Centre de Nantes
Route de Bouaye
CS4
44344 Bouguenais Cedex

Site Web : www.ifsttar.fr

Département
Aménagement, Mobilité, Environnement

Laboratoire EASE

Présentation du modèle global sélectionné et sa confrontation avec les expérimentations

Partenariat RFF - Ifsttar

Livrable 1.7

Rapport établi le :	20 novembre 2013
Auteurs :	Pierre-Olivier Vandanjon, Romain Bosquet, Alex Coiret, Tristan Lorino
Nomenclature d'activité IFSTTAR :	13W09201
Confidentialité :	Confidentiel

Établissement public à caractère scientifique et technologique

Système de management de la qualité en cours de certification pour les sites de Champs-sur-Marne, Nantes, Satory

Champs-sur-Marne (siège)
Cité Descartes
Boulevard Newton
77420 Champs-sur-Marne

Satory-Versailles
Lille-Villeneuve d'Ascq
Lyon-Bron
Marseille-Salon de Provence

IDENTIFICATION

TYPE	Rapport de recherche
TITRE	Livrable 1.7 : Présentation du modèle global sélectionné et sa confrontation avec les expérimentations
CONFIDENTIALITÉ	Liée à celle du contrat RFF « Améliorer l'efficacité énergie-carbone des investissements »

VALIDATION

ORGANISATION	NOM	RÔLE	DATE et VISA
RFF	Olivier Cazier	Partenaire industriel	

DISTRIBUTION

ORGANISATION	DATE	REMARQUES
RFF	20.11.2013	version papier et version électronique 1.1
IFSTTAR	20.11.2013	version électronique 1.1

SUIVI DES MODIFICATIONS

VERSION	DATE	RAISONS
1.0	15.11.2013	Première version pour recueil des remarques en interne
1.1	20.11.2013	Version envoyée pour recueil des remarques du partenaire

Table des matières

Chapitre 1. Introduction

L'équipe d'éco-conception du laboratoire Ease dont nous faisons partie, a été constituée autour de l'objectif général de fournir une méthodologie d'évaluation des infrastructures de transport vis à vis des consommations d'énergie, tout en prenant en compte d'autres critères tels que la sécurité et la mobilité.

Les infrastructures routières et ferroviaires sont visées par cet objectif, plus particulièrement pour l'énergie d'usage qui leur est liée (la consommation des véhicules qui y circulent), tout en ayant en comparaison les énergie de construction et d'entretien.

La modélisation de cette consommation par la circulation des véhicules, dépend des paramètres tels que : la géométrie de l'infrastructure (pentes, virages), les aménagements (points singuliers, intersections, itinéraires alternatifs), les polices d'exploitation, la gestion du trafic, ...

Pour la partie ferroviaire, Romain Bosquet a commencé sa thèse Cifre RFF-Ifsttar en juillet 2011 sur ce sujet. Des collaborations sont fortement engagées avec le GRETTIA, le LTN (Hugues Chollet, Bogdan Vulturescu) et l'Ecole Centrale de Nantes (directeur de thèse Maxime Gautier). Ces études s'effectuent dans le cadre d'un partenariat de recherche entre l'Ifsttar et RFF sur l'efficacité énergétique des investissements ferroviaires. Le responsable scientifique du coté de RFF est Olivier Cazier. Ce rapport est un des livrable prévus dans ce partenariat.

Il est la suite du logique du livrable précédent (livrable 1.6) qui était un compte rendu des expérimentations effectuées lors des essais de réception de la LGV Rhin-Rhône. Ces expérimentations constituent les données principales de la thèse de Romain Bosquet pour construire un modèle de consommation. L'objectif de ce rapport est de présenter le modèle de consommation construit à partir des mesures expérimentales. C'est un rapport d'étape. Il s'agit de présenter nos résultats dans le déroulement du contrat. Les modèles finaux seront présentés dans le manuscrit de thèse.

Par ailleurs, nous sommes à une étape où le nombre de modèles possibles et les techniques possibles de calage des modèles sur les données expérimentales entrainent une combinatoire de possibilités importante. Un traitement très techniques des mesures a aussi été effectué pour pouvoir les utiliser. Ces points sont traités lors des réunions de suivi de thèse pour lesquels des documents techniques détaillés sont produits. Lors de la réunion de suivi de thèse du 22 septembre 2013, les documents préparatoires comprenaient plus de 120 pages de précisions techniques et plus de 21 type d'identification différents étaient présentés (voir les documents Bosquet [2013a,b,c]).

L'objet de ce rapport n'est pas de reprendre in extenso ces documents techniques mais plutôt de faire une synthèse, en présentant la démarche de l'identification sur un des modèles qui nous paraît prometteur. Même si les résultats finaux seront présentés dans la thèse de Romain Bosquet, les résultats intermédiaires sont suffisamment mûrs pour avoir fait l'objet de publications et ont donc été validés (ou sont en cours de validation) par les pairs. C'est pourquoi, nous avons mis en annexe de ce document, les articles qui ont été produits à partir de ce travail.

- Un article publié dans la revue World Academy of Science, Engineering and Technology (Issue 78) sur le modèle de consommation, (Bosquet, R. Vandanjon, P-O Coiret, A Lorino, T. (2003) Model of High-Speed Train Energy Consumption. pp1912-1916). Cette revue reprend les articles présentés au congrès International Conference on Railway Engineering and Management (ICREM 2013).
- Un article soumis au Transport Research Arena 2014 (TRA 2014), congrès qui se déroulera à Paris sur l'influence du vent sur la consommation. (Experimental assessment of wind influence on high-speed train energy consumptions. Alex Coiret, Pierre-Olivier Vandanjon, Romain Bosquet, Tristan Soubrié and Guillaume Baty)
- Un deuxième article soumis au TRA 2014 sur une première utilisation du modèle de consommation en lien avec les règles de conception des lignes à grandes vitesse. (Influence of railway gradient on energy efficiency of high speed train , Romain Bosquet, Pierre-Olivier Vandanjon, Maxime Gautier, Alex Coiret, Olivier Cazier)

Le premier chapitre de ce rapport présente le modèle de consommation. Les essais sont ensuite présentés. La confrontation du modèle avec les essais est présenté dans le troisième chapitre. Il s'intitule "Identication" car il s'agit d'identifier les paramètres du modèle grâce aux essais.

Chapitre 5. Conclusion

Un modèle point associé à un rendement constant de la chaine électrique permet d'expliquer plus de 75 % de la puissance consommée mesurée pendant plus de 40 heures sur une rame TGV lors des marches d'essai de la ligne à grande vitesse Rhin-Rhône (LGV RR) « branche est ». Ce modèle qui ne pourrait être adapté qu'aux essais servant à son calage comprend des paramètres dont les valeurs sont proches des valeurs confidentielles issues de Thor. Cette validation croisée avec une source d'information indépendante des essais montre que ce modèle a un contenu physique qu'il lui permet d'être utilisé sur d'autres lignes.

Ce modèle a déjà été utilisé pour tester l'effet des règles de conceptions sur la consommation (voir la publication en annexe C).

Comme tous les partenaires s'y attendaient, le paramètre prépondérant est le terme qui est lié au coefficient aérodynamique. Une amélioration des capacités prédictives du modèle passe par une meilleure prise en compte des effets aérodynamique. Ceci est possible en se basant sur les résultats du contrat que l'Ifsttar a passé avec la société Andheo (voir la publication en annexe B) mais aussi avec une instrumentation permettant une mesure sur le train même de la vitesse du vent.

Toutefois, en phase projet, le modèle fourni dans ce rapport est suffisant pour évaluer des variantes de tracé. C'est l'objet du livrable suivant (le livrable 1.8) de présenter une évaluation de ce type.

Notre modèle est basse fréquence. Ceci n'est pas rédhibitoire pour une analyse de la consommation énergétique sur toute une ligne. En revanche, il n'est pas adapté à l'analyse détaillée de certaines caractéristiques comme l'étude des transitions entre ligne droite et courbe. Les signaux de position fournis lors des essais ne sont pas assez précis pour ce type d'analyse. Une meilleure connaissance expérimentale de la consommation liées à ces transitions nécessite des essais et une instrumentation adaptée.

Ce processus d'identification est en constante amélioration. Nous pouvons déjà affirmer que les modèles présentés dans le manuscrit de Romain Bosquet seront encore meilleurs.

Annexe A : communication à ICREM 2013

Model of High-Speed Train Energy Consumption

Romain Bosquet, Pierre-Olivier Vandanjon, Alex Coiret, and Tristan Lorino

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.

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

Romain Bosquet is with Réseau Ferre de France, 92 avenue de France, 75013 Paris, France (EU),(e-mail: romain.bosquet@rff.fr).

Pierre-Olivier Vandanjon, Alex Coiret and Tristan Lorino are with LUNAM University, Ifsttar, AME-EASE, F-44341 Bouguenais, France (EU).

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.

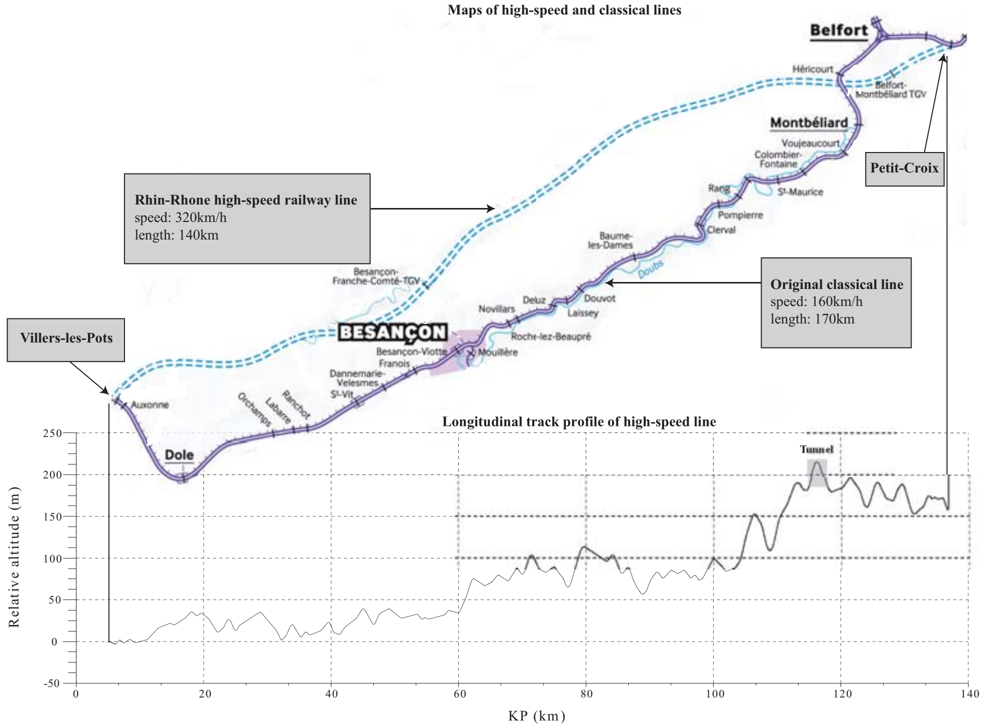

Fig. 1: Map (upper part of the figure) and longitudinal track profile (lower part) of the East branch of the high-speed railway line studied.

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.

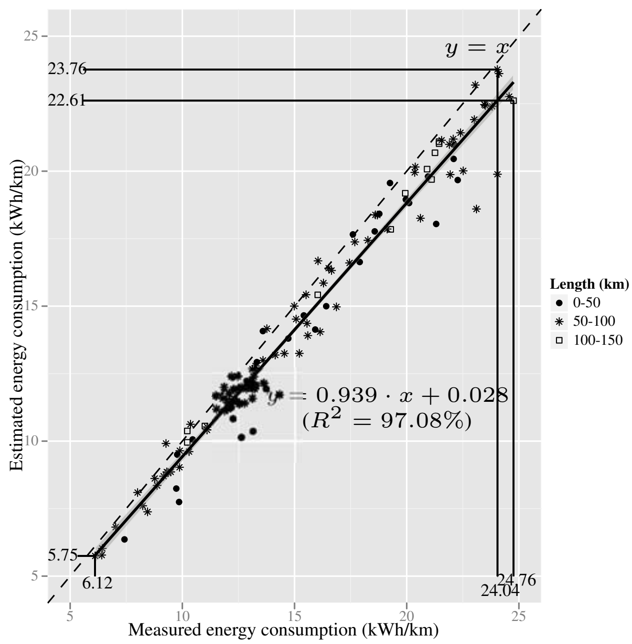

Fig. 2: Estimated and measured energy consumption of the 130 tests according to 3 classes of lengths.

Fig. 2 shows differences between measured and predicted

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:

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

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

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

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].

Acknowledgment

This investigation is part of a full life cycle railway infrastructure assessment performed in collaboration with RFF (Réseau Ferré de France) the French railway owner.

Tests were performed by INEXIA (http://www.inexia-ingenierie.com), EURAILTEST (http://www.eurailtest.com) and AEF (Railway Test Agency).

References

[1] J. Akerman. The role of high-speed rail in mitigating climate change – the swedish case europabanan from a life cycle perspective. *Transportation Research Part D: Transport and Environment*, 16(3):208 – 217, 2011. ISSN 1361-9209. doi: 10.1016/j.trd.2010.12.004.

[2] E. Andersson and P. Lukaszewicz. Energy consumption and related air pollution for Scandinavian electric passenger trains. Technical report,

Department of Aeronautical and Vehicle Engineering Royal Institute of Technology, 2006.
[3] B. Boullanger. *Modeling and simulation of future railways*. PhD thesis, Royal Institute of Technology KTH Elektro-och, 2008.
[4] M. Chester and A. Horvath. Life-cycle assessment of high-speed rail: the case of California. *Environmental Research Letters*, 5(1):1–8, 2010.
[5] M. V Chester and A. Horvath. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, 4:024008, 2009.
[6] Scilab Enterprises. *Scilab: Free and Open Source software for numerical computation*. Orsay, France, 2012. URL http://www.scilab.org.
[7] P. Fayet. *Modelisation des reseaux electriques ferroviaires alimentes en courant alternatif*. PhD thesis, EEA Lyon, 2008.
[8] A. Garcia. High speed, energy consumption and emissions. Technical report, UIC, december 2010.
[9] International Energy Agency, 2013. URL http://http://www.iea.org> Home>Statistics>World->Statisticsfor2009->Balances. Online; accessed 22-January-2013.
[10] Janic. High-speed rail and air passenger transport: a comparison of the operational environmental performance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 217, 2003.
[11] A. Jeunesse and M. Rollin. La motorisation du TGV POS. *Revue Générale des Chemins de fer*, mars 2004.
[12] Etienne Le Maout. Comparative analysis of the life cycle cost of high speed rail systems. Master's thesis, Department of Civil Engineering, The University of Tokyo, august 2012.
[13] Stephanie Leheis. High-speed train planning in France: Lessons from the Mediterranean TGV-line. *Transport Policy*, 21(0):37 – 44, 2012. ISSN 0967-070X.
[14] E. Lindgreen and Spencer C. Sorenson. Simulation of energy sinsumption and emissions from rail traffic. Technical report, Technical University of Denmark, Department of Mechanical Engineering, february 2005.
[15] P Lukaszewicz. Running resistance - results and analysis of full-scale tests with passenger and freight trains in sweden. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 221:183 – 192, january 2007.
[16] JA Nelder and R Mead. A simplex method for function minimization. *The Computer Journal*, 7(4):308–313, January 1965. ISSN 1460-2067.
[17] Raghu S Raghunathan, H.-D Kim, and T Setoguchi. Aerodynamics of high-speed railway train. *Progress in Aerospace Sciences*, 38(6–7):469 – 514, 2002. ISSN 0376-0421. doi: 10.1016/S0376-0421(02)00029-5.
[18] B.P. Rochard and F. Schmid. A review of methods to measure and calculate train resistances. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 214(4):185–199, 2000. ISSN 0954-4097. doi: 10.1243/0954409001531306.
[19] G. Martinetti T. Baron and D. Pépion. Carbon footprint of high speed rail. Technical report, UIC, november 2011.
[20] Ryo Takagi. High-speed railways : The last 10 years. *Japan Railway & Transport*, 40:1–4, march 2005.
[21] High Speed Department UIC. High speed lines in the World. pages 1–10, July 2012.
[22] Pierre-Olivier Vandanjon, Alex Coiret, Bogdan Muresan-Paslaru, Amandine Fargier, Romain Bosquet, Michel Dauvergne, Agnes Jullien, Denis François, and Frédéric Labarthe. Practical guidelines for life applied to railways project. In *Proc. International Symposium on Life Cycle Assessment and Construction, Nantes, France*, July 2012.
[23] Christian von Rozycki, Heinz Koeser, , and Henning Schwarz. Ecology profile of the german high-speed rail passenger transport system, ice. *The International Journal of Life Cycle Assessment*, 8:83–91, 2003.
[24] X C Wang and L Sanders. Energy consumption and carbon footprint of high-speed rail projects: Using cahsr and fhsr as examples. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 226:26 – 35, march 2011.

Romain Bosquet earned is bachelor of engineering degree in energy, hydraulics and environment at Grenoble I.N.P. (Grenoble Institute of Technology) in 2010. Moreover, he received the research master in electrotechnic electronic automatic and signal processing from Grenoble university. Currently, he is a second-year PhD student in modelling energy consumption of high-speed train. The aim is to study the impact of infrastructure on energy consumption.

Pierre-Olivier Vandanjon received the B. Sc and the M. Sc in applied mathematics from the Paris-Dauphine University (Paris, 1990). He graduated, as a civil engineer, from Ecole des Mines de Paris (Paris, 1992). He received the Ph. D degree from both the Ecole des Mines de Paris and the French Atomic Agency (CEA) (1995). He has been researcher with the French institute of sciences and technology for transport, development and networks (Ifsttar) since 1997. He provides robotics techniques on projects concerning civil engineering in transports systems (road and railways) in order to improve productivity, safety and carbon efficiency.

Alex Coiret obtained a PhD in civil engineering applied to fluids dynamics and acoustics in 1999. He worked then in the CSTB research center on the buildings transfert phenomena and particles simulations. He joined the LCPC in 2001, by studying road safety with fluids dynamics models and, since 2011 while LCPC and INRETS merge to create the Isttar institute, he is leading researches on energy consumptions induced by road and rail transports.

Tristan Lorino Tristan Lorino obtained a PhD in statistics applied to stochastics process modeling from the Jussieu University (Paris, 2002). He graduated, as a statistician, and received the PhD degree from AgroParisTech (Paris, 2002). He has been researcher with the French institute of sciences and technology for transport, development and networks (Ifsttar) since 2003. He provides statistical models and data analysis on projects concerning civil engineering in road maintenance in order to establish optimization models for technical and ecological policies.

Annexe B : communication au TRA2014 sur l'influence de la météorologie

L'Ifsttar et RFF ont développé un modèle énergétique des trains à grande vitesse dans le but de déterminer l'influence de la géométrie et de l'environnement des infrastructures sur les consommations énergétique des trains. La validation de ce modèle est basée sur des tests grandeur nature réalisés lors de la réception de la ligne à grande vitesse Rhin-Rhône (en 2011). Cet article vise à évaluer si l'influence du vent doit être prise en compte dans ce modèle. Cela implique la détermination numérique de coefficient aérodynamiques pour plusieurs configurations de vent et de terrain et leur utilisation pour le calcul des efforts aérodynamiques. Les caractéristiques atmosphériques sont extrapolées de mesures météorologiques à l'aide du modèle numérique AROME, sur l'ensemble de la ligne Rhin-Rhône. Les résultats les plus remarquables montrent que pour une vitesse modérée de train, d'environ 45m/s, un vent arrière de seulement 5,5 m/s diminue de 30 % l'énergie du aux efforts aérodynamiques appliqués sur le train, ou l'augmente similairement s'il est orienté frontalement.

Une communication de ces travaux sera faite au congrès TRA2014.

Experimental assessment of wind influence on high-speed train energy consumptions.

Alex Coiret[a1], Pierre-Olivier Vandanjon[a] , Romain Bosquet[b] , Tristan Soubrié[c] and Guillaume Baty[c]

[a] *LUNAM University, Ifsttar, AME, EASE, F-44341 Bouguenais, France*

[b] *Réseau Ferré de France (RFF), 92 avenue de France, 75648 Paris, France*

[c] *ANDHEO - Centre Onera , 29 avenue de la Division Leclerc BP72 - F-92322 Châtillon Cedex, France*

Abstract

Ifsttar and RFF have developed an energy model of high-speed trains in order to determine the influence of infrastructure geometry and environment on train power consumptions. Validation of this model is based on full scale tests performed for the Rhine-Rhone high-speed line acceptance of work (in 2011).
This paper aims to evaluate if wind influence is a relevant parameter for the model. This involves numerical determination of aerodynamic coefficients for various wind and ground configurations and their use for the calculation of the aerodynamic efforts. Atmospheric characteristics are extrapolated from meteorological measurements thanks to the AROME numerical model, over the whole Rhine- Rhone line. Most remarkable results show for a moderate train speed (about 45 m/s), a rearward oriented wind of only 5,5 m/s lowers by 30% the power due to aerodynamic forces applied on the train, or raises it similarly if it is forwardly oriented. In conclusion, this work points out that wind influence is of first importance for computing energy consumption.
Keywords: Railways, energy consumptions, energy model, wind, aerodynamics, high-speed train.

Résumé

L'Ifsttar et RFF ont développé un modèle énergétique des trains à grande vitesse dans le but de déterminer l'influence de la géométrie et de l'environnement des infrastructures sur les consommations énergétique des trains. La validation de ce modèle est basée sur des essais grandeur nature réalisés lors de la réception de la ligne à grande vitesse Rhin-Rhône (en 2011). Cet article vise à évaluer si l'influence du vent doit être prise en compte dans ce modèle. Cela implique la détermination numérique de coefficient aérodynamiques pour plusieurs configurations de vent et de terrain et leur utilisation pour le calcul des efforts aérodynamiques. Les caractéristiques atmosphériques sont extrapolées de mesures météorologiques à l'aide du modèle numérique AROME, sur l'ensemble de la ligne Rhin-Rhône. Les résultats les plus remarquables montrent que pour une vitesse modérée de train, d'environ 45m/s, un vent arrière de seulement 5,5 m/s diminue de 30 % l'énergie due aux efforts aérodynamiques appliqués sur le train, ou l'augmente similairement s'il est orienté frontalement. En conclusion, ce travail montre que l'influence du vent est de première importance.
Mots-clé: Voies ferrées, consommations d'energie, modèle énergétique, vent, aérodynamique, train à grande vitesse.

---

[1] Corresponding author: alex.coiret@ifsttar.fr

1. Introduction

Railways, thanks to their low rolling resistance, overtake road and air in energy-efficiency for short and medium travel. Nevertheless, rail transportation is not always competitive in terms of travel times, compared to air transport for long travels or door to door road transport for short distances. Higher speeds are then required for maintaining railways competitiveness, but this trend paradoxically lowers its initial energy efficiency advantages (Martin, 1999), especially for short inter-stop distances (Feng, 2011). Then, the optimization of rail transportation should involve energy and mobility criteria (Coiret, 2012 ; Smith, 2012, Vandanjon, 2012).

In this context, Ifsttar and RFF have developed an energy model of high-speed trains, validated with full scale tests at the occasion of the acceptance of work of the Rhine-Rhone line (in 2011). Infrastructure geometry, train dynamics and electric consumption have been used to build an energy model but wind influence was not integrated in first attempt since local weather conditions was not continuously accessible during the tests.

This last point remained to be assessed. In this context, this work, handled by Andheo and Ifsttar, aims to determine the level of wind induced aerodynamical forces, compared to other forces including aerodynamical forces due to the train speed. Various wind conditions, train speed and topological situations are considered to assess the wind influence.

2. Aerodynamic model

2.1. Field determination of atmospheric characteristics

The wind influence was chosen to be studied on several trains running on the Rhine-Rhone high-speed line. Indeed, electrical power consumptions and infrastructure characteristics are known for these runs. An energy model has been developed and validated with these data. Wind influence could be integrated in this model.

Atmospheric characteristics (wind speed and direction, pressure and temperature) were determined over the whole Rhine-Rhone line (about 140 km) for the 25 days of tests conducted in 2011 for its acceptance of work. The numerical model AROME (Seity, 2011) was used to compute these wind fields from measurements at several surrounding weather stations (figure 1 : example of computed wind field).

The wind defined at a height of 10 meters is converted to a local wind along the train line, by applying atmospheric boundary conditions and specific environmental masks to take into account cities or forest. The equation (1) gives the wind intensity for a z height, relatively to the z_0 rugosity height (here 0.05m, considering mostly countryside), d a moving length (here equal to $0.7\times h$), and k the Von Karman constant (0.4). Hypothesis leads to a value of $u(3m)$ equal to $0.75\times u\ (10m)$. Land influence is later taken into account thanks to a shading criterium of less than 100 m forests or urban areas.

$$u(z)=\frac{u_*}{k}\ln\left(\frac{z-d}{z_0}\right) \tag{1}$$

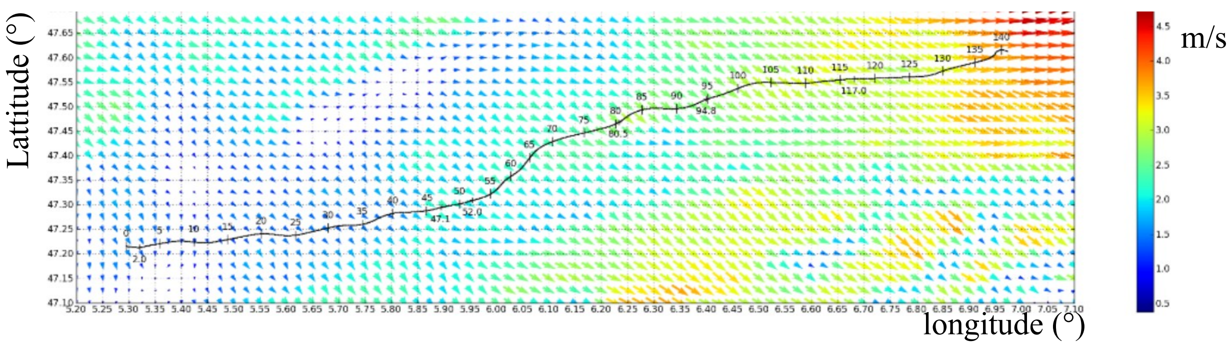

Fig. 1. Wind field plotted from AROME data, around the 140km high-speed line (at 13h, the 29/08/2011).

2.2. Run selection among wind variety and train speeds

144 runs have been performed during the acceptation of work process. It has been chosen to evaluate the wind influence for only 15 runs, to limit computational cost while ensuring sufficiently various cases, by combining various speeds and orientations of wind and various train speeds.

A classification of the whole set of run is presented on figure 2, for two variables: the “influence_vent” variable is the scalar product of the wind and train velocity vectors, divided by the train speed norm ($\vec{V}_{wind} \cdot \vec{V}_{train} / \|\vec{V}_{train}\|$). It indicates both the relative intensity and the orientation of the wind facing the train speed. The “V_moy_rel_TGV” variable is the train mean speed over the considered run (also called V_{train}).

Other classifications have led to the selection of 15 runs by considering the following mean criteria: high and low train speed, front and rear wind direction, strong or weak wind.

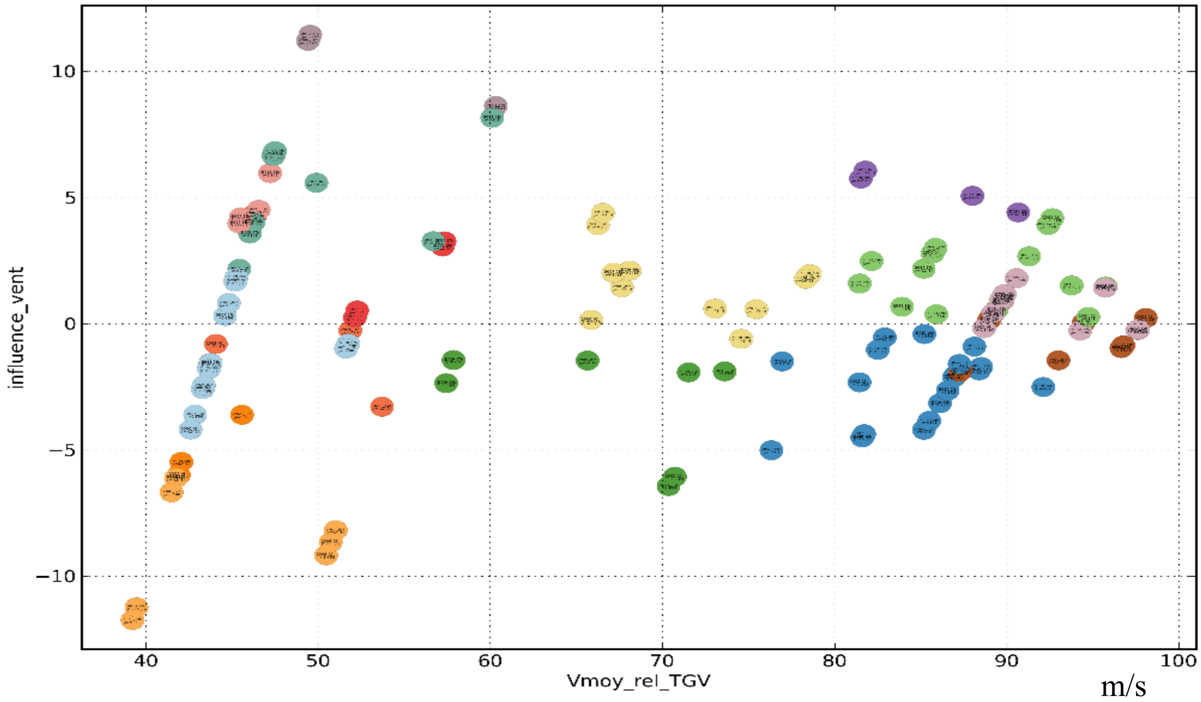

Fig. 2. Classification of the runs on the train speed, and relative wind speed (each colored spot represent a test run).

2.3. High-speed train aerodynamics modeling

In parallel, aerodynamic coefficients of the experimental high-speed train (ALSTOM TGV Duplex) were computed by resolving Navier-Stockes equations and by using auto-adaptive Cartesian meshes (figure 3, table 1). The longitudinal coefficient C_x fits with the value retained by the concerned norm and other data (Raghunathan, 2002). It is of great importance since this coefficient is used for computing aerodynamic forces. Other coefficients match less the norm, for example, C_z is 56% lower than the normative value. This is due to issues of modeling the underside of the train, but it virtually does not affect the needed tractive forces , but its influence is negligible facing the Cx coefficient.

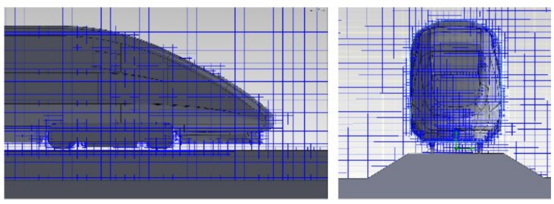

Fig. 3. Transverse and frontal views of the numerical discretization of the train.

Table 1. Aerodynamic coefficients for the trailer, with a 5 degrees wind incidence angle.

	C_x	C_y	C_z	Cm_x	Cm_y	Cm_z
Norm	0.157	0.484	-0.294	-0.317	-0.119	-1.013
Simulation	0.148	0.555	0.128	-0.334	-0.235	-1.036
Variation to the norm (%)	-6	15	-56	5	97	2

3. Results

Computed coefficients are integrated in numerical simulations for the 15 selected train runs , on a full train, for various wind angle direction and relative elevations to the natural ground. At last, power is computed all along the itineraries, while considering situations with or without wind.
The computation of the power is based on the equations (2). These equations give the aerodynamic force and momentum from the air density (rho), the front surface (S), the aerodynamic coefficient (Cx) and the speed of the air flow velocity (V). In this paper, aerodynamic forces are computing either by assimilate V to the train speed, which is the classical way to assess the energy consumption, and by calculate V from the composition of the train speed and wind speed.

$$F = \frac{1}{2} \rho S V^2 C$$
$$M = \frac{1}{2} \rho S L V^2 Cm \qquad (2)$$

The figure 4 presents significant results of these simulations. The y axis is the relative power induced by the aerodynamical forces between the with or without wind cases. Three particular runs are considered. The green curve labelled 29034 correponds to a train traveling at high speed (mean velocity is 95 m/s) in a weak mean wind (2 m/s). The red curve and the blue curves, labelled respectively 30002 and 29001, correspond to a train traveling at a moderate speed (about 45 m/s) in respectively a rear wind of 5.5 m/s and a front wind of 4.4 m/s.

One worthwhile result is that for a weak wind (2 m/s) and a train traveling at high speed (95 m/s), wind influence is of +5% and -5% on power due to aerodynamic forces on the train, respectively on front and rear wind sections of the itinerary (test run labelled 29034 on figure 4). This result is deduced from the analysis of the 29034 test run between the 70 and 120 km abscises (section for which the mean speed is of 95 m/s).

Another result is that for a moderate train speed (about 45 m/s), a stronger rear wind (5.5 m/s) lowers the needed power by 30% compared to the case without wind, and a front wind of 4.4 m/s raises it by 20% (respectively test runs labelled 29001 and 30002 on figure 4).

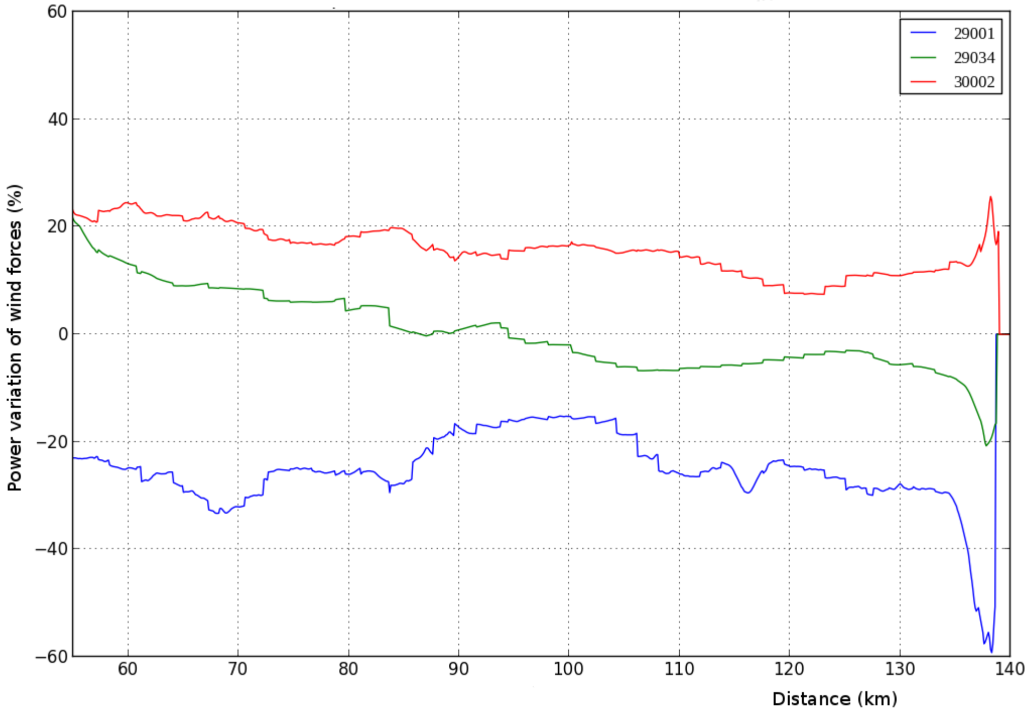

Fig. 4. Power variation of wind forces for three particular test runs (labelled 29001, 29034 and 30002).

4. Conclusions

In conclusion, this work based on a large set of full-scale experimental data, on the reconstitution of the wind field and the numerical simulation of the aerodynamic forces, points out that wind influence on total aerodynamic power consumption is of first importance.

Indeed, for the less sensible case, with a weak wind and a high train speed, wind influence has been found to be netherless noticeable, of the order of 5% of power due to aerodynamic forces on the train. For a more sensible case, with a wind speed about 5m/s and a moderate train speed of 45 m/s, the wind field is accountable of variations on this power as high as 30%.

In perspective, this experimental validation will contribute to develop a complete wind model as a component of the Ifsttar and RFF energy model.

Acknowledgements

The authors thank Meteo-France for their delivery of wind field calculations and Inexia for the train measurements.

References

Coiret, A., Vandanjon, P.-O., Bosquet, R., Jullien, A. (2012). Energy consumption induced by operation phase of railways and road infrastructures, *2nd International Conference on Road and Rail Infrastructure , Dubrovnik, Croatia , pp. 693 - 699, 7–9 May 2012.*

Feng, X. (2011). Optimization of target speeds of high-speed railways trains for traction energy saving and transport efficiency improvement. *Energy Policy*, 39, 7658 – 7665.

Martin, P. (1999).Train performance and simulation. In:Farrington,P.A., Nemb-hard, H.B., Sturrock, D.T., Evans, G.W.(Eds.), 1999 Winter Simulation Conference Proceedings. IEEE (Institute of Electrical and

Electronics Engineers), Phoenix, pp.1287–1294.

Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., Lac, C., Masson, V. (2011) *The AROME-France convective scale operational model*, Mon. Wea. Rev., 139, pp. 976-991.

Smith, R.A., Watson, R., Zhou, J. (2012). Energy and environmental aspects of high-speed rail, *2nd International Conference on Road and Rail Infrastructure , Dubrovnik, Croatia , pp. 35 - 44.*

Raghunathan, R.S., Kim, H.-D., Setoguchi, T. (2002). Aerodynamics of high-speed railways train, Progress in Aerospace Sciences, 38, pp. 469 – 514.

Vandanjon, P.O., Coiret, A., Muresan-Paslaru, B., Fargier, A., Bosquet, R., Dauvergne, M., Jullien, A., Franois, D. & Labarthe., F. (2012). Practical guidelines for life cycle assessment applied to railways project, in: *Proc. International Symposium on Life Cycle Assessment and Construction*. Nantes, France.

Annexe C : communication au TRA2014 sur l'utilisation du modèle en conception

Influence of railway gradient on energy efficiency of high speed train

Romain Bosquet[1], Pierre-Olivier Vandanjon[2], Maxime Gautier[3], Alex Coiret[2], Olivier Cazier[1*]

1 : Réseau Ferré de France (RFF), *Réseau Ferré de France, 92 avenue de France, 75013 Paris - France*
2 : LUNAM University, *IFSTTAR, AME, EASE, F-44341 Bouguenais - France*
3 : LUNAM, University of Nantes, IRCCyN, *CNRS : UMR6597 –- France*

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 implication on the construction and operation phases, since low gradients could require considerable civil engineering works.
The energy model of operation 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 railway gradient. The corresponding trajectories are compared from an energy efficiency point of view.
Results show that the gradient is not the only element to take into account. The associated length of ramp or slope is crucial too. Short section with an important gradient does not have an impact in terms of energy instead of those having 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 cost of the construction and 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. Une courte section avec une importante pente n'a pas d'impact en termes d'énergie contrairement à celle ayant 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.

[*] Corresponding author information: Tel.: +331 53 94 32 78, *E-mail address*: romain.bosquet@rff.fr.

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, train offers many advantages, as consuming significantly less energy than road or air transports and improving traffic flows near urban areas. So, about 13,000 km of tracks 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 $\boldsymbol{l}$ 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.

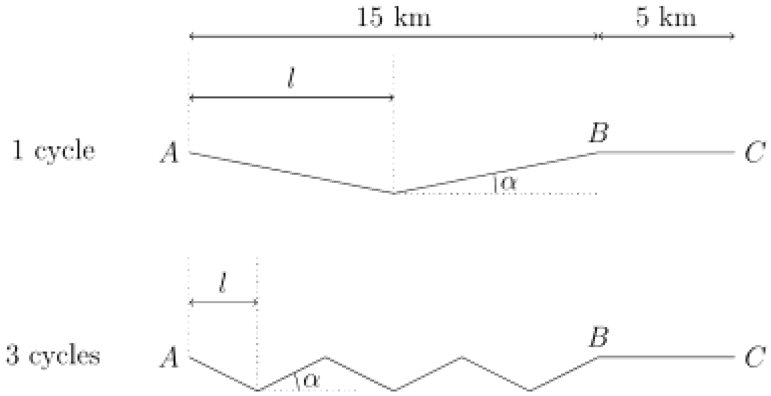

Fig. 1. Longitudinal profile. Example of two tracks.

In the following, the calculation of l is given. The longitudinal length of the track is (by using the so-called "small angle approximation") – equation (1):

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

with |AB| the distance between A and B.

l is obtained with equation (2) :

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

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	Cycle number									
(mm/m)	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).

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

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):

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

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

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

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 accelerates. 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).
These various cases are summarized in the figure 2 with example of limit and set point speed.

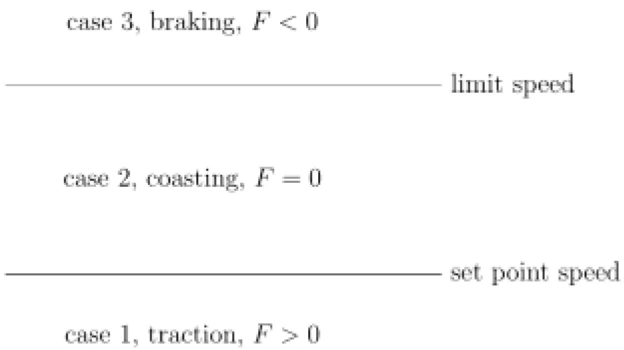

Fig. 2. Driving rules.

Driver's behaviour in the case 1 and 3 is modelled by a speed closed-loop proportional integral controller. For example, in the case of traction ($V < S_{sp}$), the error is obtained with equation (6) and F with equation (7).

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

$$F = Pe_s + I\frac{de_s}{dt} \quad (7)$$

The two coefficients of the corrector (P and I in equation (4)) 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.

In this article, set point speed is equal to 75 m/s (270 km/h), the travel time is equal to 267 s (15,000+5,000/75) 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) is used to solve the ordinary differential equation.

Figure 3 shows an example with 2 cycles and a gradient of 25 mm/m. The upper plot is the altitude (figure 3a). Figure 3b the gradient, figure 3c is the speed and the lower plot (figure 3d) is F. These four data are given in function of location (in kilometer). On the speed profile graphic (figure 3c), 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 3d 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 3 shows that our simulation is a good representation of the actual behavior of drivers.

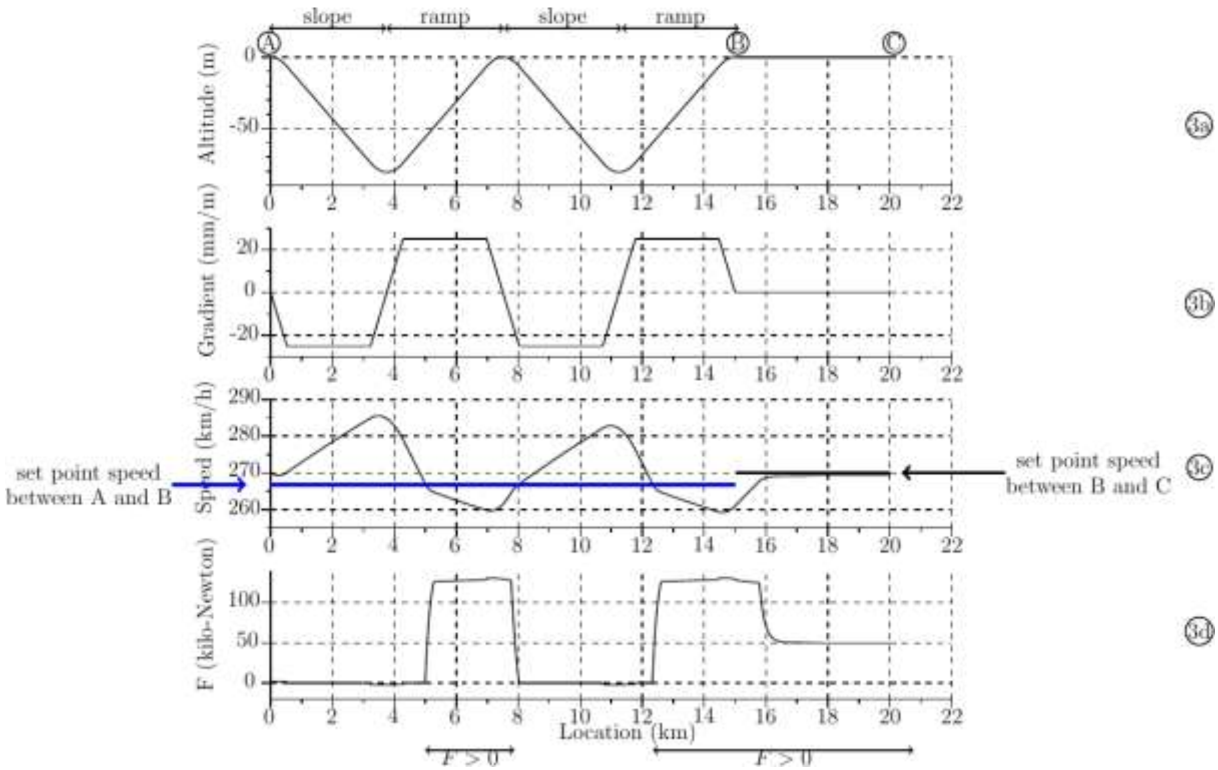

Fig. 3. Gradient, Speed and F in function of location.

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 saving 3%, 9% and 14% of the consumption.

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.

In conclusion, 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

The main result is that, 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, 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.

Our result upon slope length/gradient criterion is very important for the construction of new high-speed lines. In practical cases, this result 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.

References

Bosquet, R. & Vandanjon, P-O & Coiret, A & Lorino, T. (2003) Model of High-Speed Train Energy Consumption. pp1912-1916. World Academy of Science, Engineering and Technology. Issue 78.

Boullanger, B (2008). Modeling and simulation of future railways. pp1-68. PhD thesis, Royal Institute of Technology KTH.

Garcia, A. (2010) High speed, energy consumption and emissions. pp1-52. Technical report, UIC. December.

International Energy Agency - IEA,(2013). www.iea.org>Home>Statistics>Oil. Online accessed. April.

Jeunesse, A & Rollin, M (2004). La motorisation du TGV POS. Revue Générale des Chemins de fer. March.

Lindahl, M. (2001). Track geometry for high-speed railways - a literature survey and simulation of dynamic vehicule responce. Technical report, Royal Institute of Technology.

Lindgreen, E & Sorenson, S (2005). Simulation of energy consumption and emissions from rail traffic. Technical report, Technical University of Denmark, Department of Mechanical Engineering. February.

Liu, H & Mao, B & Ding, Y & Jia, W & Lai, S (2007). Train Energy-saving Scheme with Evaluation in Urban Mass Transit Systems. pp68-73. J Transpn Sys Eng & IT, 7(5). October.

Lukaszewicz, P. (2007). Running resistance - results and analysis of full-scale tests with passenger and freight trains in sweden. pp183-192 Proceedings of the Institution of Mechanical Engineers, Part F : Journal of Rail and Rapid Transit, 221.

Rochard, B P & Schmid, F (2000). A review of methods to measure and calculate train resistances. Proceedings of the Institution of Mechanical Engineers, Part F : Journal of Rail and Rapid Transit, 214.

UIC (2013). High speed lines in the World. pp1-10. High Speed Department. July.

Table des figures

Bibliographie

Romain Bosquet. Compte rendu provisoire d'expérimentation, partie 1 : Traitement des données brutes. Technical report, September 2013a.

Romain Bosquet. Compte rendu provisoire d'expérimentation, partie 2 : modèle chaine de traction. Technical report, September 2013b.

Romain Bosquet. Compte rendu provisoire d'expérimentation partie 3 - identifications. Technical report, September 2013c.

A. Janot, P.-O. Vandanjon, and M. Gautier. Identification of physical parameters and instrumental variables validation with two-stage least squares estimator. *IEEE Transactions on Control Systems Technology*, 21(4) :1386–1393, July 2013. ISSN 1063-6536. doi : 10.1109/TCST.2012.2199321.

P-O Vandanjon, C-E Lemaire, and M Gautier. Pratique de l'identification des systèmes mécaniques articulés. In *Problèmes inverses en génie civil*, Etudes et recherches - Série Sciences pour le génie civil SI 15. Laboratoire Central des Ponts et Chaussées, January 2009. ISBN 9782720825336.