ENERGY-EFFICIENT DRIVING IN THE PORTUGUESE RAILWAY OPERATION

The case of regional rail operation in the Douro line

João Nuno Monteiro Vieira

MSc. in Transport Planning and Operation

Instituto Superior Técnico

October 2014

Abstract

The main share of energy consumption in railways consists of traction energy, i.e., energy required to move the trains. The amount of energy consumed is much influenced by the way the train is driven within schedule. As each driver has its own driving style and since the deduction of the energy-efficient driving strategy is not trivial, there are now available Driving Advice Systems to assist drivers in choosing the most energy-efficient actions.

The aim of this study is to develop an energy-efficient driving model in order to derive, for a given route and running time, an energy-efficient speed profile. The driving model was used to build efficient driving strategies for regional and inter-regional rail services in the Douro line. The model’s energy saving potential evaluation was done by using a train-running simulator in order to compare the driver’s actions and speed profiles of real cases with the most efficient driving strategies for the same situations. The simulation results point to an energy saving potential between 11 and 15%, just by changing the driving style.

Finally, a Driver Advice System prototype was developed, in order to assist the driver in adopting an efficient driving strategy. The prototype has been developed for the Android platform, to be implemented in a low-cost equipment, such as a tablet, equipped with GPS receiver.

Keywords: Energy-Efficiency, Eco-Driving, Driving Advice System, Railways.

1. Introduction

The main share of energy consumption in railways consists of traction energy, i.e., energy required to move the trains. The amount of energy consumed is much influenced by the way the train is driven within schedule (Hansen & Pachl, 2008).

The different driving strategies may be more or less energy-efficient depending on the points, in time and space, where the driver changes the driving regime between acceleration, coasting and braking. As each driver has its own driving style and since the deduction of the energy-efficient driving strategy is not trivial, there are now available Driving Advice Systems to assist drivers in choosing the most energy-efficient actions.

The existing Driver Advice Systems point to significant energy savings only due to the driving style’s adjustment. It’s the case of the Bombardier’s EBI Drive 50, which refers savings of 15% (Schober, et al., 2010), the Transrail’s CATO, referring energy consumption reductions between 20 and 25% in freight trains (Transrail Sweden AB, 2011), or the TTG’s Energymiser, announcing energy savings between 5 and 20% (Papworth, 2013). The somewhat dissimilar values
are probably explained by the high dependency on the timetable's recovery time (margins), with the highest margins providing greater energy-saving potential.

This work aims to develop an energy-efficient driving model in order to:

1. Evaluate the energy-saving potential in Portuguese regional rail services;
2. Propose a low-cost Driver Advice System to contribute to increase the productivity of railway operations in Portugal, by reducing energy costs.

Initially, the energy consumption minimization problem theoretical framework, that underlies the developed driving model, is presented. Then, the model's energy saving potential assessment is made by the comparison of real driving situations with the model's resulting driving strategies. Finally, the prototype of the Driver Advice System, developed with the aim of assisting train drivers in an energy-efficient driving, is presented.

2. Theoretical Framework

2.1 Energy Consumption Minimization

The energy consumption minimization problem is a typical optimal control problem and has been widely studied since the 70s of the 20\textsuperscript{th} century. The collective results pointed to the existence of an optimal driving strategy, valid on a route without steep slopes, based only on four sequential stages (driving regimes):

1. Acceleration with full power;
2. Speed-hold;
3. Coasting (Zero traction force);
4. Maximum service braking.

The development of this work's efficient driving model was based on the fuel consumption model deducted by Howlett and Pudney (Howlett & Pudney, 1995). This model, based on the four sequential stages, allows us to calculate the points where the driver should switch the driving regimes, relating the hold speed, $Z$, and the braking speed, $U$:

$$ U = Z - \frac{\varphi(Z)}{\varphi'(Z)}, \varphi(v) = \frac{r(v)}{\theta(v)} \quad (2.1) $$

Equation (2.1) shows that the relationship between these speeds is a function of the characteristics of rolling stock, where $r(v)$ is the running resistance polynomial and $\theta(v)$ represents the performance of the traction chain. In the developed model, a constant efficiency of the traction chain was considered, so that $\theta(v)=1/v$.

The calculation of a generic speed profile is done by solving the train’s motion equations:

$$ \Delta x = \int v(t) \, dt, \Delta v = \int a(t) \, dt \quad (2.2) $$

$$ \Delta x = \int \frac{v}{a(v)} \, dv, \Delta t = \int \frac{1}{a(v)} \, dv \quad (2.3) $$

Equations (2.2) apply to uniform motion situations, such as the speed-hold phase or even braking phase, which are both considered as subject to constant acceleration in the developed model. Equations (2.3) are used in cases of non-uniform motion, with the acceleration term depending on the speed, being the case of the acceleration and coasting phases.

The train’s net acceleration, $a(v)$, is obtained, for each homogeneous track section, by the relationship:

$$ f_t(v) = Av^2 + Bv + C + i + ka(v) \quad (2.4) $$

where $f_t$ represents the speed-dependent specific traction force, $Av^2+Bv+C$ is the running resistance polynomial, $i$ stands for the compensated track profile acceleration and $a(v)$ reflects the net acceleration of the train affected by the parameter.
which compensates the inertia of the rotating masses.

Equations (2.2), (2.3) and (2.4) make the energy-efficient speed profile calculation possible, for a given route and time allowed:

1. Choose a hold-speed $Z$;
2. Calculate an acceleration profile forward from the initial speed point until the hold-speed $Z$, using equations (2.3) and (2.4);
3. Calculate a braking profile backwards from the final speed point until the braking speed $U$ (related to the hold-speed $Z$ by equation (2.1)), from equation (2.2);
4. Calculate a coasting profile backwards from the point where the braking speed $U$ was reached until the hold-speed $Z$, using equations (2.3) and (2.4);
5. Compute the calculated speed profiles intersection or, if they don’t intersect, introduce a speed-hold phase in order to join the acceleration and coasting or braking profiles;
6. Evaluate the total running time. If it does not match the available running time from the timetable, iterate a new hold-speed $Z$.

Figure 2.1 presents an example of an optimal speed profile on a flat track without speed restrictions.

The represented strategy is optimal provided it respects the route’s distance and available running time, the sequence of optimal actions and follows the relationship between speeds $Z$ and $U$ for the given rolling stock.

However, the presence of track profiles with steep slopes in the speed-hold phase can lead to deviations from the planned hold-speed $Z$ on a steep incline, the tractive power may not be enough to maintain the desired speed and on a steep decline it may be needed to use the brakes in order to maintain the hold-speed, which is not efficient.

The approach to this type of track, called steep sections, followed the method described in (Vu, 2006), which advocates a full power acceleration phase before the start of the incline or a coasting phase, starting before the decline. The optimal speed profile for a steep decline is calculated by the equations:

$$f(v_b) = \left[\varphi(v_b) - \gamma_0 v_b \right] M(v_c)$$
$$-\left[\varphi(v_b) - L_r(v_b) \right] \left[\gamma_1 - \gamma_0 \right] = 0$$
$$L_r(v_b) = \varphi'(V)(v_b - V) + \varphi(V)$$
$$M(v_c) = \left[\varphi(v_c) - L_r(v_c) \right] \left[\gamma_1 - \gamma_2 \right] \frac{\varphi(v_c) - \gamma_2 v_c}{\varphi(v_c) - \gamma_2 v_c}$$

While the optimal speed profile approaching a steep incline is calculated from:

$$f(v_b) = \left[ P - \varphi(v_b) + \gamma_0 v_b \right] M(v_c)$$
$$-\left[\varphi(v_b) - L_r(v_b) \right] \left[\gamma_0 - \gamma_1 \right] = 0$$
$$L_r(v_b) = \varphi'(V)(v_b - V) + \varphi(V)$$
$$M(v_c) = \left[\varphi(v_c) - L_r(v_c) \right] \left[\gamma_2 - \gamma_1 \right] \frac{P - \varphi(v_c) + \gamma_2 v_c}{P - \varphi(v_c) + \gamma_2 v_c}$$

A typical speed profile approaching a steep decline is shown in Figure 2.2.
3. Methods

3.1 Efficient Driving Model

The efficient driving strategy calculation model was developed in VBA language on Excel environment. Figure 3.1 shows the algorithm followed by the model in the calculation of an energy-efficient driving strategy.

The first step of the algorithm focuses on building a table with all the singular points of a route. Between each of these points there is a homogeneous section with constant track profiles and speed limits, allowing the calculation, for each section, of the speed profiles from the corresponding equations.

Then, we should iterate a hold-speed $Z$, compute the corresponding brake speed, $U$, and identify the steep track sections. Having the $Z$ and $U$ speed values, we’re able to calculate the acceleration, coasting and braking profiles.

The formerly calculated profiles are then joined by a constant-speed profile – the speed-hold phase – if there are no steep track sections during this phase. In the event of a steep section being present during this phase, it is necessary to compute an energy-efficient profile to approach that track segment.

Figure 3.1 – Model’s algorithm diagram

Figure 2.2 – Speed profile approaching a steep decline
Source: (Vu, 2006)
The final speed profile is composed by the intersection of all the formerly computed profiles. The total running time is then evaluated and compared to the available running time in the timetable. Should an adjustment of the running time be necessary to meet the planned arrival time, the calculation process is repeated with a different hold-speed, \( Z \).

Figure 3.2 illustrates an energy-efficient speed profile computed by the developed model for an 18,975 km route and an allowed running time of 13 minutes.

In Figure 3.2 it can be identified, through colored rectangles, the speed profiles belonging to the base strategy: full power acceleration (blue rectangle), the semi-final coasting profile (in green) and the final braking profile (in red). Between these base profiles, we can find speed-hold phases (represented by black line segments) as well as coasting (green lines) and maximum acceleration (blue) profiles to efficiently approach steep declines and inclines, respectively.

The dots over the speed profile segments identify the different sub-profiles, one for each of the homogeneous track section. In the speed-hold phase, this distinction has not been made for the sake of calculation simplicity.

3.2 Assessment of the Efficient Driving Model’s Potential

The model’s potential assessment was done by comparing actual driving strategies with model-calculated strategies for identical routes and running times.

For replication of the actual runs, measured on board of the trains, and the driving strategies calculated by the model, a train-running simulator has been developed. This simulator is based on train motion discretization in periods of one second. Thus, every second, depending on the driver’s control of the train (which acceleration notch was selected or which level of braking) and the characteristics of the infrastructure on which the train is, it is possible to model the evolution of its acceleration, speed and position according to the following equations:

\[
a = a(v)_{\text{trac}} + a(v)_{\text{resist}} + a(x)_{\text{prf}} \quad (3.1)
\]
\[ x_{t+1} = x_t + v_t \Delta t + \frac{1}{2} a \Delta t^2 \quad (3.2) \]
\[ v_{t+1} = v_t + a \Delta t \quad (3.3) \]

Where \( a_{\text{trac}} \) is the tractive or braking acceleration during the time period \( t \), \( a_{\text{resist}} \) is the running resistance acceleration and \( a_{\text{prf}} \) represents the acceleration due to the compensated track profile. The estimated energy consumption is given by the equation:

\[ E_t = m a_{\text{trac}} v_t \Delta t \quad (3.4) \]

In all equations, \( \Delta t \) equals 1 second, being the simulator’s minimum period of discretization.

Figure 3.3 and Figure 3.4 present a comparison between the speed profiles measured on board, by GPS, and the profiles obtained by the train-running simulation model for the same route and driver’s selected controls.

The adjustment between the two situations is fairly good, thus validating the rolling stock traction and running resistance curves as well as the resistances due to the track profile.

In order to evaluate the efficient driving strategies computed by the model introduced in section 3.1, a speed profiles measurement, as a function of time, position on the track and driver’s selected controls, was carried out on board of the trains. Subsequently, an energy consumption estimation for the actual runs was made by using the train-running simulator fed with the measured data. Finally, the energy consumption of the efficient driving model’s computed profiles was estimated. These profiles were computed taking into account the same restrictions of running time as the actual cases were subjected:

- If a delayed departure occurred due to operational issues as crossing trains, the actual departure time was considered, independently of the arrival time;
- If a delayed departure occurred due to commercial issues as high passenger flows, the actual dwell time was considered independently of the timetable’s dwell time.

### 3.3 Driver Advice System

In order to assist drivers in the adoption of an energy-efficient driving style, a Driver Advice System prototype was developed, presenting, for a given route and available running time, the efficient speed profile and corresponding driving controls. The prototype, currently under suitability tests, is working with pre-computed profiles. A system evolution is planned, after a successful testing phase, in order to enable the real-time calculation of efficient profiles.

The developed system is grounded in the infrastructure database, train timetable database
and in a track positioning module via GPS signal. Depending on the train’s timetable and on the position on the track, the recommended driving strategy and corresponding efficient action at the moment is presented in order to ensure the timely arrival at destination with minimum energy consumption. Figure 3.5 presents the user interface of the system’s prototype.

4. Results and Discussion

4.1 Driving Model Energy-Saving Potential

In this section, a comparison between the actual train runs and the corresponding driving strategies computed by the model are presented. Three train runs are analyzed:

1. Inter-Regional train number 865–07/2014
2. Inter-Regional train number 865–08/2014
3. Regional train number 4106–08/2014

The estimated energy saving is presented in Table 4.1, Table 4.2 and Table 4.3 for the three analyzed cases. The results are detailed by sections between the different stations of the route.

It must be noted that, although the Table 4.1 and Table 4.2 data refers to trains with the same timetable, the direct comparison of running times and energy consumption between the two runs is not possible. This is due to different temporary speed limits and altered traction conditions of the rolling stock between data measurements on board the train number 865-07/2014 and 865-08/2014. Thus, for an identical route and running time, the efficient driving strategy may be different, subject to traction conditions and infrastructure speed limits at the time.

<table>
<thead>
<tr>
<th>Table 4.1 – Analysis of the train run number 865-07/2014</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ermasinde-Paredes</td>
</tr>
<tr>
<td>Paredes-Penafiel</td>
</tr>
<tr>
<td>Penafiel-Cadéia</td>
</tr>
<tr>
<td>Cadéia-Livração</td>
</tr>
<tr>
<td>Livração-Marco</td>
</tr>
<tr>
<td>Marco-Mosteiro</td>
</tr>
<tr>
<td>Mosteiro-Aregos</td>
</tr>
<tr>
<td>Aregos-Ermida</td>
</tr>
<tr>
<td>Ermida-Reide</td>
</tr>
<tr>
<td>Rede-Régua</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.2 – Analysis of the train run number 865-08/2014</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ermasinde-Paredes</td>
</tr>
<tr>
<td>Paredes-Penafiel</td>
</tr>
<tr>
<td>Penafiel-Cadéia</td>
</tr>
<tr>
<td>Cadéia-Livração</td>
</tr>
<tr>
<td>Livração-Marco</td>
</tr>
<tr>
<td>Marco-Mosteiro</td>
</tr>
<tr>
<td>Mosteiro-Aregos</td>
</tr>
<tr>
<td>Aregos-Ermida</td>
</tr>
<tr>
<td>Ermida-Reide</td>
</tr>
<tr>
<td>Rede-Régua</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>
Table 4.3 – Analysis of the train run number 4106-08/2014

<table>
<thead>
<tr>
<th>Section</th>
<th>Distance [km]</th>
<th>Real</th>
<th></th>
<th>Model</th>
<th></th>
<th>% Energy Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Régua-Godim</td>
<td>1.5</td>
<td>21.4</td>
<td>157</td>
<td>20.8</td>
<td>156</td>
<td>-3%</td>
</tr>
<tr>
<td>Godim-C.Molelo</td>
<td>3.8</td>
<td>60.3</td>
<td>242</td>
<td>57.9</td>
<td>241</td>
<td>-4%</td>
</tr>
<tr>
<td>C.Molelo-Rede</td>
<td>3.4</td>
<td>39</td>
<td>252</td>
<td>38.1</td>
<td>236</td>
<td>-2%</td>
</tr>
<tr>
<td>Rede-Barqueiras</td>
<td>3.2</td>
<td>54.9</td>
<td>218</td>
<td>43.3</td>
<td>233</td>
<td>-15%</td>
</tr>
<tr>
<td>Barqueiras-Porte Rei</td>
<td>3.7</td>
<td>53.7</td>
<td>226</td>
<td>47.7</td>
<td>231</td>
<td>-11%</td>
</tr>
<tr>
<td>Porte Rei-Ermida</td>
<td>3.6</td>
<td>41.7</td>
<td>200</td>
<td>33.4</td>
<td>252</td>
<td>-20%</td>
</tr>
<tr>
<td>Ermida-Mirão</td>
<td>2.4</td>
<td>56.1</td>
<td>222</td>
<td>53.6</td>
<td>175</td>
<td>-7%</td>
</tr>
<tr>
<td>Mirão-Aregos</td>
<td>3.3</td>
<td>43.8</td>
<td>259</td>
<td>34.4</td>
<td>235</td>
<td>-21%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>24.9</td>
<td>347.6</td>
<td>1755</td>
<td>300.2</td>
<td>1719</td>
<td>-11%</td>
</tr>
</tbody>
</table>

On the three analyzed cases, composed by inter-regional (with less stops) and regional (with frequent stops) services, there is a non-negligible energy saving potential, varying between 11 and 15%.

Analyzing the saving potential of the different route sections, a high energy consumption differential between the actual cases and the energy-efficient strategies can be noted on some sections.

In the case of Aregos-Ermida and Ermida-Rede sections, shown in Figure 4.1, the energy consumption difference is mainly due to the existence of a comfortable recovery time in the timetable.

On the Caide-Livração and Livração-Marco sections there are prolonged steep declines, which make the correct coasting point deduction task especially hard. This section’s speed profiles are illustrated on Figure 4.2.

This margin allows to cover quite large extensions of the route on a coasting regime. This possibility is not fully exploited by the drivers as it is very difficult to derive the correct coasting point in order to keep the timetable, even for very experienced drivers (Hansen & Pachl, 2008).

On the Ermesinde-Paredes and Paredes-Penafiel sections, there is a large number of consecutive steep inclines and declines and a rather high recovery margin. Figure 4.3 shows the actual case and the model’s energy-efficient speed profiles for these sections. In this kind of situations, with highly variable track profile and large recovery time margins, the efficient driving strategy is even less trivial for a driver to derive.

Some other sections have insignificant differences between the actual cases and the efficient driving strategies. This is due to a minimum-time driving style in order to keep the timetable, being the case of the sections Régua-Godim, Godim-Caldas Moledo and Caldas Moledo-Rede on the 4106-08/2014 train run. In this particular train run, the late departure at the first station required a minimum-time driving style in order to keep the timetable. After meeting the timetable it was possible to adopt more energy-efficient
driving styles, originating the relatively high energy consumption differentials in the subsequent sections, between Rede and Aregos stations.

\[\text{Figure 4.3 – Real and model’s speed profiles on the Ermesinde-Penafiel section (train no. 865-08/2014)}\]

Finally, there are sections where the model’s efficient driving strategy originates a higher energy consumption compared to the actual caso. These situations, marked in red on Table 4.1 and Table 4.2, are due to running with slight delay and the optimal strategy to meet the timetable is a minimum-time run. In these actual cases, the train drivers had opted not to make strictly minimum-time runs and therefore these runs had a lower energy consumption level than the efficient strategy. However, having not catch up with the timetable in these sections, didn’t allow them to adopt, further ahead the route, a driving style as economical as possible because of the smaller recovery time margins to keep the timetable.

The minimum-time driving style is extremely energy-consuming. Figure 4.4 illustrates the typical evolution of energy consumption with running time, by representing the energy spent on a train run between Ferrão and Covelinhas stations, depending on the running time.

\[\text{Figure 4.4 – Energy consumption vs running time}\]

4.2 Driver Advice System Prototype

After the energy-saving potential assessment in the Douro line operation, a Driver Advice System prototype was developed in order to aid the train drivers to follow energy-efficient driving strategies and thus validating the energy saving potential in real situations.

In the first phase of testing, the prototype works exclusively with pre-computed energy-efficient
profiles. This allows to perform the prototype’s usability test by the drivers in the short-term.

A preliminary prototype test allowed to observe that the user’s interface is adequate, as the driver could easily and closely follow the system’s recommendations along the entire journey. The evolution of the train’s speed profile is well adapted to the theoretical speed profile, as seen in Figure 4.5, enabling to validate the quality of the system’s train-dynamics model.

Figure 4.5 – Real and theoretical (model) speed profiles

Since the pre-computed profiles are only useful in situations without temporary speed restrictions and perfect traction conditions, the complete implementation of the efficient driving computation algorithm is scheduled. This capacity enables the possibility of further testing the system in some particular situations like diminished rolling stock traction capability or temporary speed limits.

5. Conclusions

This work’s results point to an energy-saving potential up to 15% in regional and inter-regional rail services in the Douro line. This value is consistent with the energy saving values announced by the use of driving support systems in railway operations (Transrail Sweden AB, 2011), (Schober, et al., 2010), (Papworth, 2013).

However, the realization of this energy-saving potential, associated exclusively to the adoption of efficient driving strategies, depends on some important operational factors:

- Timetable’s recovery margins policy – higher margins can allow higher energy saving, albeit at the expense of a travel time increase. The increasing magnitude of the recovery margins, besides allowing a broader usage of the coasting regime, thus saving energy, enables the recovery of small delays, minimizing the frequency of minimum-time driving profiles, which are extremely punitive for energy consumption;
- Existence of a Driver Advice System available on board and its acceptability by the drivers – since the efficient driving strategy is difficult to derive, as it depends on the available running time, track profile and rolling stock performance, it is necessary to have a system to advise the driver about the most energy-efficient action at the time, taking into account the relevant variables.

6. Bibliography and References


Schober, M., Siefkes, T. & Tengstrand, H., 2010. Two years of success - Bombardier’s formula for total train performance (Presentation), Copenhagen: Bombardier.
