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Model of High-Speed Train Energy Consumption

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Abstract—In the hardening energy context, the transport sector which constitutes a large worldwide energy demand has to be improving for decrease energy demand and global warming impacts. In a controversial situation where subsists an increasing demand for long-distance and high-speed travels, high-speed trains offer many advantages, as consuming significantly less energy than road or air transports.

At the project phase of new rail infrastructures, it is nowadays important to characterize accurately the energy that will be induced by its operation phase, in addition to other more classical criteria as construction costs and travel time.

Current literature consumption models used to estimate railways operation phase are obsolete or not enough accurate for taking into account the newest train or railways technologies.

In this paper, an updated model of consumption for high-speed is proposed, based on experimental data obtained from full-scale tests performed on a new high-speed line. The assessment of the model is achieved by identifying train parameters and measured power consumptions for more than one hundred train routes. Perspectives are then discussed to use this updated model for accurately assess the energy impact of future railway infrastructures.

Keywords—High-speed train, energy, model, track profile, infrastructure

I. Introduction

Worldwide, about 30% of the final energy and 62% of final oil is consumed by the transport sector [9]. Reducing global fuel consumptions is one of the highest priorities for all countries for both energy security and greenhouse gas emission implications. In this context, high speed trains offer many advantage, as consuming significantly less energy than road or air transports. According to Akerman [1], high-speed consuming roughly 4 times less energy use than road transport and 9 times less than air transport (expressed as kilowatt-hour by passenger-kilometer - kWh/pkm). Even if Chester and Horvath [5] moderates this result with the life cycle assessment point of view, rail modes have the smallest energy consumption. So, about 10,000 km of tracks are under construction in the world and more than 15,000 km are planned as presented by UIC [21].

At a railway project, several alternative routes are usually studied. Nevertheless, as in Leheis [13] these studies concern more largely economic and societal fields to the detriment of these alternatives impacts on energy. The addition of an energy criterion in the decision-making process of high-speed projects is the goal of this study.

Energy consumption is analysed during two phases of the life cycle of the infrastructure: the construction and the operation (energy used by trains). This paper focuses on the operation phase which represents about the half of the energy consumption (according to Chester and Horvath [5]) for a time scale of 50 years.

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Many authors propose a consumption by train kilometer ([4], [23], [19], [10]) or by passenger kilometer ([1], [2], [12], [20], [24], [8]). Unfortunately, consumption varies greatly from one reference to another, and calculated values are rarely detailed. Many of them are based on old trains while the technology has evolved over the past 30 years. In addition, usually, the track profile is not taken into account since optimization is focused on rolling stock. For example, Garcia [8] shows impacts of speed and regenerative brake but doesn't detail track profile influence. Comparison of different routes with an energy point of view is not possible with these vehicle-oriented or not enough accurate models.

To distinguish the impact of different routes from an energy point of view, train model must be sufficiently specific to not only take into account the length but also the track profile. In this paper an operation model which considers train characteristics (engine efficiency, loss of auxiliary equipment, transformer) and infrastructure characteristics (gradient, cant, curvature) is proposed. It will consist in a complete validation of electric consumption model.

In section II the consumption model is detailed. In section III experimental data are presented. In section IV, model parameters are identified and validated. Its accuracy is also investigated. Finally, in section V, some explanations about predictive errors and model modifications are given.

II. Model

Balance of efforts applied on trains is the first approach found in the literature to estimate the electric consumption of high-speed trains. Lukaszewicz [15] or Rochard and Schmid [18] give an interesting general formulation of running resistance as a function of train characteristics like mass, number of bogies, inter-vehicle gap, number of pantographs, etc. Unfortunately in those models, the maximum speed is generally lower than 300 km/h although the projects speed of a new high-speed line are at least 350 km/h. Formulation presented in the current paper is an adaptation of these literature models to higher speeds by taking into account test data. Particularly, for high speeds, aerodynamic have to be analysed more accurately. Raghunathan et al. [17] study it for Shinkansen and its approach is adapted to the TGV Dasye in this paper.

Then, the second step of the model review is to gather knowledge on the method to convert the force developed by the train (based on a physical model) in energy consumption. Lindgreen and Sorenson [14] and Boullanger [3] propose a consumption model with information about engine efficiency, loss of auxiliary equipment and transformer. These models will not directly be used in this paper since they are not suitable for the electric French case (25 kV 50 Hz AC) and high-speed train.

To estimate the energy consumption, the train is considered as a point with a mass M [18]. Newton's second law is applied on this point – equation (1). The total force to the drive wheels provided by the electric motor is computed – equations (2)-(3). This force times the velocity gives the power required by the train – equation (4). Then, as shown by Jeunesse and Rollin [11], the electric consumption is deduced by using a ratio that illustrates the efficiency of the traction system which includes the electric motor and the mechanical traction – equation (5). Finally, this power is integrated to obtain energy consumption – equations (6)-(7).

A. Forces balance

Newton's second law applied on the train:

$$k\mathrm{M}\gamma = \mathrm{F} - \mathrm{Mg}\sin(\alpha) - \mathrm{F_r} - \mathrm{F_c} \quad (1)$$

Where in the left member of (1):

- M: the mass of the train;
- k: conventional coefficient which represent inertia of rotating masses;
- γ: the longitudinal acceleration;

Where in the right member of (1):

- F: the total force to the drive wheels provided by the electric motor;
- g: the gravity acceleration and α is local gradient of the line;
- $\mathrm{F_r}$: the resistance force;
- $\mathrm{F_c}$: the resistance force in curve.

$\mathrm{F_r}$ is composed of the following physical effects: i) Rolling resistance: it is related to the contact wheel rail. As a first approximation, it is considered as constant. Because of sticking effect, this value is not the same when the train is stop or sets in motion. ii) Mechanical resistance: it consists of friction which are viscous friction $\mathrm{F_c}$, depending mainly of the velocity, and the dry friction $\mathrm{F_s}$, which can be considered as constant (unless when the train starts for the same reason as for the rolling resistance). iii) Aerodynamic resistance, related to drag coefficient $\mathrm{C_x}$, and the weather conditions (wind, rain...). This resistance depends mainly on the squared velocity. By taking into account the previous physical interpretation, this resistance force ($\mathrm{F_r}$) is approximated by a second order polynomial [18]:

$$\mathrm{F_r} = A + B \cdot V + C \cdot V^2 \quad (2)$$

- V: the velocity of the train. Wind effects as well as variation in air pressure are neglected here;
- A, B, C: coefficients depending on the rolling stock.

$\mathrm{F_c}$ (resistance force in curve) is modelled by using the classical formula given by Fayet [7] and Rochard and Schmid [18]:

$$\mathrm{F_c} = \mathrm{M} \cdot 9.81 \cdot sin(0.8 \cdot |R_c|) \quad (3)$$

- R_c is the curvature radius in a horizontal plane.

B. Developed power and consumed power

The force F, provided by the electric motor, times the velocity gives the power to be provided by the train:

$$P_{provided} = F \cdot V \quad (4)$$

The electric consumption is deduced by using a ratio:

$$P = P_{provided} + \left| \frac{P_{provided}}{\eta} - P_{provided} \right| \quad (5)$$

- η is the efficiency of traction system. As a first approximation, this efficiency is considered as constant.

Moreover, a constant is added to take into account auxiliary equipment:

$$P_{consumed} = P + \beta(V) \quad (6)$$

- β has two values. When the train stops (*i.e.* $speed = 0$), it is the consumed power for comfort (heating, illumination, etc.). When the train moves (*i.e.* $speed > 0$), auxiliary auxiliary comprises also equipment such as ventilation and cooling of propulsion equipment, supply of compressed air for brakes, etc.

C. Consumed energy

Finally, this power is integrated to obtain the energy consumption:

$$E = \int_{time} P_{consumed} \quad (7)$$

Equation 7 implies that the negative energy (when the train uses its regenerative brakes) is directly subtracted of the consumed energy which is a key point of the energy balance of the high-speed train.

III. Tests

The reception tests of the new french Rhin-Rhone high-speed line hase been used to obtain experimental data. The line has been opened to the traffic since the end of 2011 and links Mulhouse to Dijon, via Belfort-Montbéliard and Besançon. Its 140 km route and its longitudinal profile are shown in Fig. 1.

Numerous tests have been performed on this high-speed line. Among these tests, 130 trial runs (half in the east/west direction, half in the west/east direction) have been carried out for the purpose of this study within a period of three months between June and August 2011. For field testing, 20 sensors were added to the test train. During these tests, geometry, energy, dynamic measurements, direction and velocity of the wind were recorded. The test train is the standard French TGV Duplex DASYE (duplex asynchronous ERTMS). The Table I shows complete characteristics of the test train. Speed, position and active power measured at the pantograph have been recorded at a 5 Hz frequency. Moreover, gradient and curve radius are used for result analysis.

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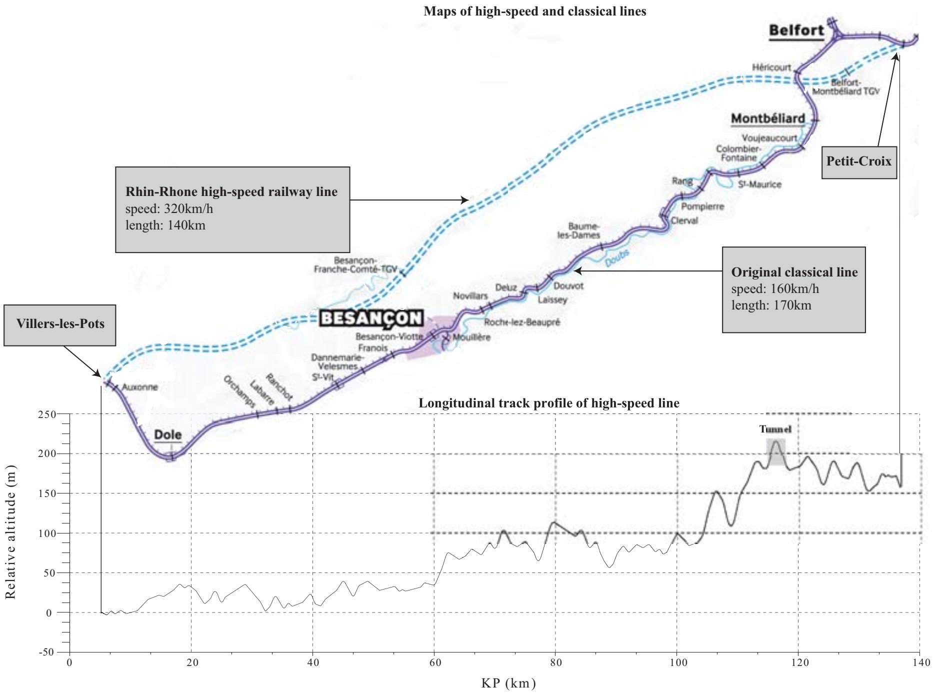

Fig. 1: Map (upper part of the figure) and longitudinal track profile (lower part) of the East branch of the high-speed railway line studied.

TABLE I
General technical characteristics of train used for tests

Characteristic	Detail
Composition	power car + 8 trailers + power car
Maximum speed in commercial service	320 km/h
Power with alternating current	9,280 kW
Traction	Insulated Gate Bipolar Transistor and asynchronous motor
Mass	Empty: 380 t; 80 kg/passengers
Dimensions	Length: 200.19 m; Width: 2.896 m; Height: 4 m
Number of motors	8
Number of bogies	On engine: 4; on trailers: 9
Axle load	17 t

IV. Identification of Model Parameters

In this section, experimental data are used to identify parameters of literature models.

The value of the mass M comes from general public characteristics of the train. Classical value of the inertia coefficient of rotating masses k is taken as Fayet [7] and data of Jeunesse and Rollin [11] is used for η. A, B, C and β are identified with classical non linear least squares method (the software Enterprises [6] is used with a function which applies the Nelder-Mead algorithm as explained by Nelder and Mead [16]). All the parameters are shown in Tab. II.

Fig. 2 shows differences between measured and predicted

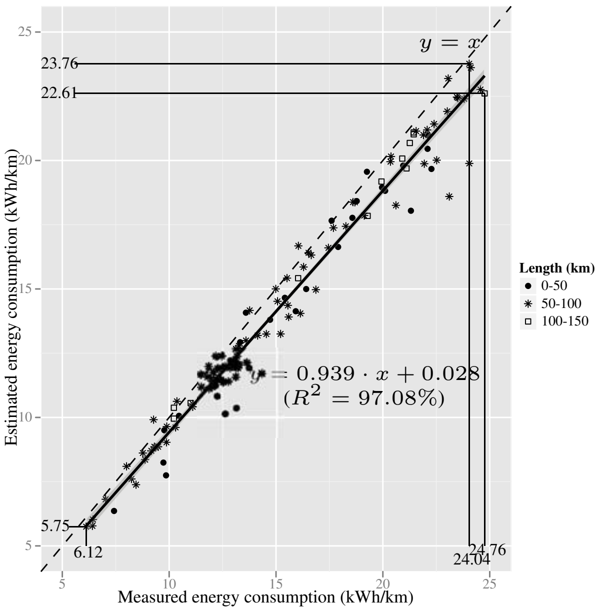

Fig. 2: Estimated and measured energy consumption of the 130 tests according to 3 classes of lengths.

TABLE II
Coefficients used with the predictive consumption model

Coefficients	Value
k	1.04
A	$1.668 \cdot 10^{-2}\ N \cdot kg^{-1}$
B	$4.637 \cdot 10^{-6}\ N \cdot kg^{-1} \cdot m^{-1} \cdot s$
C	$1.514 \cdot 10^{-5}\ N \cdot kg^{-1} \cdot m^{-2} \cdot s^2$
$\beta(speed = 0)$	250 kW
$\beta(speed > 0)$	300 kW
η	87 %

energy. With a perfect model, all tests should be on the line $y = x$. With the model presented in this paper, a straight linear regression can be drawn. Its equation is $y = 0.9397{\cdot}x{+}0.0288$. This means that the total consumption is a bit underestimated. Moreover, the Fig. 2 shows significant differences in consumption between tests from 6.12 to 24.76 kilowatt-hour by kilometer (kWh/km). This is due to different tests conditions:

i) Track test section for each test is different. As it can be seen on Fig. 1 on track profile, the potential energy for a test between KP 20 and KP 40 is different with a test between KP 100 and KP 120 for instance.

ii) Test length is different (between 5 and 140 km). This changes the ratio of braking phase where energy is lost. For instance on a short test the braking phase will be greater than on a long run.

iii) Average speed is different (between 130 km/h and 350 km/h). The faster tests will lose more energy with the aerodynamic force than the slower tests.

Overall, this energy consumption is consistent in terms of magnitude with Janic [10] who has obtained a consumption of 19 kWh/km for a TGV and 22 kWh/km for ICE (German high-speed train) and also with Andersson and Lukaszewicz [2].

To measure the accuracy of the model, the root mean square error (RMSE) and its coefficient of variation (SD_{RMSE}) are calculated (equations (8) and (9)). The RMSE is based on the differences between values predicted by the model (y_{est}) and the measured values (y_{mes}). More precisely, it is defined as the square root of the mean square error:

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{1}{n}(y_{\text{mes}} - y_{\text{est}})^2} = 1.2 \qquad (8)$$

The relative standard deviation (SD) of the RMSE is defined as the RMSE normalized to the mean of the observed values:

$$\text{SD}_{\text{RMSE}} = \frac{\text{RMSE}}{\bar{y}_{\text{mes}}} = 0.080 \qquad (9)$$

The RMSE of the 130 tests is equal to 1.2 and the SD of the RMSE is equal to 0.080: this a variation of 8% which is a low value. Both statistic parameters show good prediction.

With the help of this rather good identification, if considering other non controlled parameters as wind influence, investigation of the infrastructure parameters influence on energy consumption can be done by simulation using the model presented in this paper.

V. Model improvements and prospects

As shown in this paper, a simple model gives good predictive energy consumption despite numerous assumptions. For instance, weather conditions and some characteristics of the track specificity such as tunnels are neglected. As shown by Lukaszewicz [15], Raghunathan et al. [17] and Andersson and Lukaszewicz [2] model improvements could be done by incorporating these elements.

This paper focuses on the energy consumed by the train. The minimum consumed by the train is not necessarily the minimum provided by the infrastructure (*i.e.* sub-stations) if power line losses (catenary) are taken into account. Similarly, the result can be still different if electricity produced by power station is taken into account.

These work prospects are currently being studied and will soon be integrated into an improved model.

In a first step, the model presented in this paper will be used to compare the various alternative routes in the high-speed Montpelier-Perpigan project. Indeed, this project in the south of France is in the process of selection of variants distance of 100 to ,000 meters. Traffic, train and infrastructure data from public debate will be used.

VI. Conclusion

Many countries are now betting on high-speed train for its energy efficiency. However, it is important to assess in advance the impact of future energy lines. Unfortunately, there was no bibliography for model consumption allowing evaluation of different routes with an energy point of view.

In this paper, an energy consumption model is proposed to assess operation phase. Along a route, the model provides instantaneous power supply as well for acceleration, deceleration and constant speed phases in function of route profile. Thanks to this model, key infrastructure parameters affecting the energy consumption can be identified. The energy consumption of the new 15,000 km of high-speed line, which are planned in the world, represent the issue of such energy models.

This study is part of a global project, where consumption of construction phase is also studied. Some details can be found in Vandanjon et al. [22].

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