PRES LUNAM
Ecole Doctorale STIM
Sciences et Technologies de l'Information et Mathématiques

Spécialité :
Laboratoire : IRCCyN
Equipe : Robotique

Model of high-speed train energy consumption[1]

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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 trains 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.

Keywords: *High-speed train, energy, model, track profile, infrastructure*
Collaborations : RFF (Réseau Ferré de France - the French railway owner), Ifsttar (French institute of sciences and technology for transport, development and networks)

1 Introduction

Worldwide, about 30% of the final energy and 62% of final oil is consumed by the transport sector [1]. 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 [2], 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 [3] 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 [4].

At a railway project, several alternative routes are usually studied. Nevertheless, as in [5] 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.

Many authors propose a consumption by train kilometer ([6], [7], [8], [9]) or by passenger kilometer ([2], [10], [11], [12], [13], [14]). 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, [14] 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.

[1] This article is based on a paper submitted to ICREM 2013 : International Conference on Railway Engineering and Management.

2 Model

Balance of efforts applied on trains is the first approach found in the literature to estimate the electric consumption of high-speed trains. [15] or [16] 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.

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. [17] and [18] 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 [16]. Newton's second law is applied on this point. The total force to the drive wheels provided by the electric motor is computed. This force times the velocity gives the power required by the train. Then, as shown by [19], 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. Finally, this power is integrated to obtain energy consumption.

2.1 Forces balance

Newton's second law applied on the train:

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

Where : M: the mass of the train; k: conventional coefficient in order to take into account inertia of rotating masses; γ: the longitudinal acceleration; 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.

2.2 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. The electric consumption is deduced by using a ratio:

$$P = P_{provided} + \left|\frac{P_{provided}}{\eta} - P_{provided}\right| \tag{2}$$

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 (heating, air condition and the cooling systems of the locomotive motors, etc.).

2.3 Consumed energy

Finally, this power is integrated to obtain the energy consumption. This 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 high-speed trains.

3 Tests

The reception tests of the new french Rhin-Rhone high-speed line has been used to obtain experimental data. The line (140 km) has been opened to the traffic since the end of 2011 and links Mulhouse to Dijon, via Belfort-Montbéliard and Besançon.

Numerous tests have been performed on this high-speed line. Among these tests, 130 trial runs 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

Table 1: 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 %

French TGV Duplex DASYE (duplex asynchronous ERTMS). 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.

4 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 [20] and data of [19] is used for η. A, B, C and β are identified with classical non linear least squares method (the software [21] is used with a function which applies the Nelder-Mead algorithm as explained by [22]). All the parameters are shown in Tab. 1.

To measure the accuracy of the model, the root mean square error (RMSE) and its coefficient of variation ($\mathrm{SD}_{\mathrm{RMSE}}$) are calculated. 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.

5 Conclusion

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

In this paper, an energy consumption model is proposed to assess operation phase. This model is validated with the reception tests of the new french Rhin-Rhône high speed line. Along this 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 [23].

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