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Influence of railway gradient on energy efficiency of high speed train

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Abstract

In the context of reducing the global energy consumptions in transport systems, railways offer many advantages. Therefore the construction of new high speed railways has been planned. This article assesses the impact of the gradient of the railway on the train energy efficiency. This key parameter has a direct influence on the construction and operation phases energy amounts, since low gradients could require considerable civil engineering works.

The energy model of the railway operation phase presented in this paper takes into account the infrastructure geometry, the train characteristics and the speed profiles. It is applied to different generic cases in order to illustrate the impact of the infrastructure gradients. The corresponding trajectories are compared from an energy efficiency point of view.

Results show that the gradient is not the only one element to take into account. The associated length of ramp or slope is crucial too. For example, it is shown that short section with an important gradient can require less operation energy than lower gradient on longer distances. It is therefore possible to determine a couple of slope/ramp length and gradient for a given rolling stock which contributes to the minimization of the global construction cost and of the operating energy consumption.

Keywords: energy ; efficiency ; high-speed train ; gradient ; model.

Résumé

Dans le contexte de la réduction des consommations globales d'énergie, le système ferroviaire offre de nombreux avantages. La construction de nouvelles lignes à grande vitesse a donc été programmée. Cet article évalue l'impact du tracé en long (pente ou rampe) de la voie sur la consommation d'énergie des trains. Ce paramètre clé a une implication directe sur la phase de construction puisque de faibles pentes peuvent requérir des travaux d'ingénierie considérables.

Le modèle d'énergie d'exploitation du système ferroviaire présenté dans cet article prend en compte la géométrie de l'infrastructure, les caractéristiques des trains et les profils de vitesse. Il est appliqué à différents cas génériques dans le but d'illustrer l'impact des pentes des voies. Les trajectoires correspondantes sont comparées d'un point de vue énergétique.

Les résultats montrent que la pente n'est pas le seul élément à prendre en compte. Les longueurs de rampe ou descente associée sont cruciales également. Par exemple, il est montré qu'une courte section avec une pente importante peut nécessiter moins d'énergie à l'usage qu'une pente plus faible sur des distances plus longues. Il est alors possible de déterminer un couple de longueur et de pente de descente/rampe pour un matériel roulant qui minimise le coût global des phases de construction et d'exploitation.

Mots-clé: modèle ; énergie ; rendement ; train à grande vitesse ; déclivité.

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1. Introduction

Worldwide, about 62% of final oil is consumed by the transport sector (IEA, 2013). Reducing global fuel consumptions is one of the highest priorities for all countries for both ensuring energy access and limiting climate change. Besides, there is an increasing demand for long distance travels and high-speed. In this context, high-speed train offers many advantages, as consuming significantly less energy than road or air transports and improving traffic flows near urban areas. So, about 14,000 km of high-speed line are under construction in the world and more than 16,000 km are planned (UIC, 2013).

The purpose of this article is to propose modifications to the technical standards in order to minimize the energy impact of the construction and operation phases of the rail system. More precisely, we focus on the maximum gradient allowed. Indeed, for high-speed infrastructure, this criterion varies from one country to another. According to Lindahl (2001), maximum gradient is 40 millimeter per meter (mm/m) in Germany, 35 mm/m in France and 15mm/m in Japan. Previous works, as Garcia (2010) or Liu (2007), associate increasing the gradient with increasing the energy consumption but without taking into account the impact on recovering the potential energy.

The gradient has a direct implication on the construction. Lower is this limit, more major civil engineering works such as tunnels or bridges are required. Therefore, to assess the energy cost of this limit is interesting. To reach this goal, numerical models are developed to simulate operation energy consumptions and recovering.

In the first part, the virtual track will be described. Thereafter, the energy model is briefly presented. Then, method to obtain speed profile will be developed. Finally, in the last part, the various itineraries are compared from an energy point of view.

2. Model setup for infrastructure evaluation

This section presents the model developed for identifying the infrastructure influence on operating energy consumptions. It involves a simple representation of the track longitudinal profile, a parametric train power model and speed profiles hypothesis. In this work, infrastructure modeling is focused on various constant gradients, associated to different lengths, since the impact of the combination of these two parameters on power consumptions is not as well-known as the gradient impact alone.

2.1. Virtual track

A simple model is retained for the track, in the perspective of modeling both gradient levels and lengths. For that, we consider three points, A B and C, of equal elevation. A and B are separated from 15 km and B and C are separated from 5km. Between points A and B, we construct a virtual track that includes a succession of cycles. A cycle is composed of one slope and of one ramp. Eventually, a track is characterized by three parameters: i) a gradient (identical for slope and ramp) recorded α , ii) the length of one ramp (or one slope, it is the same) recorded l iii) and the number of cycles recorded nb_c . Two examples of track are presented in figure 1. In order to limit the vertical acceleration perturbation, a ramp cannot be directly joined to a slope. A transition curve is required. According to track design rules, this transition curve is an arc of circle. Its radius is 21,000 m. In the following, the gradient, α , is varied from 0 to 45 mm/m and the number of cycles, nb_c , through 1 to 10.

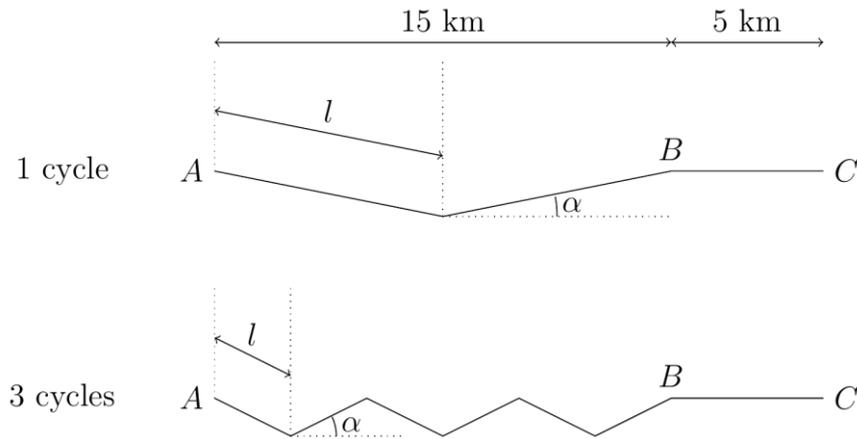


Fig. 1. Longitudinal profile. Example of two tracks.

In the following, the calculation of l is given. The longitudinal length of the track between A and B is (by using the Taylor series for the trigonometric function: $\sin(\alpha) \approx \tan(\alpha) \approx \alpha$):

$$l_t = \frac{|AB|}{(|AB|\alpha/1000)^2 + |AB|^2} \quad (1)$$

with $|AB|$ the distance between A and B.

l is obtained with equation (2) :

$$l = l_t / nb_c \quad (2)$$

Table 1 lists all track tested. The lengths are rounded to the meter. Some combinations are impossible (denoted via two asterisks) due to the length of the transition curve.

Tab. 1: l in meters in function of gradient and number of cycle (nb_c).

Gradient (mm/m)	Cycle number									
	1	2	3	4	5	6	7	8	9	10
0	7500	*	*	*	*	*	*	*	*	*
5	7500	3750	2500	1875	1500	1250	1071	938	833	750
10	7500	3750	2500	1875	1500	1250	1071	938	833	750
15	7501	3750	2500	1875	1500	1250	1072	938	833	750
20	7501	3751	2500	1875	1500	1250	1072	938	**	**
25	7502	3751	2501	1876	1500	1250	1072	**	**	**
30	7503	3752	2501	1876	1501	**	**	**	**	**
35	7505	3752	2502	1876	1501	**	**	**	**	**
40	7506	3753	2502	1876	**	**	**	**	**	**
45	7508	3754	2503	**	**	**	**	**	**	**

2.2. Train model

The operation model presented in this paper takes into account train characteristics (engine efficiency, auxiliary equipment and transformer), traffic (journey time, speed limits) and infrastructure (catenary, gradient, cant, curvature).

As Rochard and Schmid (2000) or Lukaszewicz (2007), a simplified dynamic model train is used. The train is considered as a point with a mass M . Newton's second law is applied on this point to calculate the total force to the drive wheels (F) provided by the electric motor – equation (3).

$$F = kM\gamma - Mg \sin \alpha - Fr \quad (3)$$



Where:

- k : conventional coefficient which represent inertia of rotating masses;
- M : the mass of the train;
- γ : the longitudinal acceleration;
- Fr : the resistance force. It is approximated by a second order polynomial: $Fr = A + BV + CV^2$ with V the velocity of the train.
- g : the gravity acceleration and α is local gradient of the line

Then, as shown by Jeunesse and Rollin (2004), Lindgreen and Sorenson (2005) or Boullanger (2009), the electric consumption is deduced by using a ratio η that illustrates the efficiency of the traction system and a constant (P_a) is also added for auxiliary equipment.

The mechanical power (P_m) is calculated with the equation (4):

$$P_m = FV \quad (4)$$

Then, the electrical power (P_e) is calculated – equation (5):

$$P_e = \frac{P_m}{\eta} + P_a \quad (5)$$

The model calculates the balance of power to the catenary between the power required for traction and the power recovery when using motors as generators for braking.

The aerodynamic, mechanical and electrical powers are simulated. The model was validated (Bosquet et al., 2013) by using consumption measurement carried out during reception tests of the new French high-speed Rhine-Rhone line. Parameters used are those of a French TGV Dasye train.

2.3. Speed profile simulation

For each track, a speed profile is simulated. The constraints are:

- Travel time of all tracks must be identical;
- The train speed at the beginning and end of the course must be the same for all tracks;
- The train does not exceed the maximum speed.
- The braking and traction force are limited.

In the following, F represents the total force to the drive wheels provided by the electric motor. If F is positive, the train is in traction phase. If F is negative, the train brakes.

Simulation of the driver

The rules of driving are as follows: two limits speed are introduced. The first one is the set point speed (S_{sp}). If the speed of the train is lower than the set point speed then F is positive. It is the case 1 (traction). The second one is the limit speed (S_l). If the speed of the train is between the set point and the limit speed then F is zero (case 2, coasting). If the speed of the train is above the limit speed then F is negative (case 3, braking).

Driver's behaviour in the case 1 and 3 is modelled by a speed closed-loop proportional-integral controller. The proportional term produces an output value that is proportional to the current speed error value. The integral term eliminates the residual steady-state error that occurs with a pure proportional controller. For example, in the case of traction ($V < S_{sp}$), the error is obtained with equation (6) and F with equation (7).

$$e_s = S_{sp} - V \quad (6)$$

$$F = P \cdot e_s + I \cdot e_s \cdot \Delta_t \quad (7)$$

The two coefficients of the corrector (P and I in equation (7)) are chosen so that i) the force F is maximal if the speed deviation (e_s in equation (6)) is greater than 10 m/s, ii) the closed loop represents the dynamic behaviour of a driver iii) the actual speed has to be stable, without overshoot, steady-state error and oscillations. P and I are manually tuned. Moreover, to respect the mechanical limitation of F , saturation is added.

The train model is summarized on the figure 2. The Forces balance part requires position and speed. Indeed, Fr varies according to speed and α according to position. A focus on the controller is proposed on the figure 3. It



was noted that P and I coefficients vary according to the maxim tractive (F_{max}) or braking force (F_{min}) available, which vary according to speed. Moreover, the set point and limit speed vary according to position.

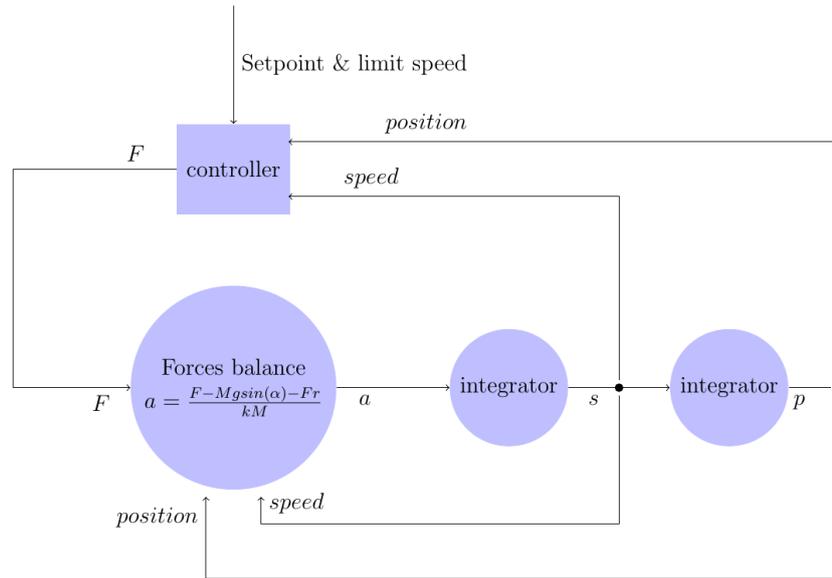


Fig. 2: General train model

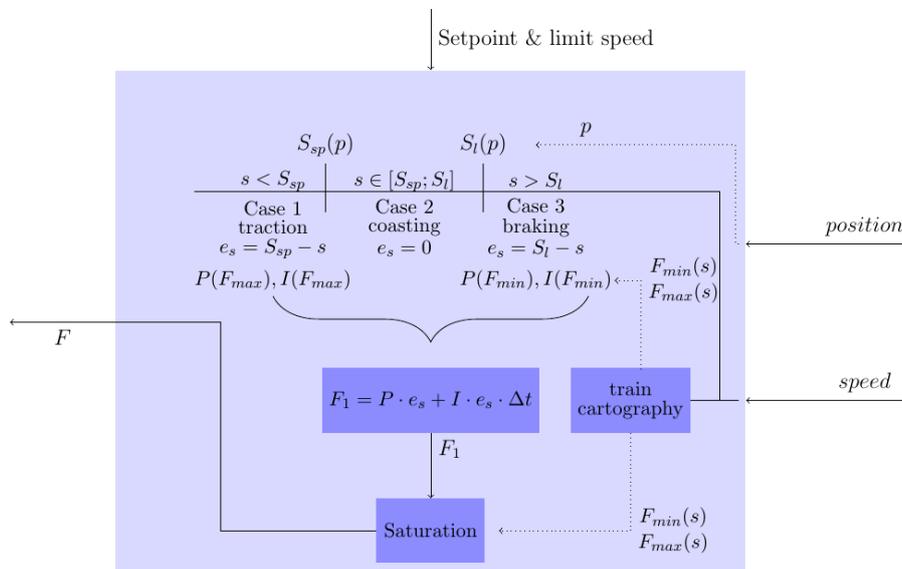


Fig 3: Controller focus

In this article, the mean speed is equal to 75 m/s (270 km/h), the travel time is equal to 267 s $\frac{15,000\text{ m} + 5,000\text{ m}}{75\text{ m/s}} = 267\text{ s}$ and the limit speed is equal to 89 m/s (320 km/h).

This set point speed is constant from A to B, but varies from one track to another (in order to observe the travel time) and is equal to 75 m/s from B to C for all tracks (in order to observe the same speed at the end of the track for all simulations).



A classical numerical method (Adams method) with Scilab software is used to solve the ordinary differential equation.

Figure 4 shows an example with 2 cycles and a gradient of 25 mm/m. The upper plot is the altitude (figure 4a), figure 4b the gradient, figure 4c is the speed and the lower plot (figure 4d) is F. These four data are given in function of location (in kilometer). On the speed profile graphic (figure 4c), the set point speeds are added. The speed increases during slopes. Moreover, the tractive force is zero when the speed is under the set point speed. In this example, it is not necessary to brake. In order to improve the readability of the second graph, the limit speed (320 km/h) is not represented. On the figure 4d between 5 and 8 km and between 12 and 16 km, the traction force F is saturated (due to engine limit of the train). This figure 4 shows that our simulation is a good representation of the actual behavior of drivers. For example at the end of the slope located at 15 km, the speed increases to respect the set point speed. During this phase, the force decreases gradually. Train speed does not exceed the set speed, steady-state error is null and there are no oscillations.

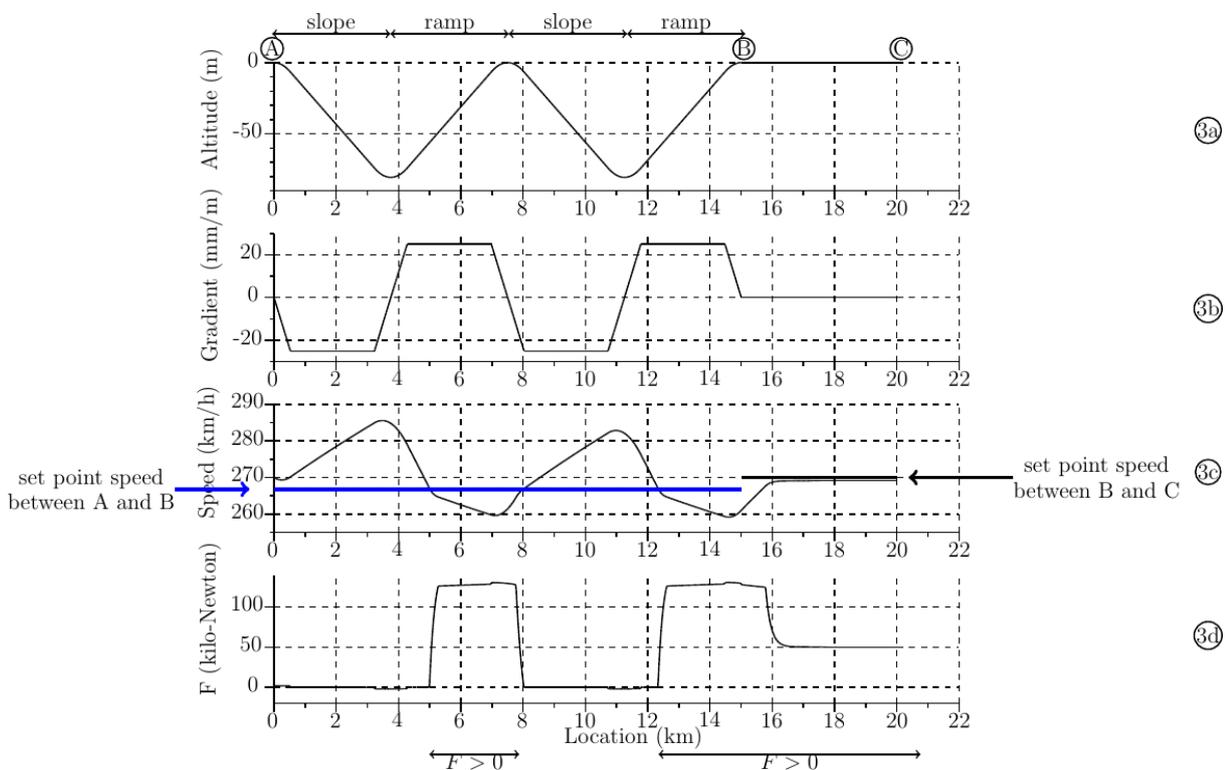


Fig. 4. Gradient, Speed and F in function of location.

3. Results

In Table 2, energy required to travel through the route A to C is provided in kilowatt.hours. Negative electrical energy (when the train uses its regenerative brakes) is directly subtracted to the consumed energy, which is a key point of the energy balance of the high-speed train.



Tab. 2: Energy consumption in kilowatt hour in function of gradient and number of cycles.

Gradient (mm/m)	Cycle number									
	1	2	3	4	5	6	7	8	9	10
0	342	*	*	*	*	*	*	*	*	*
5	342	342	342	342	342	342	342	342	342	342
10	342	342	342	342	342	342	342	342	342	342
15	342	342	342	342	342	342	342	342	342	342
20	344	342	343	343	342	343	343	343	*	*
25	346	343	342	343	342	342	343	*	*	*
30	349	344	343	343	343	*	*	*	*	*
35	356 (10)	345	343	343	343	*	*	*	*	*
40	367 (36)	345	343	343	*	*	*	*	*	*
45	378 (63)	346	344	*	*	*	*	*	*	*

The recovered energy is noted in red. For example, with one cycle and a gradient of 35 mm/m there is "356(10)". This means that energy consumption is 366 kWh, the recovery energy is 10 kWh. Consumption on the route is 356 kWh.

The analysis of the table 2 gives the following results:

- The minimum consumption is 342kWh and it is in the flat track case (as expected).
- There is no more energy consumption when there are more than two cycles. This corresponds to a length of ramp or slope less than 3.75 km.
- There is no more energy consumption with the longest cycle ($nb_c=1, l=7.5$ km) if the gradient is less than 30 mm/m.
- An overuse of 4, 6 and 10 % is noted with the longest cycle and a gradient of 35, 40 and 45 mm/m respectively. These three situations can be explained by the need to brake in slope to respect the maximum speed.
- In this three cases, the recovered energy (i.e. $P_e \partial t$ when $P_e < 0$) saves 3%, 9% and 14% of the consumption. This is the energy generated at the pantograph by the train during brakes phases.

Other small differences in energy consumption (of 342-349 kWh) can be explained by the difference in distance traveled by the train and the quadratic form of aerodynamic losses. These differences are negligible.

As a general result, an important gradient does not necessarily impact overconsumption compared with consumption on a horizontal railway; the length of the ramp has to be analyzed too.

4. Discussion and conclusion

From an energy point of view, the gradient is not the only element to take into account. The associated length of the ramp or slope is crucial too. According to this model experimentally validated with full scale tests on a real track (Bosquet et al., 2013); short section with an important gradient does not have an impact in terms of energy instead of lower but longer slopes. For example, a gradient of 45 mm/m on a succession of slope/ramp of 3,750 m with an average speed of 75 m/s does not impact the energy consumption in comparison with flat track. Thanks to the simulation, various configurations can be tested.

This result upon slope length/gradient criterion is very important for the construction of new high-speed lines. In practical cases, it means that a better match from the track to the natural ground is possible without implying overconsumption of trains. Thus, it will reduce the impact of the construction of the line without impacting energy operations.

Other criteria are taken into account in determining the maximum allowable gradient, as safety, comfort, etc. This paper brings to the stakeholders results concerning a more and more significant criterion, the energy consumption.



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