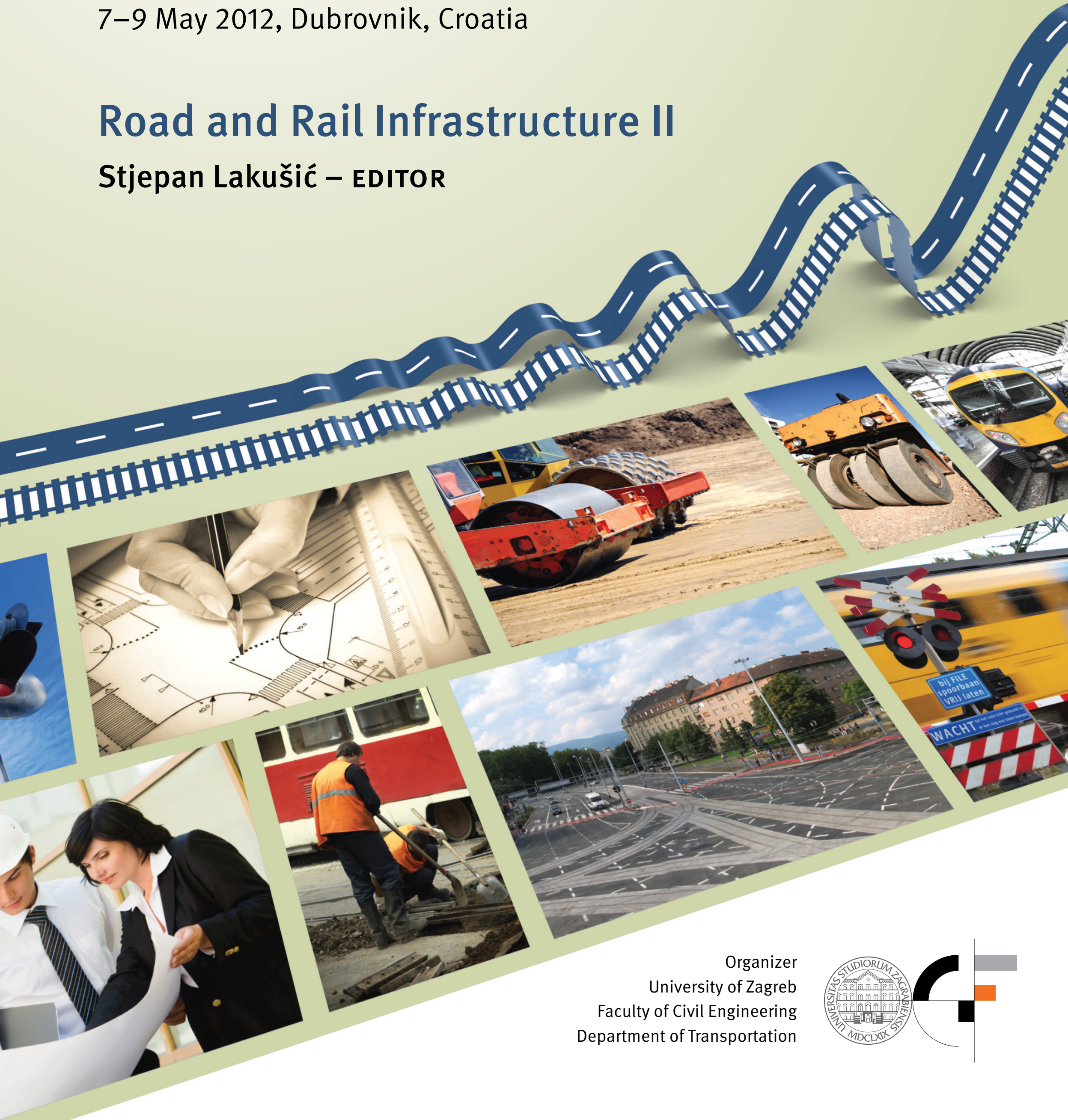
CETRA^{2012}

2^{nd} International Conference on Road and Rail Infrastructure

7–9 May 2012, Dubrovnik, Croatia

Road and Rail Infrastructure II

Stjepan Lakušić – EDITOR



Organizer
University of Zagreb
Faculty of Civil Engineering
Department of Transportation

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TITLE
Road and Rail Infrastructure II, Proceedings of the Conference CETRA 2012

EDITED BY
Stjepan Lakušić

ISBN
978-953-6272-50-1

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Katarina Zlatec · Matej Korlaet

COPIES
600

A CIP catalogue record for this e–book is available from the National and University Library in Zagreb under 805372

Proceedings of the
2nd International Conference on Road and Rail Infrastructures – CETRA 2012
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ENERGY CONSUMPTION INDUCED BY OPERATION PHASE OF RAILWAYS AND ROAD INFRASTRUCTURES

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Abstract

Up to now, transport systems have mainly been designed by considering time–efficiency, mobility and safety criteria. Today hard constraints on resources savings and environment preservation have to be taken into account at the different phases of design, maintenance and operation of these networks. This study, focused on the operation phase, aimed to provide a common framework for rail and roads energy consumption assessment. For that, the influence of infrastructure characteristics on energy consumption of vehicles was assessed, in a optimization perspective. A method for energy consumptions evaluation by exploiting contact forces models was proposed. Two models were developed, for a road and for a railway, and validated with experimental data of a vehicle on a test track and full–scale measurement of a high speed train on a given line. At last, numerical simulations are worked out with the validated models to exhibit the influence of successions of uphill and downhill on energy consumptions. These simple mechanical models pointed out the differences of the two transportation systems, in terms of developed contact forces and consumed energy.

Keywords: energy consumption, roads, railways, vehicle model, full scale tests.

1 Introduction

1.1 Background and objectives

Transport systems are usually designed by considering criteria of time–efficiency, mobility and safety. Up to now, many researches based on these criteria have been conducted [1, 2, 3]. Nowadays, current hard constraints on resources savings and environment preservation have to be taken into account, for design, maintenance or operation of these networks.
In this study, only road and rail transport systems were considered as other transportation means handle very small fractions of traffic (air, sea, inland waters) [4]. Furthermore, attention is focused on the operation phase since rising energy costs are increasing its importance relatively to less energy–dependant costs of construction and maintenance. The overall aim was to provide a common framework for rail and roads energy consumption assessment and to determine the influence of infrastructure characteristics on vehicles energy consumption, for optimization. A method relying on contact forces models was proposed, in order to focus on the infrastructure parameters.

1.2 International context

Physical limits of energy resources as oil, gas and coil, added to an increasing demand for theses resources lead to the development of the Peak Oil Theory that describes the unbalance between oil demand and production [5, 6]. As pointed out by Friedrich [7], it is more a question of oil production amount than oil reserves and numerous forecasts indicate peak oil occurrence at 2011 [8]. In the International Energy Agency New Policies Scenario [9], it is expected that world oil production reaches 96 million barrel/day in 2035 on the back of rising output of natural gas liquids & unconventional oil, as crude oil production plateaus. Almost half of the net growth of demand comes from China alone, mainly driven by rising use of transport fuels [10], since rapid growth of vehicles in China is accounted to raise energy demand at 734 million tons of oil equivalent by 2050 in the business as usual case, more than 5.6 times of 2007 levels. These projections reinforce the need to model the energy consumption of transport operation phase in the perspective of energy savings.

1.3 Energy efficiency design methodology

Technical constraints guide the conception of infrastructures as follows:

- Curvature radius, transverse slopes and speed limitations are dependant under comfort and safety relations. For example the minimum curvature radius of a high speed railway is bellow 5200m for a speed of 90m/s. For a car traveling at 25m/s on a road, radius of 400m and 475m are consistent with the comfort rules for respectively cross–slopes of 2.5% and 0% [3];
- Longitudinal profiles are generally limited for high speed railways at a level of 3.5‰, both by considering engine power and contact forces limitations. Road longitudinal profiles are limited at 8 to 10% for coping with low grip cases (ice);
- High speed railways electric supply is dependant of substations locations and – to a limited extent– of power plant locations…

Thus, railways are much less adaptable to the traveled territories, compared to roads, partly due to the weakness of contact forces, which are the counterpart of low rolling resistance. Moreover, vehicles efficiency and differences in energy sources lead to choose a common comparison criterion: the contact forces. Indeed, avoiding considering internal efficiency of vehicles, by opting for nearly arbitrary efficiency coefficient, is a mean to point out the infrastructure parameters influencing consumptions. Thus, running resistance can be expressed as the integration of power developed at the M contacts points of a vehicle along an itinerary, providing a simplified expression of the energy consumption C_{iti} developed from the applied contact forces ($\mu=F_x/F_z$; $\tau=F_y/F_z$), considering the efficiency coefficient E_{eff}:

$$C_{iti} = \frac{\int_{iti} F_z(\vec{\mu} + \vec{\tau})_{(M)} \cdot \vec{V}_{(M)} ds}{E_{eff}} \qquad (1)$$

2 Application to roads

2.1 Vehicles and road dynamical model

The road model needed for contact forces evaluation is derived from a previous study on road safety [11], in which the influence of road properties on controllability limits of a vehicle has been experimentally approached on a test track (Fig. 1) and analyzed by a numerical model [12, 13].

Typical numerical models for safety diagnostic on itineraries (as presented in Fig 2a) are based on the application of the Newton/s second law, which, for a bicycle model, leads to equations involving forces and momentums, in the form of:

$$F_{xf} + F_{xr} = (P2m\vec{a} - P1P2\vec{P})\vec{x} \tag{2}$$

$$\begin{cases} -F_{zr} * l_r + F_{zf} * l_f + (F_{xf} + F_{xr})H = I_{yy}\ddot{\varphi} \\ F_{yf} * l_f - F_{yr} * l_r = I_{zz}\ddot{\psi} \end{cases} \tag{3}$$

Where l_f and l_r are the distances between front and rear wheel to the centre of gravity, F_{xf}, F_{xr} the front and rear components of forces on x, a the vehicle acceleration, m its mass, H its centre of gravity height, P1 and P2 transformation matrix, P, the weight vector, $\ddot{\varphi}$ the pitch acceleration, $\ddot{\psi}$ the yaw acceleration and I_{yy} and I_{zz} the vehicle inertia terms.

Figure 1 Experimental test track for models validation

A four wheel model is presented and validated (Fig. 2a and Fig. 2b) by using experimental data (mu_cons) and other models: simple point model 'mu_point', two point model 'mu_trans', .and a commercial four wheel model 'mu_Callas'.

The test vehicle is a passenger car traveling at 24m/s; running a constant radius curve of 110 meters and two clothoïds which are connecting the curve to the straight section (see Fig. 1). Rather good correlation is achieved by the tested models with the experimental data (Fig. 2b), especially for the constant curve part (Time period in the interval 6 to 11 seconds) and the four wheel model.

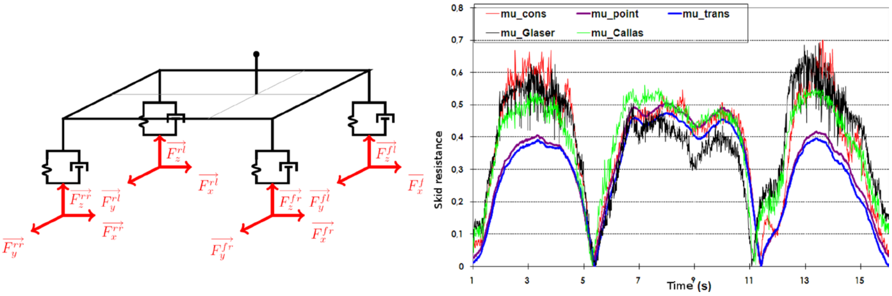

Figure 2 four wheel model of road/vehicle interactions (left); modeled and experimented grip resistance (mu_cons) on the curved test track (right)

2.2 Road infrastructure parameters influence on mobilized forces

This subsection illustrates the use of a classical model dedicated to safety analysis for eco–design. It is considered that a vehicle is traveling from A to B (points); going up a slope on the first half of the travel and going down to B which is at the same height as A. Simulations are done for every percent of slope from 0% to 10%. The speed of the vehicle is maintained at 90km/h. The driving forces are computed thanks to the four wheel model. According to Eq. (1), these forces are integrated along the path to get the work, energy variations with the percentage of the slope are plotted on Fig 3.

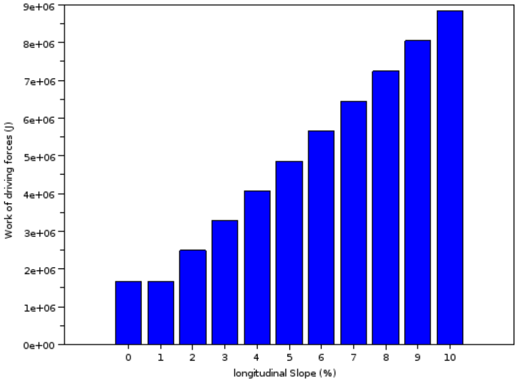

Figure 3 Modeling of the influence of longitudinal slopes (combined uphill & downhill sections of increasing levels from 0 to 10 %)

As illustrated in Fig. 3 the consumed energy increases with the longitudinal slope, apart for weak slope values (below 2%) when there is no need for the driver to brake on the downhill phase (rolling and aero resistances are sufficient to keep the actual speed below the desired one). Energy increasing predictions are much higher than estimated ones [3], where longitudinal slope are prone to raise energy consumption of 12% of initial level for each additional percent of slope over the 2.5% level. This relies on the fact that low internal efficiency of vehicles is shadowing the much less impacting slope influence on rolling resistance.

3 Application to rail infrastructures

3.1 Dynamical contact model

The train of M mass is considered as a point. Newton's second law gives the developed contact forces (Eq. (6)). Then the electric consumption is deduced by using a constant ratio which illustrates the efficiency of the traction system.

$$M\cdot\gamma = F - R - M\cdot g\cdot \sin(\alpha) \tag{6}$$

γ is the longitudinal acceleration, F the total force to the drive wheels provided by the electric motor, α the slope, R the resistance force which is composed of the rolling resistance (wheel to rail contact), of the frictional resistance, (viscous friction $F_v(q)$ and dry friction $F_s(q)$) and aerodynamic resistance. With A,B,C quite empirical coefficients, R is a function of the V speed [14]:

$$R = A + B\cdot V + C\cdot V^2 \tag{7}$$

3.2 Full scale experimental tests

In France, the Rhine–Rhone high–speed railway line forms an essential rail link between North and South of Europe. The test section is 140 km long, from Villers–les–Pots (to the East of Dijon) to Petit–Croix (to the South–East of Belfort) (Fig. 4). Collected data on this section for trial runs are used for mechanical model testing. The application of Eq. (7) to the geometry of the test section is illustrated by Fig. 4 giving the consumed power along the line (versus the kilometric point). Fig. 5 illustrates the model validity along a part of the tested track. Calculated power variations are in good agreement with measured energy on the train.

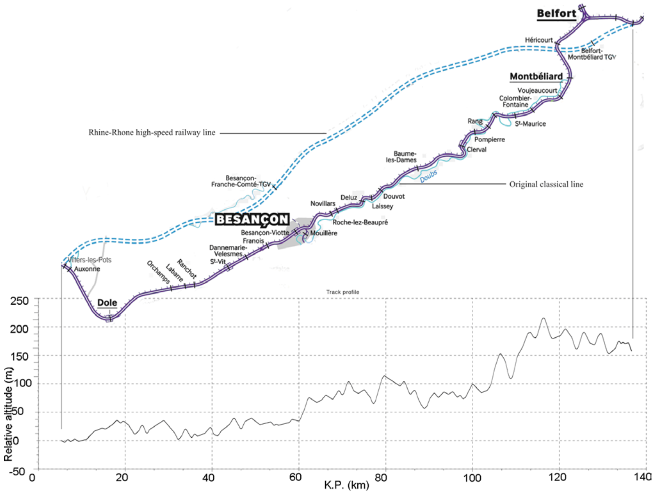

Figure 4 Map and track profile of the test section

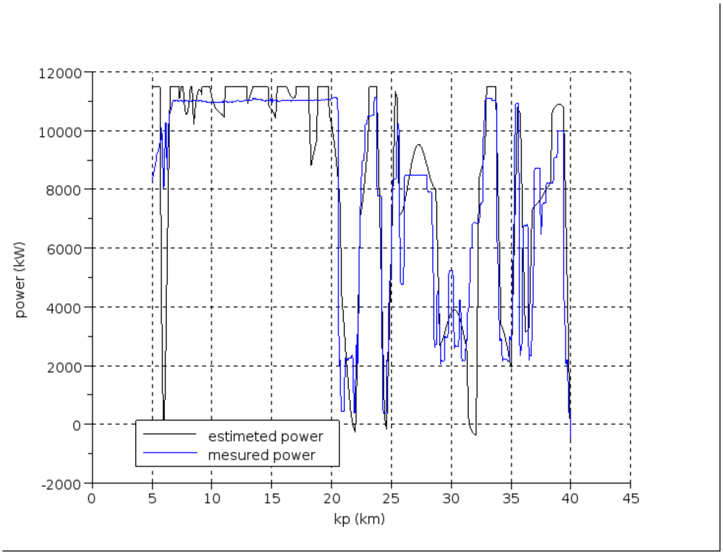

Figure 5 Modeled power versus measurements on a part of the test section

3.3 Energy evaluation methodology

A numerical application of the mechanical model is worked out on similar test cases that have been conducted for road evaluations. A high speed train is traveling at 320km/h between points C and D points while climbing a slope of 10 increments from 0 to 4.5 ‰ on the first half of the itinerary and down coasting to D which is at the same height as C. The speed of the train is always maintained.

As shown in Fig. 6, the energy consumption to go from C to D increases with slope. In the first case (slope 0 ‰), the consumed energy is identical between first and second section of course. Then, total consumed energy is almost constant up to a 15‰ gradient. Indeed, the train does not need to brake during the descent. This is due to the aerodynamic drag. Above this threshold, the train have to brake during the descent, that is why consumed energy increases.

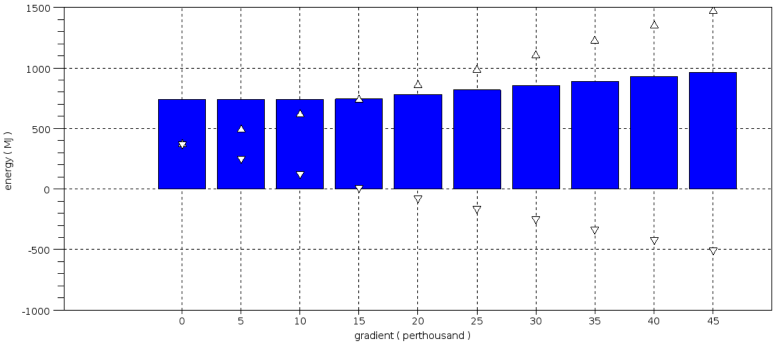

Figure 6 Modeling of the influence of longitudinal slopes (positives (△) and negatives (▽) slopes of increasing levels from 0 to 4.5 ‰)

Conclusions

Short–term expectations on peak oil and climate change are justifying new investments of transport systems in order to improve their energetic efficiency.

This study, focused on the operation phase of road and rail infrastructures, aims to provide a common framework for energy consumption assessment. A method for energy consumptions evaluation by exploiting contact forces models has been proposed, prior to the development of two models, for road infrastructures and railways, and their validation with the help of dedicated experimental data. Numerical simulations have shown the influence of one type of elementary infrastructure characteristics on energy consumptions, via contact forces integration along itineraries. Differences between the two transportation systems are pointed out by the application of simple mechanical models for representing each one, in terms of developed contact forces and consumed energy.

These models open opportunities to investigate the influence of chosen geometry paths to the energy consumption, to evaluate energy recovery system, to optimize localizations of electric substation, and to calculate the influence of the speed references to the energy consumption. The simple models presented were limited to the fundamental equation of dynamics. The energy need for the operation phase was characterized and can be useful for network managers, aside information on infrastructure building and maintenance. The motors efficiency and energy lost by transformations before usage (inline lost for railways, transportation for oil, etc.) are still to be addressed in future work.

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