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Development and application of energy optimization models in a railway environment: from railway design to ecodriving

Desarrollo y aplicación de los modelos de optimización de energía en entornos ferroviarios: del diseño ferroviario a la conducción eficiente

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Resumen

Este documento tiene por objeto describir y analizar algunas de las características y los resultados relativos al desarrollo y aplicación de nuevos modelos matemáticos concebidos para la optimización de funcionamiento de perfiles de velocidad, así como la energía de tracción consumida en la operación ferroviaria. En primer lugar se muestran los principios básicos y las fortalezas de los modelos para posteriormente discutir la importancia de la utilización de diferentes modelos matemáticos en todo el proceso de optimización de la energía mostrando los resultados de algunos ensayos ya realizados.

Finalmente se muestran importantes conclusiones derivadas de los potenciales ahorros en el consumo de energía, especialmente para los diferentes tipos de material rodante, condiciones de infraestructura y horarios.

Palabras clave: Optimización, algoritmo, conducción eficiente, energía, ferrocarril.

Abstract

This paper aims to describe and to analyze some of the characteristics and results concerning the development and application of new mathematical models conceived forthe optimization of running speed profiles as well as the traction energy consumed in the railway operation.First we show the basic principles and strengths of the models and afterwards discuss the importance of the use of different mathematical models in the whole process of energy optimization showing the results of some trials already done. In the swifter models we emphasize their potential in anin-cab optimization use which gives them ecodriving potential.

Finally important conclusions are drawn regarding the potential savings in energy consumption, especially for different types of rolling stock, infrastructure conditions and schedules.

keywords: Optimization, algorithm, ecodriving, energy, railway.

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1. Introducción

For some time now there has been a hugeconcern for energy efficiency among railway operators and many other stakeholders. Nowadays since de dramatic increase of the oil prices the energy problemshave taken new proportions and the worries aboutthe environmentalconsequences of poor management in natural resources are more present.In the past few years, cumulated experience from all over the world has been very helpful and now several practical and theoretical approaches concerning energy optimization in the railway sector can be easily identified.Simultaneously the introduction of new technologies, particularly in the rolling stock, allowed a faster materialization of sometheoretical approaches with good results.

Both theoretical and practical approaches have been used with the purpose of finding new methods to optimize the speed profiles of the trains. In the last decades many theoretical solutions where developed based on different kindof algorithms particularly inmetaheuristicswith most of them havingachievedquite good results.Howeversomeof those theoretical solutions are yet not tested from the operating point of view and sothere are doubts concerning their performance. On the other hand, afterknowing the general ideas of a reasonable optimize energy driving, more practical solutionshave been introduced allowing for some interesting results mainly focusedon the driver'sonsite training. Yet, however interesting these practical approachesstill loses a huge part of the potential for energy optimization.

The two models presented in this paper weredeveloped with the sole purpose of optimizing the running speed profiles. The first one is based on linear programmingand gives the optimal solution considering the infrastructure geometry, rolling stock characteristics and all the operational restrictions.The second approach resulted in a heuristic which is able to achieve a very good solutionwhile being extremely fast. Thus the second model may be used in real timedrivingas it's capable toswiftly perform optimized speed profiles and still respect all the restrictions of the infrastructures, operation targets and the rolling stock characteristics (ecodriving).

Mathematical Models

The main driving options of train which lead to a more rational energy consumption are well known: coasting after achieving the highest points; avoid mechanical braking; start up with the maximum power; cut the power mainly at the highest speeds. However it's extremely difficult for the driver to identify the geometry of the track profile while drivingand so to know the exact locations where to change throttle position. Furthermore most often the driver doesn't know the impact of its driving options on the schedule hence he usually adoptsa conservative approachconsiderably restricting the optimization potential of the run.This sort of situationsclearly illustrate the relevance of the effort put into the developingof theoreticalmodels toallow the identification ofoptimized drivesthat ensure schedule fulfilment and,simultaneously, consider all the infrastructure restrictions.

When formulating mathematical models for energy optimization it is very important toadequately identify the factors whichcan explain the traction consumption in one railway journeyin order for them to be properly considered.Whereas energy optimization is concerned most mathematic formulations found often consider the geometric parameters of the railway, the operation restrictions or the major characteristics of the rolling stock. Over and over again we also see that authorsuse detailed information in their models such as the rolling stock length (Ko et al, 2004), the energy recovered on a regenerative breaking systems or the energy consumed on the auxiliary equipment.Nevertheless the important is thatmathematical model considers the inputs which are necessary to ensure the goals.

Although both part of an extensive process of optimization the two developed models presented in this paper assume different philosophies.The first one is called ECOLP (Energy Consumption Optimization Linear Programing) and uses a linear programmingapproach which allows us to find the optimal solution.When conceiving the goal was to developa model that could give us the best possible solution considering the infrastructure and the rolling stock restrictions without any driving modes constrain. Hence in this model considers assumptions such as: the drivercanincrease or decrease poweras oftenas he wants even when humanely impossible. This degree of freedom could lead us to unpractical solutions but at the same timeensuresthat the best solution we could ever achieve is found.In the equations (1) and (2) we can see in a very simplified way the linear programming approach formulation.The objective is to minimize the energy consumed (E) without jeopardizing the established journey time (T) andrespecting all the speed restrictions (V) which are a function of the positionof the train and its characteristics also speed related (f(x,V)).

$$\text{Objective Function: } \min E \qquad (1)$$

$$\text{Restrictions: } T \leq T_{max} \ \wedge \ V_{(x)} \leq f(x,V) \qquad (2)$$

The approach integrates the basic concepts of kinematics and follows Newton's Second Law of Motion. As can be seen in the following equations, it was adopted the formulation with the position as anindependent variable (in opposition to time as anindependent variable). Consequentlythe speed of a train in a certain (x+1) positionis calculatedconcerning the value of the speed inthe position immediately before (V(x))and the acceleration or braking capacity (a(x)) of the rolling stock. To calculate the acceleration we also need to know the total mass of the rolling stock (m) as well as the resistance forces of the train. The resistance forces of a train (F_r)compriseforemost the wind resistance and the tangential part of the gravitational force (g_{tag}). Knowing the rolling stock traction force (F_t) we are able to calculate in every single iterationthe total force and thus the value of the acceleration. With the values of the traction force, the mass of the rolling stock and the engine yields (g) we can easily calculate the energy (E).

$$V_{(x+1)}^2 = V_x^2 + 2 \cdot a_{(x,v)} \cdot \Delta x \qquad (3)$$

$$a_{x,v} = \frac{F_{t(x,v)}}{m} + \frac{F_{r(v)}}{m} - g_{tag(x)} \qquad (4)$$

$$t = \sum_{x=0}^{x-1} \left(\frac{\Delta x}{\frac{v_{(x)} + v_{(x+1)}}{2}} \right) \qquad (5)$$

$$E_x = \begin{cases} \dfrac{F_{t(x,v)} \cdot \Delta x}{\gamma_t} & se \ \ F_{t(x,v)} \geq 0 \\ F_{t(x,v)} \cdot \Delta x \cdot \gamma_f & se \ \ F_{t(x,v)} \leq 0 \end{cases} \qquad (6)$$

The geometry of the railwayis accurately deemed as well as the rolling stock characteristics. Like most of other mathematical models, the trains are considered as a single point and thus itslength isn'ttaken into account. The energy is the product of the traction force and the distance, times the engine yield (6).When the rolling stock has a regenerative breaking mechanism the ECOLP model is ableto calculate the returned energy using a different yield value(g_f).Nonetheless, regenerative breaking is only considered till a certain value which can be defined in the model and establish the difference between the electric and the mechanical break.

Since the ECOLP model uses a linear programing approach we had to overcome the obstacle of the nonlinear equations (3), (4) and (5). To dealwith this we used two linearization technics: i) variable substitution; and ii) piecewise approximation. Although these technics have some well-known mathematical limitations, they have proved to be quite effective insolving this sort of problems. In its final formulation the model was set up as a multi objective problem solver. The elementary objective function (1) was changed to a general scope functiontranslated by formula (7). The latestincludes coefficients relatedto the cost of energy and time (c_E and c_t).With this option we have developed a model that is able to perform a natural trade-off between the energy consumptionoptimization and the journey time increase. Consequently a general objective functionwas reached comprising information about the auxiliary energy consumption,such as cooling or ventilation devices, losses of incomes due the demand elasticity concerning the travel time, or the reduction of positiveeconomicexternalities benefits.

$$\text{Objective Function: } \min (c_E \cdot E + c_t \cdot T) \qquad (7)$$

This exact model can then find the optimal speed profile for anyjourneyand thus establish a maximum standard for each case. Therefore it's possible to quantify and analyze the differences between the ECOLP solution and the results of alternative approximated models.

After developing a mathematical model able to find the optimal solution we have looked forward to find a more simplified model. The goal was to ensure good and fast optimized solutions and simultaneously their operational and driving feasibility. This type of problem has been analyzed for many years using heuristics based on dynamic programming (Ko*et al*, 2004), genetic evolutionary stochastic algorithms (Chang andSim, 1997; Bo and Wu, 2007; Wei *et al*, 2009) or swarm intelligence algorithms (Hu *et al*, 2010) and other metaheuristics. Although these models are able to reach good solutions they are usually complex,stochastic and many times computationally slow.There is then room todevelopnew models able to achieve faster optimized and deterministic solutions without compromising all kinds of operational restrictions.

Guided byquality, simplicity and feasibility principles a new model called ECOH (Energy Consumption Optimization Heuristic) was developed.As the ECOLP model, the ECOH approach integrates the basic concepts of kinematics and follows Newton's Second Law of Motionas well. So the speed and energy calculation is based in the same simple equations (3), (4), (5), and (6) using an iterative processwith distance increments.

The main philosophy of the ECOH approach is to find the best points where to start coasting or to maintain speed. Thus the calculation becomes simpler than the ECOLP model ensuring at the same time its consistency with real train driving.The ECOH approach is a heuristic with several sequential routines:

calculation of the minimum journey time in full power driving; identification of the section where the train must start coasting; identification of the sections where the train must maintain the speed. These routines are perfectly consistent with railway driving which is also directly withthe rolling stock characteristics. Being a quite good representation of the operational reality the model only allows five different kinds of driving: full power (maximum acceleration); constant speed; coasting; regenerative breaking; mechanical breaking. With this approach the computationtime is extremelyshortened and the results match perfectly with real driving and operation options as well as restrictions.

2. Model's performance

The models were tested and validated under different perspectives in order to show their performance, feasibility and suitability to real life situations. Two approaches were followed: detailed analysis of ECOLP model running time and results; comparative analysis of ECOH model faced to ECOLP model, in order to assessthe quality and robustness of the results of the former model (Talbi, 2009).Simultaneously the evaluation of the differences between theoretical results and real operational requirements were compared. In all measurements donein real journeyswe have tried as far as we couldto quantify the energy consumption and thus the potential of the energy saving given by the models.

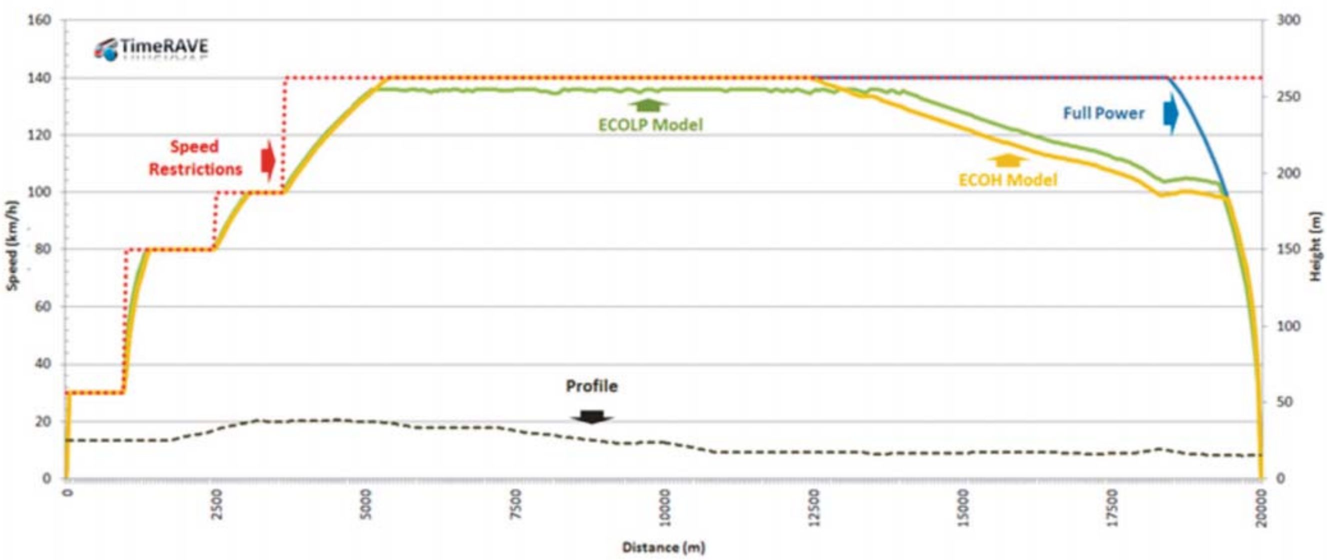

Figure 1. Optimized journeys usingthe ECOLP and ECOH models

In order to illustrate the behaviors of the two developed models we shall analyzethe speed profiles for a particular railway stretch (Figure 1). In yellow we can see the ECOH speed profile and in green the ECOLP profile. Figure 1 shows that from the real driving point of view the ECOLP model gives us a quite feasible result even without any driving restriction in its mathematical approach.The only exception can be easily identify in Figure1 as it occurs in a section where the proposed driving it's absolutely impossible to perform, approximately between point 5000m and 14 000m. In this section the ECOLP model presents several humanely and technically impossible changes in the speed. To correct this situation the ECOH model suggests the implementation of a constant speed slightly higher than the ECOLP model and starts coasting earlier.When we have compared the values of the traction energy consumption given by the two models we realize that they are almost alike. This sort of result was found in most of the analysis performedfor different types of railways services and rolling stock. Such results allow us toreach the following conclusion;besides returning the absolute maximum value of energy saving,for most casesthe ECOLP model is also able to offer, feasibledriving solutions.

The second step was to evaluate the performance and the quality of the ECOH model results. Comparing the results between the heuristic and the linear programming approach (ECOLP) we have concluded that their values were very similar. In average the difference among the two theoretical models was under 2%($1,00 < E_{ECOH} / E_{ECOLP} < 1,02$). Furthermorewe found that the differences between the two models were only slightly larger only in two specific situations. The first situation is when we increase the journey time. However only in unusual situations such as when the difference to the full power journey time was higher than 30% did the results show a slight diversion.The second situation occurred mainly in suburban movements where the maximum speed is not too high.Still the results of both models were always very close. From the computational point of view the ECOH model has revealed to be extremely fast even forquite long stretches. This property enables several swift and consecutive energy optimizations making it possible to be used in an in-cab application (ecodriving).

3. Real-life Tests

Comparing the theoretical results using the mathematical models with the values of the real time journeys we haveclearly identified several situations where it's possible to achieve very significant energy reductions (see Table 1). This type of situation remains truth even in scenarios where the operator has already taken measures in order to reduce traction energy consumption.In our tests we used different railway services with different types of rolling stock andin all situations we found great potential savings. The major potential savings were found inlong distance services. In these cases we easily found traction energy savings over than 20% comparing to present situations.Although also promising, the results for the suburban services were not so impressive. This mainly happened because the schedules of the suburban services analysedhad less freedom. Thus the trainswere operating most of the times in full power condition.Yet there were several cases of suburban services where we have achieved greater potential savings without sacrificing the established schedules.

Scenario	Journey Time		Average Speed		Total Lenght		Consumed Energy	
	Intercity	Suburban	Intercity	Suburban	Intercity	Suburban	Intercity	Suburban
Full Power Journey	87.0 min.	5.0 min.	145 km/h	106 km/h	211 km	9 km	1794 kWh	67 kWh
Performed Journey	92.8 min.	6.2 min.	136 km/h	87 km/h	211 km	9 km	1806 kWh	52 kWh
Optimized Journey	95.5 min	6.0 min.	132 km/h	90 km/h	211 km	9 km	1340 kWh	42 kWh

Table 1. Real measurements and optimized journeys using the ECOH approach

Although we haven't got real measurements concerning freight services so far, our expectations are very optimistic.Several theoretical testes were undertaken in order to compare full powerjourneys for freight trains and optimize speed profiles. The results have clearly shown a significant energy saving in this kind of service with small time increments on the established schedules.It is our opinion is that this happen especiallyfortwo mainreasons:first in these casesthere issignificant energy consumption as a direct consequence of the cargo weight; secondwe usually find more permissive schedules, hence withmorespacefor optimization. In short, we found evidences that there is a significant portion of energy waste in freight services too. Thesecircumstances could be easily solved with the theoretical approaches exposed in this paper.

4. Ecodriving

Based on the ECOH model presented in previous sections, a prototype of a real-time driver assistant system (Ecodriving) was developed. The system architecture, supported by GPS technology, allows it to work stand alone.The goal behind this architecture is to swiftly performoptimized speed profilesregarding the established schedules without the need to communicate with any train instrument. This way the system can give periodic instructionsabout the more economic driving options to the driverwithout compromisingany safety condition.

The developed system uses dynamic optimization routines which continuously updates both trainposition and speed recalculating the optimized speed profile, as illustrated in the next figure.

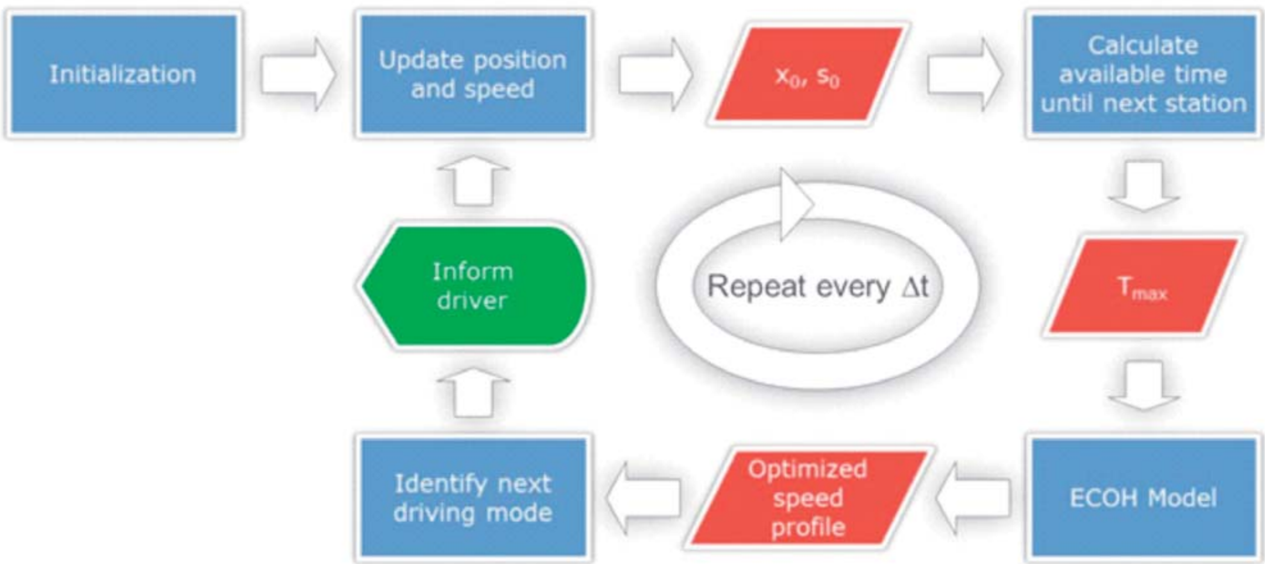

Figure 2. Flowchart of Dynamic Optimization Routines embedded in Ecodriving System

In addition to suggesting the best driving mode at each moment, the system is capable to provide other useful information to the driver. For instance it may also offer the next recommended driving mode along with where and when it will occur, the current and next speed limits, the time and distance to the next station and to the end of journey, the compliance with the schedule, the driving energy efficiency and so forth. The driver may enhance the information he wants to pay more attention thus ensuring the highest effectiveness of the system.

The prototype is now in an on board testing period.The first tests supported the aptitude of the system to be implemented as an in-cab tool since the optimization algorithm remains extremely fast even in long railways routes. The system also proved to be very efficient in adjustingto perturbations during the journey. Furthermore it was shown that the inputs possibilities of the ECOH modelcover the majority of the operational situationssuch as the rolling stock characteristics, signalling or infrastructure specificities.

5. Potential applications

Several important applications of the developed models (ECOH and ECOLP) are foreseen both for operators and railway infrastructure managers. Although most of situations are frequently connected to operator'sbusiness, themodels may also be used in a wide range of situations by railway infrastructure managers. For instance,in early stages ofstudies development (feasibility or design)of a future railway linesit's possible to analyse and optimize technical options while ensuring its operation feasibility. Consequently, by using this sort of tools and methodologies it's possible to achieveconstruction cost reductions even in the preliminary steps of the studies.Another possible optimization using these mathematical approaches is the railway scheduleswhere it is possible to achieve the besttrade-off between established journey times and the energy consumptions.

For the railway operators, however, it's possible to identifymore situations where the developed toolsmay be used. In fact, there are several perspectives from which these approaches can be quite profitable to an operator. Between all the possible benefits the most important one is the direct consequence in energy consumption of an intelligent driving, which is none the less but the energy bill reduced.As mentioned before, this kind of tool can identify optimized speed profiles of a certainrailway stretch.So, for every available schedulethe driver is able to perform an optimized journeyby knowing exactly where to accelerate, coasting or breaking. Besides if a real-time driving assistant is installed in the train the driver can perform an optimized driving even if changes occur during the journey. Comparing to present situations, results have shown that with thesemethodologies it's easy to achieveenergy savingover 20%.

Anotherpossibleuse to this type of tool may be to train and to evaluate drivers. The identification of optimized journeys increases the driver's knowledge about ecodrivingsince it establishes several relations between the speed profile, the infrastructure and the rolling stock own characteristics. Moreover is possible to use this sort of theoretical approach to stimulate a more rational conscience amongthe drivers. At the same time the successes and the failures of the drivers could be evaluated by establishinga balance between a real journey and the benchmark, generated by the ECOLP model.

It is also possible to quantify any disturbances on the railway operationusing ECOH and ECOLP models. Every change on the schedule can be evaluated. For example we can quantify the extra energy consumed in a delay dueto aninfrastructure work. But even in these situations is possible to mitigate the energy consumption and optimize the journey with different restrictions and goals.This type ofevaluation is useful for both the railway operators and the infrastructure managers.

6. Conclusions

Two different mathematical models were developed, named ECOLP and ECOH. Both models can easilygenerate optimized speed profiles considering the infrastructure geometry, rolling stock characteristics and all the operational restrictions. However they have different goals in the energy optimization process and as we have shownthe two methods complement each other.

The ECOLP model is able to find the optimal solution but itscomputational time is high. Furthermorethe ECOLP model results have shown that although the model doesn't integrate any driving constraint,thesolutions were most of the times feasible from the driver's point of view.These characteristics have revealed that this model could be a very strong tool to solve planning and design problems, such as schedules or technical alignments optimization. In the other hand the ECOH model has demonstrated a very fast computational time and with optimized solutions very close to the optimal.The solutions are also absolutely adjustable to realtime train driving. For these reasons we claim that the ECOH model could be a powerful tool to be used in all situations especiallyin an in-cabdriver assistant system (ecodriving).

Several real-life testswere done andsome of them are presented in this paper. The results clearly show that using these two approachesit's possibleto achieve an energy saving over 20% for the train operators.Besides the methodologies work very well in all kind of trains and services. We have done several experiences in suburban railway connectionsas wellas in long distance trains withvery expressive results. Although only theoretical tests were made concerning freight trains services,reached results revealed considerable energy savings too.

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