Braking dynamics

Target here is not to propose a complete course about railway dynamics, nor explain in details macroscopic physics of trains braking, but only to understand the difficulty not to theoretically determine a train braking performance but to find easy methods to determine the most precisely possible the performance of a train during daily operation, in particular when this train is composed of very different vehicles with very different performances.

Several parameters have to be considered among which:

- Train length: when the braking control is pneumatic, response times are very different as a function of train length (see page on pneumatic brake control), and directly influence the stopping distance.
- Friction characteristics of brake components (brake shoes, discs and pads): these characteristics may vary as a function of several factors (such as initial braking speed, instantaneous speed, humidity, type of material, etc.) and have a direct impact on the stopping distance.

We will see how to practically determine the braking performance of a train before it will be set into operation. This process has a very important aspect as it leads to define the operating speed of a train as a function of operated line characteristics: any mistake can thus lead to a too high operating speed in relation to braking capacities, and as a function of signaling block length.

Note that this braking performance is one of the parameters introduced by the driver in the main unit of the KVB during train composition, and which then enables this KVB to determine speed control curves at any time of the train operation.

Equations of the dynamics

Those who keep some reminding of their student courses will remind that the stopping distance of a vehicle slowing down with a constant deceleration is given by the uniformly varied motion law:

$$D = \frac{1}{2} \times \gamma \times t^2$$

where γ is the vehicle deceleration, and t is the time.

Braking time is obtained with the following formula:

$$S_0 = \gamma \times t$$

where S_0 is the initial braking speed.

Thus, from the previous two formulas, it is possible to get two other formulas linking the stopping distance and the deceleration:

$$D = \frac{S_0^2}{2 \times \gamma} \quad \text{or} \quad \gamma = \frac{S_0^2}{2 \times D}$$

Finally, it shall be recalled to mind that the deceleration comes from the following formula:

$$F = M \times \gamma$$

where M is the vehicle mass and F the sum of all brake forces applied to the vehicle.

Note - The mass M considered here is what is called the dynamic mass of the train. Indeed, the various devices in rotation (such as axles, brake discs, traction motors, transmissions) are "consuming", internally to the train and due to their rotational inertia, a part of applied brake force: the deceleration finally obtained shall therefore take into consideration the internal loss of brake force.

Notion of braked weight and percentage of braked weight

Introduction

The mathematical process mentioned above is convenient for railway vehicles design, but its use is quite difficult for daily operation. This mathematical process is also adapted for the definition and determination of braking performances of rolling stock with fixed composition (e.g. trainsets) during their design as well as during their operation, but is quite more difficult to use when the train is composed of different vehicles with sometimes different performances, in particular for operating needs.

However, the major part of traffic remains ensured by a train composed of a locomotive hauled trains. Therefore it is of interest for the operator to be able to easily determine the braking performances of each train as a function of specific braking capacities of each vehicle in the train, and taking also into consideration the fact that length and the load of the train can change from one day to the other.

Moreover, it shall also be taken into consideration that the braking capacities of the trains will have to be determined by agents in charge of their composition, these agents not having means nor time to perform the determination of the braking performance of each train composed during a day of operation by means of a complex mathematical calculation. And if today micro-computers (of digital pads) can include applications rendering this type of complex calculation accessible to all; it was not the same only thirty years ago !

This is the reason why UIC defined easy methods for determination of braking performances of trains, so that these performances can be used to immediately define the train category, its maximum operating speed and eventual operating restrictions to which it will be submitted as a function of the characteristics of the infrastructure on which it will be operated. In addition these methods shall also be commonly admitted by all the members in order to enable international operation on the common basis.

Thus where developed the notions of braked weight and percentage of braked weight. The basic idea of these parameters is the following: each vehicle in a train shall have one or several braked weight, and the braked weight of a train is the sum of braked weight of the vehicles composing the train. This is the reason why the braked weight is mentioned on all vehicles that may be exchanged between Operators (as well as on locomotives), as it enables to determine the braking performances of trains composed with these vehicles.

Taking into consideration the complexity of the methods and the numerous particular cases which it is subject to, target is here to only present a very general synthesis that makes it possible to understand the general principle of this method. To know all details, please refer to UIC 544-1 leaflet.

General principle

UIC defined as a basic principle that a train composed with 15 coaches, two bogies (60 axles) which stops in 1000 meters from an initial speed of 120 kph has a percentage of braked weight of λ = 80%.

Based on this principle, UIC realized abacus for a single vehicle and for a train with 60 axles, making it possible to define, as a function of the braked weight, the stopping distance for the both common operating speed at this time: 100 kph and 120 kph.

Well… Very nice... But this does not define how to determine the λ of a vehicle… There are in fact two methods:

- By means of tests.
- By means of calculations.

Determination by means of tests

The stopping distance is measured for all speeds mentioned on the UIC abacus between 100 kph (wagon) or 120 kph (coach) and the maximum operating speed of the vehicle, for braking mode P and in emergency braking:

- Either for the single vehicle with uncoupled tests (the vehicle is hauled by means of remote controlled coupler, then the locomotive is uncoupled and the vehicle is braked).
- Or for a 400 m (coaches) or 500 m (wagons) train composed only with concerned vehicles hauled by an unbraked locomotive.

Generally, both types of tests are performed.

The measured stopping distance is then reported in the UIC abacus, which makes it possible to determine the λ. The braked weight if then deduced from the λ for each initial speed, and the lowest value obtained will be mentioned on the vehicle.

Example

A train composed of 15 coaches with 2 bogies each, all identical and with a weight of 42 tons each, hauled by an unbraked locomotive with a mass of 150 tons, has a stopping distance of 875 m from 120 kph. UIC abacus shows a λ corresponding to 93%, which gives for the train a braked weight of:

$$B_{train} = \lambda \times M_{train} = 0,93 \times (15 \times 42 + 150) = 725,4 \text{ tons}$$

Thus each coach has a braked weight of:

$$B = \frac{B_{train}}{15} = \frac{725,4}{15} = 48,36 \text{ tons}$$

Thus the braked weight at 120 kph of a coach is 48 tons.

The only problem is: this type of test is very heavy, expensive and long to perform. Moreover, when the concerned vehicle is a new one, it is not very easy to wait for having a sufficient number to compose a 400 or 500 m train: this is the reason why this method is now only used in particular conditions.

Determination by means of calculations

Existing calculations means make it possible to perform a stopping distance calculation taking into consideration all characteristics of brake equipment (brake cylinders pressure, friction coefficients, efficiency, etc.) and to deduce, from abacus (or associated formulas) of the UIC 544-1 leaflet, the λ of the vehicle.

Calculations are performed for the different speeds mentioned in the abacus, as for the tests.

Determination by means of calculation: particular case of vehicles only equipped with cast iron brake shoes

This method, which is only valid for P10 cast iron brake shoes and for an operating speed of 120 kph (thus practically only for some wagons), makes it possible to determine the λ only by calculation.

F_a being the brake force delivered by brake equipment of a vehicle in motion, the braked weight is defined by:

$$B = \frac{k \times F_a}{g}$$

where k is a constant parameter, specific to the vehicle, and g is the acceleration due to gravity.

The UIC leaflet provides formulas and abacus for the parameter k (which in particular depends on the geometry of the shoe holders that are used).

Influence of train length

Response times of the pneumatic brake are strongly dependent on the train length (see page on the pneumatic brake). However these response times have a direct influence on the final performance, i.e. the stopping distance.

It is accepted that a length under 400 m for a train composed with coaches and under 500 m for a train composed with wagons, the braked weight obtained by summation of braked weights mentioned on vehicles remains valid. However, this braked weight shall be corrected if the train length exceeds these values (except for vehicles equipped with EP assist – EP brake – or with venting accelerating devices).

Thus the UIC 544-1 leaflet includes abacus providing the correction factor that shall be applied on the braked weight obtained by summation of braked weights of the vehicles composing the train.

Practically, this correction essentially concerns wagons operated in brake mode P, passenger trains rarerly reaching a length over 400 m.

Particular case of freight trains operated in brake mode G

We have seen above that the braked weight is always determined in brake mode P. However freight trains are operated mainly in brake mode G, this in order to limit the longitudinal traction or compression forces (see page on the pneumatic brake).

For freight trains and for the most commonly used types of cast iron brake shoes, abacus have been realized on the basis of tests results in order to be able to determine, in particular as a function of the λ the train (summation of λ of wagons) and of the slope, the stopping distance for each typical speed limit (90 kph, 100 kph, 120 kph) and for a train length up to 700m, this for a pneumatic brake.

Therefore it mainly corresponds to abacus destined to trains operation, and not for determination of braked weight during vehicles design.

It shall be noted that this method only concerns trains composed with vehicles that are only equipped with cast iron brake shoes.

Particular case of passenger trains: Pédelucq formula

For passenger trains composed of vehicles equipped with cast iron brake shoes, a formula has been established by Mr Pédelucq:

$$D = \frac{\varphi \times V_0^2}{1{,}09375 \times \lambda + 0{,}127 - 0{,}235 \times i \times \varphi}$$

where φ is a coefficient that varies as a function of braking initial speed V_0 (and is given by tables), and I is the track gradient (with a – sign is uphill and a + sign if downhill). A correction is then applied as a function of train length, here again thanks to specifications of UIC 544-1.

This formula has been derived from several tests. Anyway it is no more in use today.

Evolution of brake equipment

You probably noticed that it is often mentioned that formulas and abacus cited in the text have been established for vehicles equipped with cast iron brake shoes, and with pneumatic brake control. It is exactly where the problem lies… Indeed the increase of speeds and passenger trains weights have required to use other types of brakes than the cast iron brake shoes (see page dedicated to bogie brake equipment): disc brake, composite brake shoes, use of the traction motors as generators to provide a retarding force, magnetic track brakes or eddy current brakes.

But it has been very quickly of evidence that using these types of brakes, often combined one with the other, made obsolete the use of λ as a basis for braking performance determination, this famous λ not being constant any more (in particular as a function to the initial speed). In addition, some rolling stocks (e.g. MI79 or MI2N) have been equipped with an electric braking control, which characteristics are rather different from the pneumatic braking control.

It would then have been necessary to register vehicles in a huge table, providing the corresponding λ for each speed.

Concerning wagons, the fact that the cast iron brake shoes remain widely used make it possible to rely on UIC methodologies. But the tendency goes towards a generalization of composite brake shoes and disc brakes, which different behavior imposed to review, at least partially, UIC calculation methodologies. Thus specific abacus were created for these brakes, taking also into consideration the increase of operating speeds up to 160 kph in first instance, then up to 200 kph.

Braking performances of modern rolling stocks

As we mentioned above, classical methodologies have shown their limits within the past twenty years, with regards to new braking technologies.

In order to take evolution of these technologies into consideration, in terms of bogie brake equipment as well as in terms of energy used for braking control or(and) brake application (use of other energy than pneumatic one), new methodologies and tools had to be developed.

These are based on step by step calculations that are quite time-consuming when performed by hand with a slide rule, but are highly facilitated since the beginning of the years 1990 by the huge development of personal computers. Modern rolling stocks are thus subject to precise performances calculations, in which are taken into consideration all parameters (including fiction coefficients of bogie brake equipment, as well as their variations as a function of different parameters such as speed). These softwares are supplied by return of experience, provided that commissioning of a new vehicle necessarily requires validation of its performances by means of tests (verification of design and of performed calculations, fine tuning to get the specified performances).

Moreover, introduction of modern signaling systems (TVM, KVB, LZB, ERTMS, etc.) requires to know the braking performances of a train in form of an equivalent deceleration, which shall even be a guaranteed one (thus including degraded adhesion, a defined level of brake equipment isolation on the train, tolerances on brakes forces and friction coefficient of materials, etc.). Thus these performances are accessible only by means of a step by step calculation, and not by means of a braked weight type methodology.

Some orders of magnitude as a conclusion

In order to have an idea about braking performances of railway vehicles, under are some examples for typical rolling stocks. For more details, you can also refer to rolling stocks technical data proposed on the present web site.

Wagons

Wagons generally have a very low λ, around 40 to 80% in G mode (freight operation). For wagons equipped with P mode (passenger operation), two sub-modes exist: S mode, for which a minimum λ of 65 to 70% is required, and SS mode (operating speed of 120 kph) for which the minimum λ is of 100%.

Classical passenger trains

For speeds greater than or equal to 140 kph, the minimum required λ is of 150 to 170% in tare load, which corresponds to the sub-mode R (marked with a lozenge on the vehicle). For vehicles operated at 200 kph, the λ often reaches around 180% in tare load.

Practically this means that a 15 Corail coaches train authorized for 200 kph operation stops in a distance of ca 980 meters from 160 kph, and 1620 meters from 200 kph.

Locomotives generally have lower λ, essentially because of their important weight. A BB 22200 has a maximum λ (corresponding to the simultaneous use of electrodynamic and friction brakes in P mode) of 119% at 160 kph (thus a stopping distance of around 1200 meters from 160 kph). This λ falls down to 72% with friction brake only and from 120 kph in G mode... The BB 26000 (Sybic) is a little bit more performing, with a λ of around 130% at 160 kph (in the same conditions as the BB 22200), and of 150% at 200 kph.

Trainsets

The X 72500 diesel trainset stops in distance of 1050 meters from 160 kph, which would correspond to a λ of around 140% if we consider it is a single vehicle considering its small length. From 120 kph, the stopping distance is 610 meters, thus a λ of around 120%.

On the other hand, the Z2N electric trainset stops in a distance of 650 meters from 120 kph, thus a λ of around 120%.

TGV trainsets

A TGV trainset stops in a distance of 1300 meters from 200 kph, thus a λ greater than 220% !...

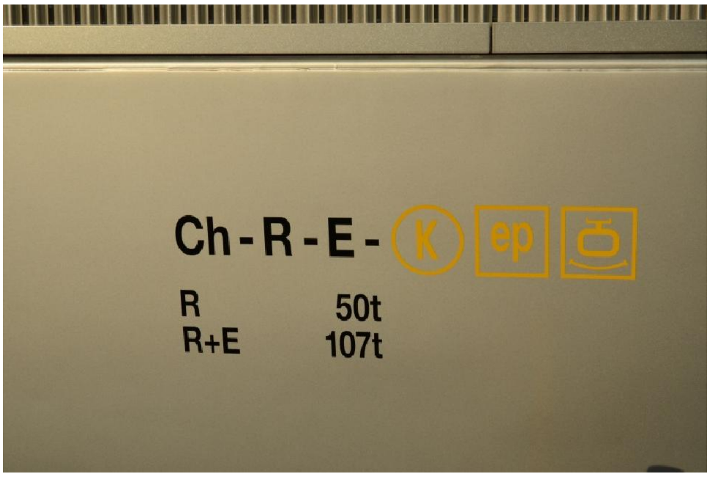

Figure 1 – Braked weight marks on a motor car of a RGV trainset for Morocco (R = Friction brake alone, R+E = Combined friction and electrodynamic brakes)

Tramcars

Tramcars are, with rubber tires metros, the most performing railway vehicles in terms of braking. Average decelerations often reach 3 m/s², which correspond to a stopping distance of 82 meters from 80 kph. As a comparison, a XTER diesel trainset will stop from the same initial speed in a distance of 290 meters… Such a level of performances has nothing more to do with a λ !