: moving block and ATO. Therefore it can be stated that the signaling needs to be adopted for very high speeds but it is not limiting the development.

4. Operational Aspects related to higher train speed

Travel time savings are only possible if the train uses high-speed lines (HSL) for a big part of the journey. Therefore new tracks are necessary to increase the speed to over 320 km/h, which is the current speed maximum in Europe.

Furthermore an efficient operation is only possible with lines exclusively used by high-speed trains during the operation time of day. The higher the speed difference on mixed-traffic lines is (with high-speed, freight and regional trains) the more line capacity gets lost. For a speed over 200 km/h it is difficult to operate mixed traffic lines [30]. Many of the HSLs in the world are used exclusively by high-speed trains: Ligne a grande vitesse in France, Shinkansen in Japan, Passenger Dedicated Lines (PDL) in China and Lineas de Alta Velocidad (LAV) in Spain. The different gauge between HSL and the old network in Spain and Japan prevents these lines of being used by conventional trains. In Germany most of the HSLs are built to allow mixed traffic all the day. The advantage is a better line utilization and a more efficient freight train operation due to shorter route length, low gradients and possibly longer trains. Due to safety reasons in tunnels and capacity restrictions the freight traffic is limited to the night time when there is no passenger traffic. The disadvantage is this concept is the lack of time for maintenance works which has to be done with track or total line closures [31]. In France or Japan HSLs are completely closed for intensive maintenance all the night.

To increase the capacity of an HSL the trains should be operated at the same speed. For this also trains with more stops (comparable to the Kodama trains on the Tokaido Shinkansen in Japan, which stop every 15-50 km) have to use strong motorized vehicles [32].

A general problem of increasing the speed of passenger trains is a growing disparity between the operational effort (energy, wear, etc.) and the travel time savings. The travel time reduces in a hyperbolic way, the additional benefit diminishes with higher speed, but the effort grows exponentially.

4.1 Optimized Traction force with very high speed

For the operational analysis special train models for 300, 500 and 600 km/h are derived from the specified NGT 400. For the 300 km/h level also a special version of the NGT is used and not existing HSTs to preserve comparability.

The dimension of the engines increases drastically with the speed. The 400 km/h version has to handle 18 MW driving power whereas the 600 km/h version has to be designed with at least 40 MW. The latter value doesn’t include efficiency losses and power demand of auxiliary and comfort systems so the electrical systems have to be designed with significantly more power. Usually trains are designed with additional traction force for instance to handle gradients. In view of the enormous propulsion power to install the idea is to dispense with a reserve. A simulation showed that the effect of this saving is not significant. For a line like the new built one from Stuttgart to Ulm there are some sections with 25‰ gradient. Considering a quite low slack time percentage of 3% the journey between the two cities would be only 20 seconds longer. Thus other use cases look similar and it can be stated that a design without a traction force reserve is acceptable.

4.2 Demand analysis for the reference line Paris-Vienna

To gather information about the effect on passenger demand of increased travel speed, the NGT reference line from Paris to Vienna is chosen for analysis. An operational concept for this line for 400 km/h was developed at an earlier stage of the NGT project [33]. The model is reused and modified for the following speed levels: 300, 400, 500 and 600 km/h. The passenger demand model is based on the European rail network. It includes almost all cities with 50 000 inhabitants and more. These are 1900 cities with 237 Mio inhabitants in countries totaling 525 Mio inhabitants. 120.000 kilometers of rail lines (50% of the real network) are used by 2000 routes with an accurate modelling of travel times and stops. Statistical data for the calibration originates from Eurostat [34]. It has accuracy on the NUTS-2 level. These are smaller countries in Germany or regions in France. Additional data from the UIC statistics was used to complement and verify the Eurostat values [35]. The model is used with four operational scenarios corresponding to the speed levels.

Table 1 shows the results of the analysis. With 600 km/h a train journey between the stations in Paris and Vienna would take approx. three hours. 83 Mio passengers would use the 1145 km line with intermediate stops in Strasbourg, Stuttgart, Munich and Salzburg. The 400 km/h train covers the distance within around 4 hours and attracts 69 Mio passengers, while the 300 km/h version takes around 5 hours and attracts 55 Mio passengers.

The transport performance is raised by two thirds between 300 and 600 km/h from 19 to 31 bn. pkm/year. The acceleration from 300 to 400 km/h generates almost half of this benefit (5 bn. pkm/year). The increase from 500 to 600 leads to an increase of 2.6 bn. pkm/year. So the benefit gets smaller with rising speed, which is directly related to the travel time savings.

Table 1: Growing Demand on the reference line Paris - Vienna depending on the speed

	300 km/h	400 km/h	500 km/h	600 km/h
Travel time Paris-Vienna [h:min]	4:42	3:51	3:23	3:03
Passengers [Mio/year] on reference line	55.3	69.1	77.2	83.0
Passenger km [Bn.Pkm/year] on reference line	19.00	24.84	28.38	30.99
Mechanical energy consumption (at wheel level) [MWh] for one run Paris Vienna	19.2	31.6	44.8	60.8

Hence the doubling of the travel speed from 300 to 600 km/h results in a reduction of travel time by 35%, an increase of travel demand by 63% and an increase of energy consumption by 216%.

The heaviest usage of the line can be found between Paris and Strasbourg, between Stuttgart and Munich and on the Austrian part of the line. Despite the strong national traffic volumes, the international traffic profits most of the new travel speed. The traffic volume between Austria and Germany as well as between Austria/Germany and France is growing much stronger than the national ones.

4.3 Impact of very high speed on the operation

The increasing traffic volume effects a more intensive train operation as shown in Figure 4.

One train per hour and direction with a capacity of 800 passengers is necessary when the line is designed for 300 km/h. With 600 km/h two and a half trains per hour and direction have to circulate. Additional trains run between Paris and Strasbourg and between Stuttgart and Vienna. More additional trains are necessary between Stuttgart/Munich and Salzburg/Vienna.

A train every 15 minutes will run between Stuttgart and Munich with 300 km/h. This increases to a frequency of every 10 minutes between the two cities with 600 km/h. All these values are valid in the morning peak hour.

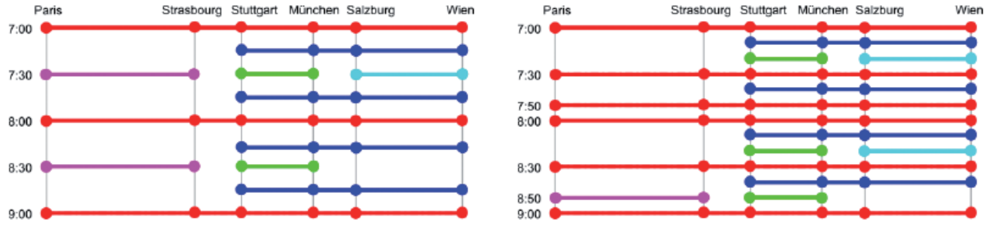

Figure 4: Timetable scheme for 300 km/h (left) and 600 km/h between Paris and Vienna. the most densely traffic occurs between Stuttgart and Munich

Table 2 shows the results of the operational analysis of the different speed levels. The average speed between Paris and Vienna is increasing by 53%, whereas the average speed of all passengers using a part of line is increasing by 23%. The big percentage of using classical railway and the access and egress times reduce this kind of speed. But this value tells us to require big efforts for a network-wide increase of speed and the combination of fast access transport modes like urban public transport or private car or car-sharing in less-dense populated areas.

The number of necessary trainsets is similar over the speed levels, because the higher speed allows a more intensive use of trains which compensates the higher demand. The traffic (operational) performance increases by 57%, though the speed is doubled and the energy consumption triples. This figure shows the faster growing effort compared to a regressive benefit. The operational performance of the trainsets is impressively high; at 600 km/h the project-defined limit of one million kilometres per year is exceeded. A very intensive maintenance is necessary. Probably this will be a big part of the operational cost. The life expectancy probably won’t be 30 years as those by other rail vehicles, especially taking the lightweight construction into account. Thanks to a compulsory reservation and the relative small vehicle size, it’s possible to reach high seat utilization of above 80%.

Table 2: Compilation of operational aspects for the speed levels

	300 km/h	400 km/h	500 km/h	600 km/h
Average speed between Paris and Vienna [km/h]	244	297	338	375
Average speed of all passengers using the line at least for a part of the journey including dwell/ access/egress times [km/h]	119	130	138	146
Specific energy consumption at wheel level [Wh/(km * seat)]	21.0	34.5	48.9	66.4
Number of NGT trainsets (incl. 10% operational buffer)	37	40	42	44
Operational performance on the line Paris-Vienna [Mio trainset-km/year]	29.4	36.3	40.7	46.3
Average operational performance of one NGT trainset [km/year]	786 000	916 000	973 000	1 052 000 *(above limit)*
Seat utilization (reservation compulsory)	81%	86%	87%	84%

5. Conclusions

However even if the exact quantitative values are treated with reserve, Figure 5 nevertheless presents a common trend: whatever effort is considered, there is a progressive rise with respect to the maximum operational speed. The higher the considered level the more costly each additional speed step-up turns out to be.

This is contrary to the expected benefit in terms of travel time reduction, which performs on a diminishing scale. Traveling at 400 km/h maximum speed results in a travel time reduction of 18% compared to travelling at 300 km/h, while 600 km/h maximum speed reduces the travel time just by 10% compared to 500 km/h. Note, already the time span $t(v)$ required to travel a fixed given distance s is a hyperbolic, i.e. a declining, function of the velocity v, reviewed under steady-state conditions temporarily disregarding operational aspects.

As a final result, the authors expect the maximum velocity in operation to tend against a saturation point, but which is depending on external factors, too. The balancing of the benefits, efforts and issues such as crosswind stability and energy supply substantiates the assumption that a further increase of the maximum speed of wheel-rail systems beyond 400 km/h will depend on external influences and looks apparently not reasonable today, which could change in the future under changed conditions. The technology will be there to support to run with even higher speeds.

6. References

- [1] E. Musk, SpaceX, “2013. [Online]. Available:

  http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130612.pdf. [Zugriff am August 2017].
- [2] - H. Hochbruck, High-speed trains, “ETR - International Edition, pp. 6-16, 1 / 2015.
- [3] - L. Sharpe, Japan prepares to build 500 km/h MAGLEV Line, “Engineering & Technology, 2013.
- [4] - K. Ebeling, High-speed railways in Germany, “Japan Railway & Transport Review, Bd. 40, pp. 36-45, 2005.
- [5] - K. Sawada, Outlook of the superconducting Maglev, “Proceedings of the IEEE, Bd. 97, Nr. 11, pp. 1881-1885, 2009.
- [6] - H. Geerlings, The rise and fall of new technologies: Maglev as technological substitution?, “Transportation Planning and Technology, Bd. 21, Nr. 4, pp. 263-286, 1998.
- [7] - K. Knothe und S. Stichel, Schienenfahrzeugdynamik, Berlin: Springer-Verlag, 2003.
- [8] - D. Thompson und C. Jones, Handbook of Railway Vehicle Dynamics, “S. Iwnicki, Hrsg., Taylor \& Francis, 2006.
- [9] - B. Bergander, G. Dendl, A. Nefzger und D. Nicklisch, Die Entwicklung von Rad- und Schienenprofilen, “ZEVrail Glasers Annalen, Bd. 127, pp. 482-493, 2003.
- [10] - G. Sauvage, Running Quality at High Speeds, “Vehicle System Dynamics, Bd. 15, Nr. sup.1, 1986.
- [11] - A. Wickens, Fundamentals of Rail Vehicle Dynamics - Guidance and Stability, Lisse: Swets 6 Zeitlinger Publishers, 2003.
- [12] - R. Kratochwille, Zum Nutzen schaltbarer Schlingerdämpfer in Trassierungselementen mit veränderlicher Gleiskrümmung, Hannover: Dissertation, Universität Hannover, 2004.

- [13] - P. Delfosse, Very-High-Speed Tests on the French Railway Track, “Vehicle System Dynamics, Bd. 20, Nr. 3-4, pp. 185-206, January 1991.
- [14] - J. Kalker, Three-dimensional elastic bodies in rolling contact, Bd. 2, Springer, 1990.
- [15] - F. Braghin, R. Lewis, R. Dwyer-Joyce und S. Bruni, A mathematical model to predict railway wheel profile evolution due to wear, “Wear, Bd. 261, Nr. 11, pp. 1253-1264, 2006.
- [16] - E. Curtius und A. Kniffler, Neue Erkenntnisse über die Haftung zwischen Treibrad und Schiene, “Elektrische Bahnen, Bd. 21, Nr. 9, pp. 201-210, 1950.
- [17] - K. Barrow, French Smash World Speed Record: Test Train Reaches 574.8 km/h on TGV Est, “International Railway Journal, Bd. 12, Nr. 5, 2007.
- [18] - J. A. Schetz, Aerodynamics of high speed trains,“Annu. Rev. Fluid Mech”, Bd. 33, pp. 371414, 2001.
- [19] - N. Shirakuni, Y. Endo, K. Takahashi und K. Yamamoto, Overview of new vehicles for the Yamanashi Maglev Test Line, “in Proceedings of the 17th International Conference on Magnetically Levitated Systems (Maglev 2002), Paper 5104, Lausanne (Switzerland), 2002.
- [20] - J.-L. Peters, How to Reduce the Cross Wind Sensitivity of Trains, “in The Aerodynamics of Heavy Vehicles: Trucks, Buses, and Trains, Lecture Notes in Applied and Computational Mechanics Vol. 19, Springer, 2004, pp. 453-467.
- [21] - M. Schober, A. Orellano, A. Tietze, M. Weise und S. Steilen, Vehicle front end with reduced sensitivity to side winds,“. Patent EP 2383161A1, 2011.
- [22] - A. Heckmann, B. Kurzeck, T. Bünte und S. Loose, Considerations on active control of crosswind stability of railway vehicles, “Vehicle System Dynamics, Bd. 52, Nr. 6, pp. 759775, 2014.
- [23] - C. Talotte, “Aerodynamic noise: a critical survey,” Journal of Sound and Vibration, vol. 231, pp. 549-562, 2000.
- [24] - E. Latorre Iglesias, D. J. Thompson und M. Smith, Component-based models to predict aerodynamic noise from high-speed trains, “in Noise and Vibration for Rail Transportation Systems, Volume 126 of the series Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Springer, 2015, pp. 481-488.
- [25] - E. Iglesias Latorre, D. J. Thompson and M. Smith, “Experimental study of the aerodynamic noise radiated by cylinders with different cross-sections and yaw angles,” Journal of Sound and Vibration, vol. 361, pp. 108-129, 2016.
- [26] - T. Kurita, “Development of external-noise reduction”, Journal of Environment and Engineering, vol. 6, no. 4, pp. 805-819, 2011.
- [27] - H. Yamada, Y. Wakabayashi and T. Kurita, “Noise evaluation of Shinkansen high-speed test train (FASTECH360S,Z),” in Proceedings of the 8th World Congress on Railway Research, Seoul, Korea, 2008.
- [28] - M. Ikeda, T. Mitsumoji, T. Sueki and T. Takaishi, “Aerodynamic noise reduction in panthographs by shape-smopothing of the panhead and its support and by use of porous material in surface coverings,” Quarterly Report of the RTRI, vol. 51, no. 4, pp. 220-226, 2010.
- [29] - W. Baldauf, R. Blaschko, W. Behr, C. Heine and M. Kolbe, “Development of an actively controlled, acoustically optimised single arm pantograph,” in Proceeding of the World Congress of Railway Research WCRR, Colonge, Germany, 2001.
- [30] - S. Andersen, Zur Problematik des Mischbetriebes von Reise- und Güterzügen bei

hohen Geschwindigkeitsunterschieden, “Eisenbahntechnische Rundschau, pp. 351-360, 05 1995.

- [31] - O. Grein, Success Factors of the German High Speed Rail System, “in Conference High Speed Rail in Europe and the Czech Republic, Prague, 2014.
- [32] - S. Andersen, Hat der Hochgeschwindigkeitsverkehr in Deutschland noch eine Zukunft?, “ZEV rail Glasers Annalen, Bd. 136, Nr. 5, pp. 186-193, 2012.
- [33] - T. Schumann, Operational concept Paris to Vienna, “RTR Special - Next Generation Train, 12 2011.
- [34] - Eurostat, Eisenbahnverkehr - Innerstaatlicher und Grenzüberschreitender jährlicher Eisenbahnpersonenverkehr nach Einsteige- und Aussteigeregion, “2005. [Online]:

http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=tran_r_rapa&lang=de. [access: 15.09. 2011].

- [35] - UIC, International Railway Statistics, Synopsis, 2009.