ARTICULATED TRAIN OF DEEP WELL CARS FOR HIGH-SPEED CONTAINER TRANSPORT

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ABSTRACT

A literature search on the length, mass and speed of passenger and freight trains revealed a close connection; particularly high speeds seem to be allowed only trains whose mass is distributed over a correspondingly large length. The product of mass per length (t/m) and speed (m/s) appears in the dimension (t/s) to represent a kind of stress or footprint for the infrastructure of the tracks and bridges. Resonances caused by air flow around the successive vehicles within the train at the same distance can be avoided by the surface design. Resonances caused by wheel–rail vibrations can be damped by unsymmetric chassis such as those under the Talgo and AGV. High board walls prevent containers from detaching from the train due to vibrations. Derailments due to speed that is too high for the track geometry (e.g. track arches that are too narrow, transition arches that are too short) can at least be partially prevented by particularly large wheelbases, semi-permanent couplings between bogies and lateral buffers. In this way, the vehicle frames would be connected by a separable Jacobs bogie, which would transmit rolling torques along the train and prevent individual axles from climbing up. Unfortunately, despite all the safety systems, there are still collisions between trains. The proposed container train is very long for its mass, with only one high-cube container 40 ft per wagon and with a large wheelbase. This length can act like a built-in brake bumper in the event of a collision. In the event of a collision, the container load is protected by shortening the train as necessary. The development of the new high-speed container train is to be supported with data from our own simulations and measurements as well as from previous literature.

Keywords: mass per length, speed, stress for tracks and bridges, footprint, vibration resonances, asymmetric chassis, derailments, detachable Jacobs bogies, simulations, measurements.

1 INTRODUCTION

According to Watson et al. [1], there is a market for transporting priority cargo on high-speed freight trains and in 2020 [2] a vehicle and a fleet of trains were proposed to transport 40 ft high-speed high-cube containers (Fig. 1). The literature on high-speed trains (HS) and interesting freight wagons, in particular container wagons, was reviewed (Table 1). A strong correlation between velocity and a quotient C of the concentration mass per length was found (Fig. 4). All examples from the literature seem to “stick” to the axes below threshold values.

However, the Pocket Wagon [3] is already in use in the UK, which transports high-cube 40 ft containers through the low and narrow loading dimensions of the UK. In order to be able to start the high-speed container service earlier, the Pocket Wagons+ should travel at 201 km/h using the Mark III bogies and locomotives of the now discontinued HST125 fast diesel multiple unit [4].

These were the proposals of 2020, illustrated with simple 2D graphics. In the meantime, the vehicle and train evolved into a new design called the Aero, and its graphic representation evolved as well. Now there is a 3D axonometry (Fig. 2) and even a PowerPoint animation film with a central perspective. Fig. 3 shows a screenshot of it, supplemented by streamlines. In Figs 2 and 3, the cross-section of the Aero is slightly v-shaped, so that cross-wind currents such as those that caused the Tacoma Narrows Bridge to collapse in 1940 [5] do not endanger it.

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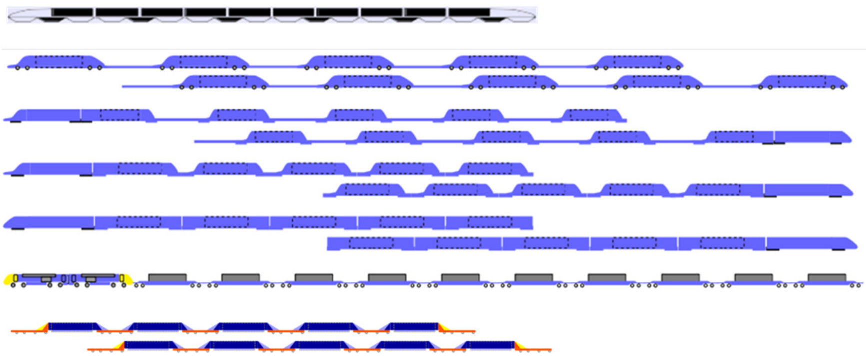

Figure 1: High-speed container train projects (from the top): Aerosprinter2002, four Aeros and Pocket Wagons+2020, Aero2022.

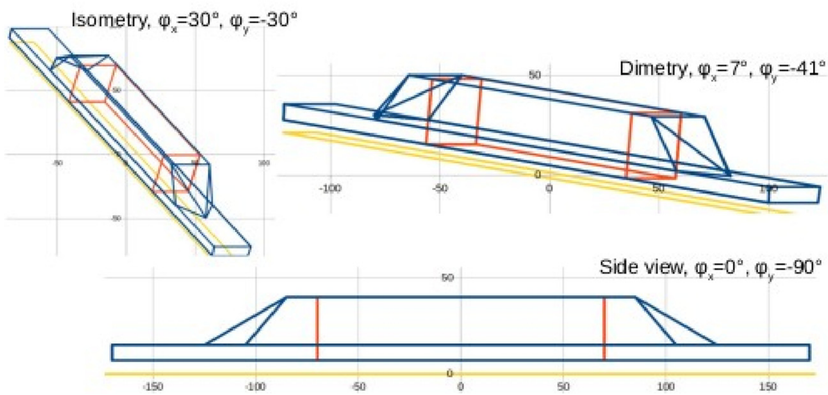

Figure 2: Aero vehicle in 3D axonometry.

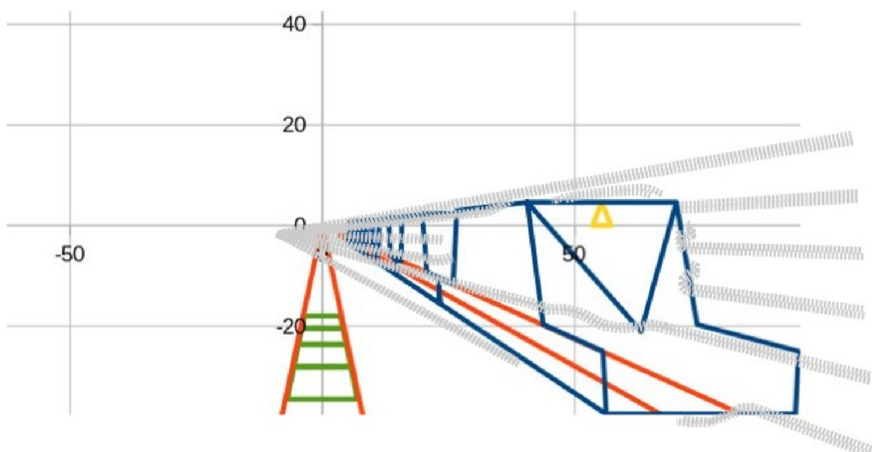

Figure 3: Aero train sketch with headwind and crosswind streamlines.

Table 1: Vehicles and trains.

Type	L (m)	m (t)	C = m/L (t/m)	V (km/h)	A = C × V/3.6 (t/s)
Freight cars DR/DB [8]:					
Fad 169	12.81	64.9	5.07	80	112.66
Hbis 298	14.02	40.8	2.91	100	80.84
Habiss 345	21.70	80.0	3.68	120	122.65
Laae 540	22.12	39.7	1.80	80	40.00
Laeqrss 548	26.24	45.4	1.73	120	57.66
Laaes 549	113.74	151.3	1.33	100	36.95
Saads 704	31.87	126.5	3.97	100	110.29
Sdkms(s) 707	16.44	51.5	3.13	120	104.32
Sahs 711	16.40	95.8	5.84	100	162.24
Sgjs(s) 716	21.08	79.7	3.78	120	125.99
Tefhss	11.74	39.0	3.32	120	110.66
TT.nhhrs 19	16.27	65.5	4.03	100	111.95
Ibblpqrs	14.02	39.7	2.83	100	78.62
Fals 183	12.54	89.8	7.16	100	198.90
Eas 5951	14.04	80	5.70	100	158.35
Soviet Highboard cars [9]:					
4-axles	13.92	83.0	5.96	100	165.57
6-axles	16.40	126.0	7.68	100	213.35
8-axles	20.24	167.8	8.29	100	230.30
Soviet or Russian Railcars [9]:					
DP-01-08	158.7	367	2.31	104	66.74
DP-1-10	78.9	138	1.75	120	58.33
DP-11/12	48.1	90	1.87	125	64.93
DP-14	70.2	161	2.29	160	101.77
DP-15	69.5	161	2.32	160	103.10
DP-21	73.6	165	2.24	120	74.66
ER-200-8	208.0	442	2.13	180	106.50
ER-200-14	364.0	787	2.16	180	108.00
Sokol-250	158.0	356	2.25	250	156.24
TGV family [10]:					
Paris-Sud-Est1	200.2	428	2.14	270	160.50
Paris-Sud-Est2	200.2	409	2.04	300	169.99
Atlantique	237.6	479	2.02	300	168.33
Réseau	200.2	388	1.94	320	172.45
Postal	200.2	345	1.72	270	129.00
Eurostar	394.0	752	1.91	300	159.16
Thalys PBKA	200.2	416	2.08	320	184.89
Duplex	200.2	380	1.90	320	168.89
Est-Européen	200.2	423	2.11	320	187.56

Table 1: Continued.

Type	L (m)	m (t)	C = m/L (t/m)	V (km/h)	A = C × V/3.6 (t/s)
Shinkansen family [10]:					
A	49.5	120	2.42	250	168.04
B	99.5	240	2.41	250	167.35
0, 16 cars	400.3	967	2.42	220	147.89
961	150.3	351	2.34	260	168.99
962	150.3	348	2.32	210	135.33
200, 16 cars	400.3	1.088	2.72	240	181.34
100	402.1	925	2.30	230	146.95
2000	402.1	1.088	2.71	275	207.02
300	402.1	710	1.77	270	132.75
400	128.2	312	2.44	240	162.67
WIN 350	151.6	230	1.52	350	147.77
Others [10]:					
HST/IC-125	220	435	1.98	201	110.54
ICE 1	410.7	911	2.22	250	154.16
ICE 2	205.0	412	2.01	260	145.16
Velaro family	250.0	667	2.67	250	185.40
Special examples:					
300 X	152.0	210	1.38	400	153.33
Parcel-IC	197.4	525	2.66	160	118.21
CS/T-Long	118.2	308	2.61	120	86.99
CS-Light	90.4	233	2.58	120	85.99
CargoSprinter	90.4	281	3.11	100	86.40
Talion-Light	90.4	238	2.63	120	87.66
Talion	90.4	286	3.16	100	87.78
Container Train	259.4	840	3.24	100	90.01
CargoMover Train	259.4	940	3.62	90	90.50
WELL cars (USA)	174.4	830	4.76	112	148.08
FLAT cars (India)	135.6	863	6.36	100	176.68
empty Uaai 839	50.3	263	5.22	80	115.99
Uaai 839	63.8	717	11.23	65	202.81
Projects:					
AeroSprinter-Railcar	407	628	1.54	350	**149.72**
AeroSprinter-Long	370	754	2.04	310	175.66
AeroSprinter-BC	305	716	2.35	270	176.25
AeroSprinter-A	305	736	2.41	230	153.97
Pocket Wagons+	255	871	3.41	160	151.54
AeroSprinter 2002	250	1.001	4.00	230	255.56
AeroSprinter 2020	250	1.001	4.00	100	111.12
Aero 2022	536	750.4	1.4	360	140

A = C × V/3.6 (t/s)	
226.94	ar.mean+2*std.dev.n
181.27	ar.mean+std.dev.n
158.44	ar.mean+1/2*std.dev.n
135.60	ar.mean
45.67	std.dev.n

As a newcomer, Aero will meet with a lot of scepticism and must never be involved in accidents or even cause them. Considerations on accidents and their prevention were already under way in 2020 [2]. Therefore, in Section 3 and 4 it is proposed to experiment with models on a larger scale.

Simultaneously with the container train Aero, a footprint theory had been developed in 2020 based on literature data and inspired by Sato [6]. As explained in Section 2, this has also evolved since then.

2 THE FOOTPRINT THEORY

In Haferkorn [2], literature data of vehicles and trains were defined as "admissible" if they belong to a union set defined by the thresholds maxV ≤ 160 km/h or C = m/L ≤ 2.8 t/m, as shown in Fig. 4. Both thresholds seem arbitrary, but are apparently confirmed by practical experience. A less arbitrary approach is to add another column to Table 1 and let the point cloud data itself decide admissibility.

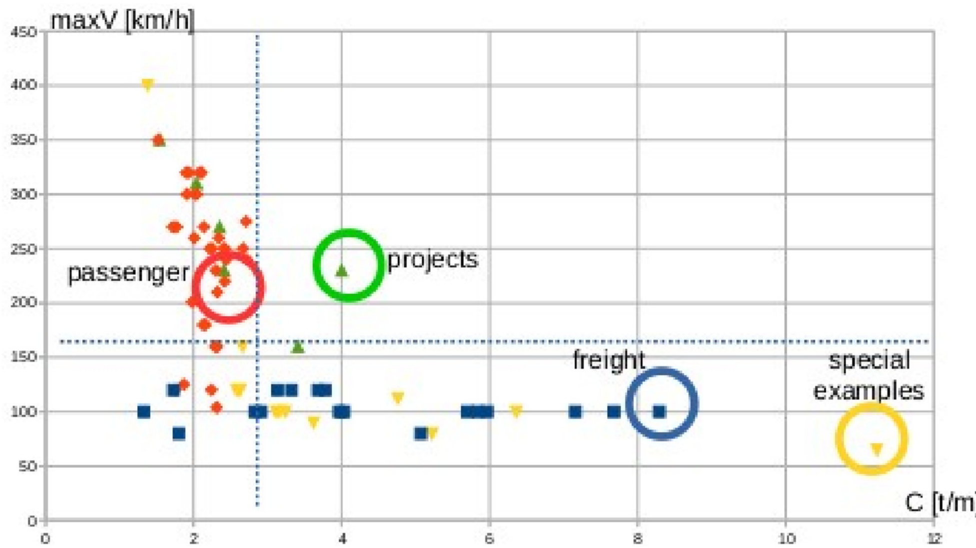

Figure 4: MaxV and mass per length concentration C of vehicles and trains.

Multiplying maxV with C gives a product value A (t/s); A = V × C/3.6. Like the constant c in the hyperbolic formula x × y = c, A is a scalar and statistical value with an arithmetic mean and a standard deviation (Table 1, Fig. 5). So it is quite easy to explain why the AeroSprinter 2002 is not allowed again (the ar.mean + std.dev threshold is clearly exceeded), and the Soviet highboard vehicles with two, three and four axle bogies should be checked for speed. But A is also a meaningful value: it is the stress amplitude, the footprint of a train on the infrastructure. In the early days of the railway, at least one reason for the collapse of the Tay Bridge was that trains often ran over it too fast to keep to the timetable. (Other reasons were the weak bridge construction and the heavy storm at that night [7].)

Figs 6 and 7 show how different tensile masses, lengths and mass per length (mpl) concentrations C have to be compensated by velocities V in order to keep products A = C × V/3.6 at a reasonable level. The mass m (t) is represented by a yellow 3D ball, which

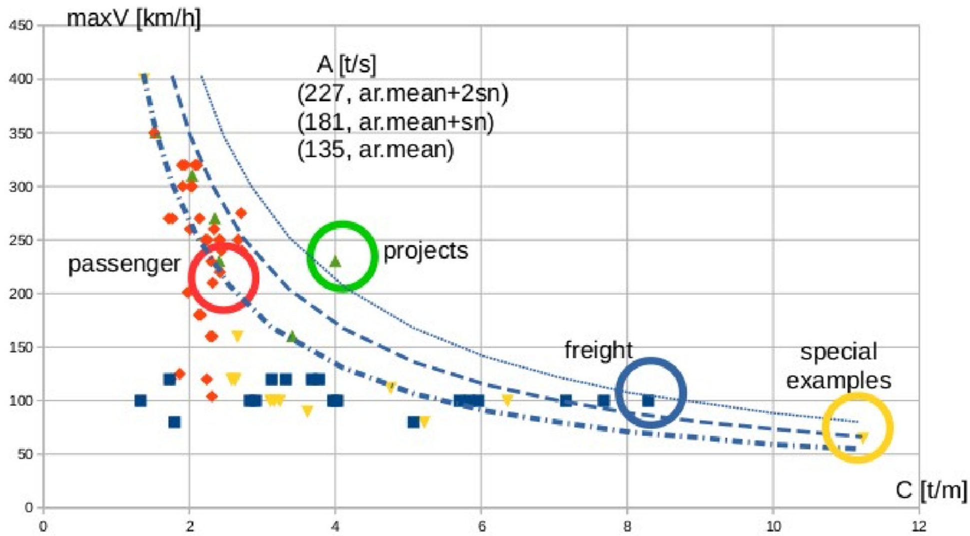

Figure 5: Vehicles and trains, maxV vs mass per length concentration C plus levels of stress amplitude A.

of course has to be distributed over the train length. The speed V (km/h) is represented by two parallel lines, the horizontal distance of which corresponds to the length of the train and the vertical distance of the time. The trains in Fig. 6 seem to run on more or less thick blue lines, which are supposed to represent the respective mpl concentrations C.

In Fig. 7 on the left, the black train lengths and blue mpl concentrations are transferred to the green driving times and the red voltage amplitudes A via the diamonds below. The masses m are shown here as yellow 2D surfaces:

$$C \times L = m \text{ and } v \times A = m.$$

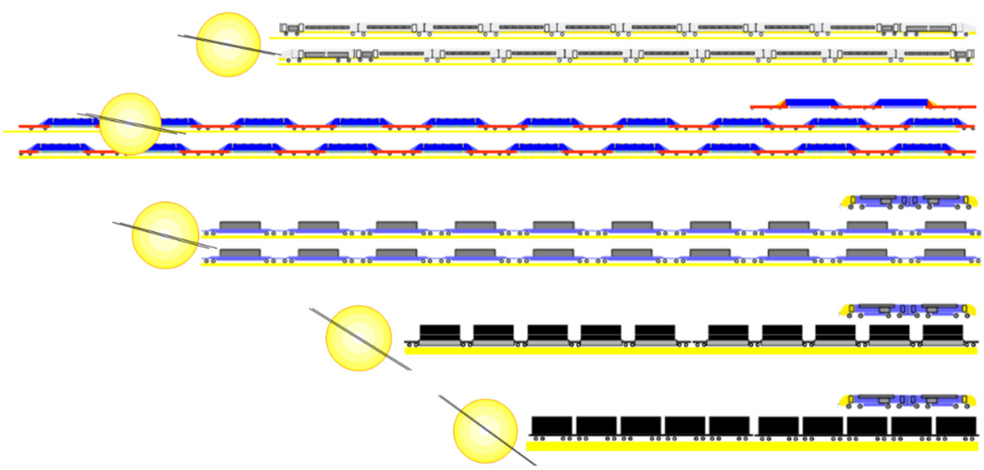

Figure 6: Mass, speed, length and mass per length concentration C of (from top to bottom) Eurostat, Aero, Pocket Wagons+, Well cars (USA) and Flat cars (India).

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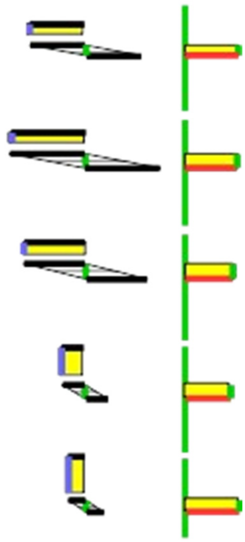


	m [t]	L[m]	C [t/m]	V [km/h]	A [t/s]	T [s]
			mass.concentration		stress.amplitude	
			m/L		C*V/3,6	L/V*3,6
Eurostar	**752**	**394**	**1.91**	**360**	**191**	**3.94**
Aero	**750.4**	**536**	**1.40**	**360**	**140**	**5.36**
Pocket Wagons+	**1000**	**438**	**2.28**	**270**	**171**	**5.84**
WELL cars (USA)	**830**	**161**	**5.16**	**112**	**160**	**5.18**
FLAT cars (India)	**863**	**126**	**6.85**	**100**	**190**	**4.54**

Figure 7: Length, mass-per-length concentration C, speed V and stress amplitude A, the footprint on infrastructure.

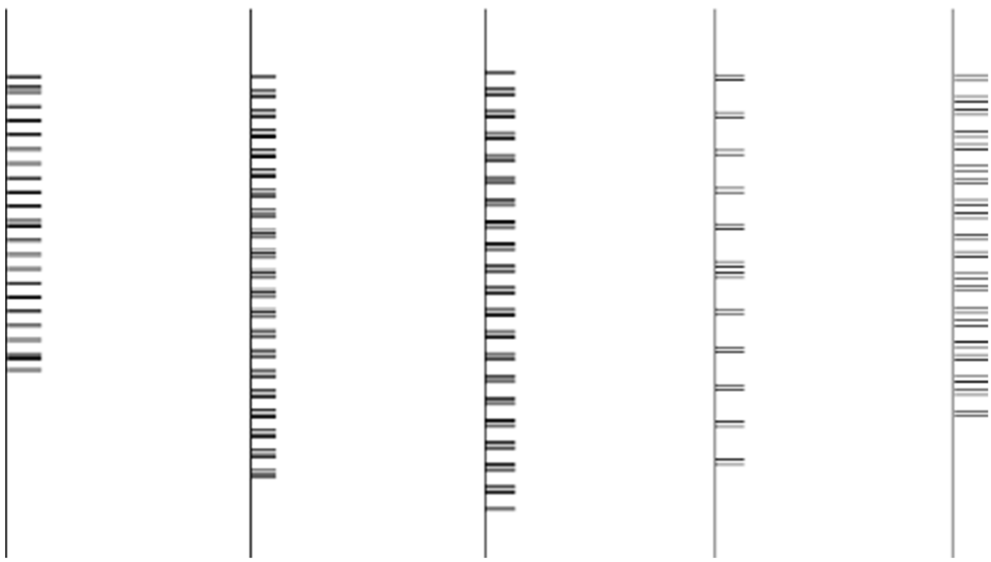


Figure 8: Probable vertical acceleration marks of (from left to right) Eurostar, Aero, Pocket Wagons+, Well cars (USA), and Flat cars (India).

Further right in Fig. 7 the amplitudes A are plotted along the green vertical time axis. The voltage amplitude A seems to act at a certain point in the infrastructure like a short stroke between long rest periods.

As confirmed by the literature [6], [8], [9], the effects of the stress amplitude A of trains on infrastructure, in particular on bridges or switches, can be measured in the form of vertical acceleration. Fig. 8 gives an idea of what A might look like if it was recorded or sounded if it was intercepted. The trains come in very different masses, lengths and speeds. But the corresponding time T, the height of the diagrams, and the corresponding voltage amplitude A, the width of the diagrams, do not differ too much. Fig. 8 is a data visualization that has yet to be confirmed by measurements. However, the individual trains already seem to show the individual footprint of their bogies or even their axles.

3 DESIGN STUDIES, ACCIDENTS PREVENTION, IMPACT MITIGATION

A long list of rail vehicles and even some road vehicles influenced the Aero design. The most important factor, however, was how to prevent accidents or at least mitigate their consequences.

The stress amplitude A has an effect on bridges and track arches, in particular turnouts [6], [8], [9]. Low-voltage amplitude trains such as the Spanish Talgo, the Italian Italo, the British APT, the Swiss light steel high-speed trains [10] and the German Schienenceppelin [11] could have been much faster, but could not have been justified due to accident concerns.

Chen and Guo [12] saw collisions [13] and derailments [14] as the most common types of accidents, and Table 2 tries to get an idea of where to take corrective measures/solutions for a new train as the Aero.

Table 2: Railway accidents, types, causes and remedies/solutions.

Accident types	**Causes**	**Remedies/solutions**
Collision	Lost containers	(Deep) well cars
Collision	Runaway train	Internal buffer stops
Derailing (jackknifing)	Cornering too fast	Articulated/Cardanic coupling
Derailing (capsizing)	Crosswind	Articulated/Cardanic coupling
Derailing	Resonance	
Resonance	Repeated surface shapes	Reversed wing profile
Resonance	Short rails	Continuously welded track
Resonance (hunting)	Rolling system symmetry	Asymmetric rolling system

3.1 Resonance due to flow around the container well and shaking in the chassis

First, flow resonance: In order to separate the containers far from each other, the Aero vehicles became very long, and large distances remained between the container wells, which were supposed to be flow-friendly on their own (Figs 2 and 3). These distances allow streamlines to flow around vehicles and trains without turbulence at high speed. However, the constant return of the same forms can also lead to resonance. Which scenario really occurs has to be clarified in a separate study.

The skeletal structure of the Schienenzeppelin [11] gives an idea of how the Aero wells can become light, long and flow-friendly. However, the silver canvas coating should be replaced by thin steel sheet with stabilising golf ball embossing in order to hold the streamlines together [15].

Alstom AGV [16], Talgo [17], [18] and Hanover's TW 3000 [19] suggest that hunting [20] can also be calmed by an asymmetry of the suspension. Asymmetry is naturally found in all road vehicles [21], so that lightweight components [22] and independent wheels [23] can be derived for rail vehicles.

3.2 Derailments: Shongololo rolling system

Shongololo is a giant millipede [24] and a nickname for trains in the South African isiZulu. Alstoms TGV [25] and AGV [26] use Jacobs bogies to prevent derailments. Like millipedes, they transmit torsion moments between adjacent vehicle frames and thus prevent the climbing of wheel flanges. Fig. 10 shows a TW 3000 [19] as a special edition fife-element articulated shongololo train, which crosses an arc of 50 m diameter without derailing.

However, the Aero requires cardan-coupled bogies or detachable Jacobs-type bogies to transmit the roll moments [27] and to prevent its vehicles from derailing at high speeds. Side buffers are supposed to catch the yaw moments [28].

3.3 Collisions: telescopic drawbars as built-in buffer-stops

In Fig. 11 two variants of the asymmetrical Aero rolling system are shown as a built-in buffer-stop [29]. They combine the rolling system of the (original) Talgo [18] with conventional bogies (Fig. 9), drawbar dollies for truck trailers [21] and railway buffer-stops [29].

The Aero has become unusually long in order to keep the mpl concentration low in favour of the high speeds. In the event of a collision, this additional length in the telescopic drawbar shortens and intercepts the impact like a built-in buffer-stop [29].

4 ENGINEERING: PROTOTOTYPING, TESTING PLANTS AND TESTING DRIVES

It will be a technical task to prove the footprint theory and to develop prototypes of a highspeed container train. In 2020 [2] the tasks were formulated in specifications, in 2022 a list of study assignments will follow.

Simulation and model experiments (1:10) are often combined [30], [31]. Simulation is a great tool to answer questions and will certainly be used. But in the end prototypes have to be built and tested. With regard to derailment, collision, high speed, development time and cost, this should not exclude smaller models [32] or narrow gauge vehicles [33].

The following list of study assignments will be examined:

- Speed and mpl concentration are the factors for the infrastructure stress: C[t/m] × v[m/s] = A[t/s].
- Low and narrow vehicle cross-section enveloping HC-40ft containers enables the worldwide use of high-speed container trains, even under British loading gauges.
- Low and narrow as well as air-flow friendly container wells between long and low chassis enable low-vibration, high-speed operation even in strong crosswinds.
- Steel sheet with golf ball embossing as outer skin reduces air resistance and mass and increases strength.
- Asymmetric articulated Jacobs bogies ensure smooth running even at high speed.
- Wheel set bogies can replace loose wheels.
- Cardanic (torque-resistant) semi-permanent coupled bogies with side buffers prevent derailments and jackknifing.
- Telescopic chassis mitigate collision impacts.

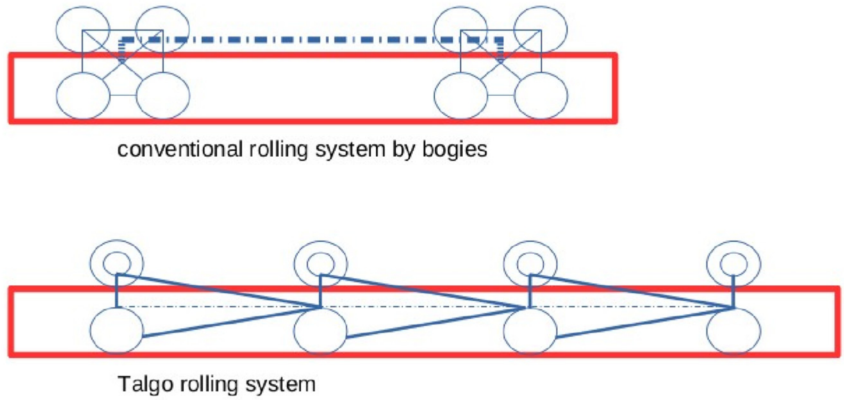


Figure 9: Rolling systems in comparison (Talgo).

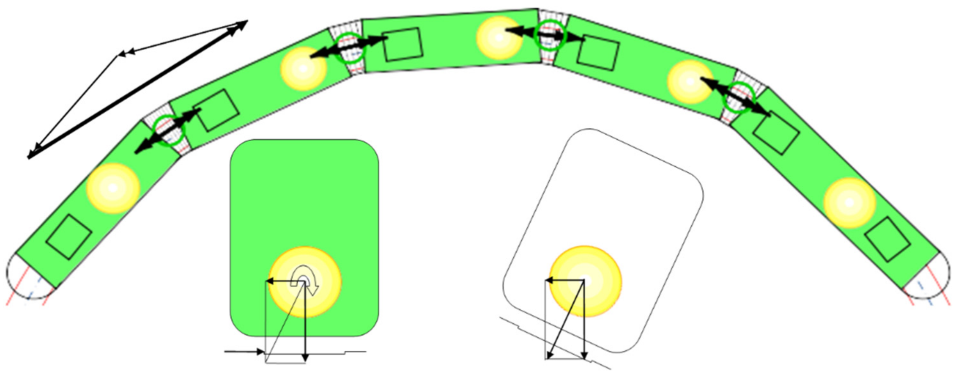


Figure 10: Hannover ÜSTRA's TW3000 is made an asymmetric derailment-resistant "Shongololo" millipede (TW3000).

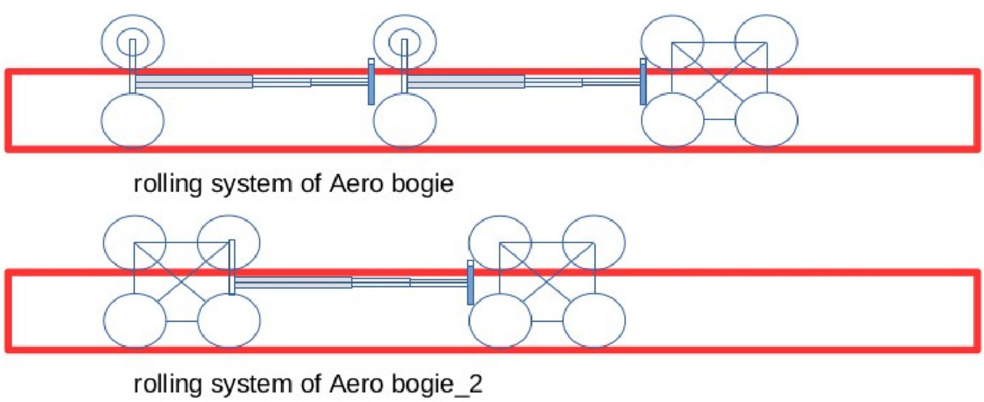


Figure 11: Asymmetric Aero rolling systems with telescopic onboard buffer-stops.

4.1 Testing the footprint theory

Video cameras are already being installed in tiny model trains [34]. The installation of acceleration sensors in trains and also locally (e.g. under track connections) of model railway systems should therefore be possible without any problems, but also in full scale vehicles and rail systems. The on-board sensors measure and send their data to a local receiver where it is combined with the data from the local sensors on the route to determine velocity v, mpl concentration C and stress amplitude A.

4.2 Aero-prototyping

Small prototypes can be tested in a tub-shaped arrangement with gravity drive (Fig. 12). This is tilted by an angle to compensate for the rolling resistance of the prototype. The prototype starts on the left at a height h above the ground, and without the other prototype standing in its way, it would reach the same position on the right. However, both prototypes collide and come to a halt in the middle of the hull with their bogies shortened by the impact.

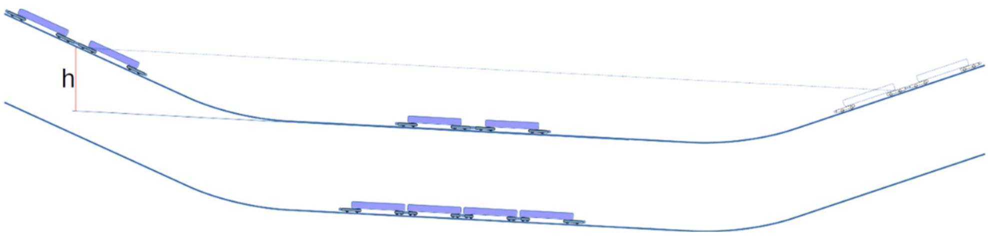


Figure 12: Gravity drive, trains before and after collision.

Another application of gravity drive is the testing of rolling system prototypes. It has to be clarified whether resonance can be soothed by asymmetric suspension or also by independent wheels.

The gravity drive can also be used to determine which speed and track curvature separable and torque-transmitting Jacobs bogies can withstand without derailing. The circular curved track arch is located in the middle part of the hull, where the speed is constant [31].

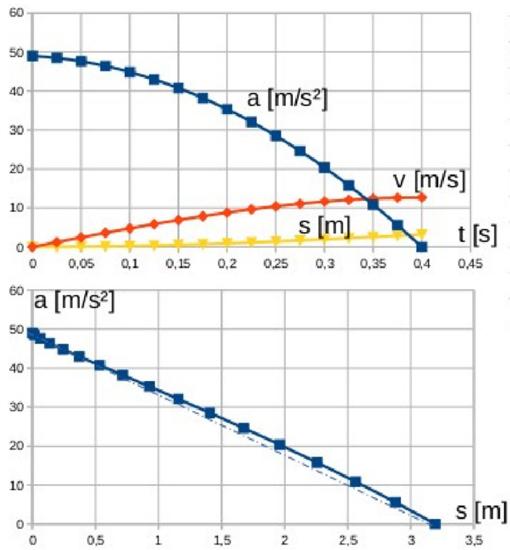
For H0 models, the 24-hour timetable is reduced to 15 minutes on a scale of 1:87 (and train speeds accordingly), i.e. to 7 1⁄2 minutes day and 7 1⁄2 minutes night. This also means that a world record train in 1:87 scale instead of 574.8 km/h [32] would not go faster than 1.84 m/s in such a 1:87 scene.

In gravity drives the acceleration a = a0 is constant. The velocity v = a0 × t is linear and does not depend on the mass or the gradient. When a vehicle or train runs down from height h, velocity v and altitude h follow the formulae $v = \sqrt{(2 gh)}$ and $h = v2/ (2 g)$.

With a gravity drive, the discharge height h of the record 1/87 scale train would be only 0.17 m.

For large prototypes in scale 1:5 or 1:2 or in narrow gauge [33], a rubber belt drive is required (Figs 13 and 14). The acceleration a(t) (starting with about 5 g) is a quadratic function of time t. Speed v(t) and path s(t) as integrals of a are greater powers of t, and here they are also dependent on the mass of the prototype. Against the path s(t) is a(s) approximately linear. (Ultimately, it's all about speeding up prototypes with limited budgets to impressive speeds.)

Figure 13: Rubber belt drive. Start = full lines; Stop = dashed lines.



a(t)=(a2*t+a1)*t+a0
v(t)=((a2/3*t+a1/2)*t+a0)*t
s(t)=(((a2/12)*t+a1/6)*t+a0/2)*t²

a0	a1	a2	
49	**-14.5**	**-270**	
t [s]	a [m/s²]	v [m/s]	s [m]
0	49	0	0
...	...	...	...
0.4	**0**	**12.7**	**3.19**
		(45.72 km/h)	

Figure 14: Rubber belt drive functions a(t), v(t), s(t), a(s).

The world speed record on the LEGO tracks is 30.67 km/h = 8.52 m/s [35]. The record holder is an AGV Italo in scale 1:47. (For the "big" train this would be 1,438 km/h.) Even a gravity drive of 3.70 m height could reach 30.67 km/h.

The rubber band drive from Fig. 14 goes even further with V = 45.72 km/h = 12.7 m/s, provided the acceleration a(t) really starts at 5 g. The gravity drive would need a height of 8.22 m to accelerate trains to that speed.

5 CONCLUSIONS AND OUTLOOK

The Japanese concept trains on the island of Kyushu [36] are a good model for the Aero. Even if they are passenger trains and not container trains, they show how ideas are put into plans and plans into full-scale reality.

It looks as if the container train Aero can be used in conjunction with passenger trains and on the same tracks, for example on the HS-2 in Great Britain [37], [38], for reliable (i.e. accident-proof) and sustainable high-speed operation. It will take a lot of time and money to prove this and to develop and manufacture the Aero, even if only models are used as prototypes.

It is not the speed of the container train that is of greatest interest, but the overall speed of the container from door to door. Therefore, the collection and distribution of containers over the last kilometres and metres to and from the terminals should also be investigated. It is to be hoped that other rail systems will take over a large part of this and not leave too much to road transport.

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