Introduction
SNCF is one of the first energy consumers in France. Its energy bill represents nearly one billion euros, out of which 82% is electrical energy for traction. Moreover, the current environmental context aims at reducing the carbon emission and the general power consumption. Thus, improving the traction energy efficiency is an essential research subject for our company, both economically and environmentally.

Several axis may be followed to achieve this goal: improvement of the material aerodynamic characteristics, improvement on the power supply system, or improvement on the driving strategy. In this paper we focus on the third axis, the driving strategy. Our aim is to define the optimal driving strategy in terms of energy consumption; this must not be achieved without taking into account the constraints induced by the commercial timetable.

The optimization presented here provides an optimal train path subject to these time constraints. It is based on a dichotomy search method. This paper will first introduced the problem more in details, then give the results from numerical experiments, and then conclude on the efficiency of the algorithm presented and on further works.

Problem description
The traction energy optimization can be tackled either by taking into account a whole transport plan or by working on a single train driving strategy. Our work is focused on this second way: we consider a single train on its track, with no signalling restriction. Thus the only constraints the driver has to respect are the speed limits and the stop points (stations).

In this context, our aim is to compute the optimal driving strategy in terms of energy consumption, respecting the time constraints.

Let us first explain how the time constraints are defined in SNCF. For a given journey from origin O to destination D, and its profile and speed limits characteristics, and for a given rolling stock and its mechanical and electrical characteristics (such as maximum speed, acceleration and braking performances, etc.), one can easily compute the so-called base path. The base path is the path when the rolling stock is used at its maximum capacities for accelerating and braking, as shown in figure 1:

In this base path, there are three phases:
- **Phase A**: the train accelerates at its maximum capacity until Vmax
- **Phase B**: the train stays at Vmax

![Figure 1: base path at maximum speed](image-url)
Challenge A: A more and more energy efficient railway

- Phase C: the train brakes at its maximum capacity until it stops
Where V_{max} is the minimum between the speed limit and the rolling stock maximum speed.

It should be noted that in our study we do not take into account the energy regeneration capacities of the train.

The base path allows us to know the minimum time T_{min} needed to realize the journey from O to D. To this minimum time, a time slack, or margin is then added, in order to make the journey time more robust. It also means that, if there is no delay when the train leaves its origin, the driver can use this time slack to adopt a less energy-consuming driving strategy.

So, the time constraint the train must actually respect is to perform the journey within the time T = T_{min} + T_{s} (T_{s} being the time slack authorized). This additional amount of time can then be used to improve the energy consumption, by introducing a new phase, the coasting phase. In this phase, the train stops its engine and its speed is only defined by the profile and the rolling stock resistance.

Figure 2 shows the different phases of what we call the economic path:
- Phase A: the train accelerates until V_{tar}
- Phase B: the train stays at V_{tar}
- Phase B': the train stops its engine
- Phase C: the train brakes until it stops
Where V_{tar} < V_{max} is a target speed.

Considering this path, the problem becomes to define the speed sequences that will lead to the optimal train path in terms of energy consumption. This problem is also called Speed Tuning problem (see [CHE2010]).

It is possible to simplify the speed tuning problem by considering only two phases of the path. Indeed, [LAN1981] or [ALB2008] show that phases A and C (accelerating and braking) must be performed at the rolling stock maximum capacities; actually, their point is that:
- in acceleration mode, the motor efficiency is better when the speed is higher, so there is no interest in staying at low speeds
- in braking mode, and since energy regeneration is not taken into account, no energy is involved, when the journey time is increased if the braking phase is longer

In conclusion, the accelerating and braking curves are given by the rolling stock characteristics and are then input data instead of optimization variables.

Consequently the optimization problem relies on phases B and B', that is to say cruising (B) and coasting (B') phases.

For the cruising phase, the variables defining it are V_{tar} the target speed, and the point where the engine is stopped, let us call it P. If the values of these variables are known, it is easy to compute the accelerating curve until V_{tar} is reach, and then the point where the cruising phase begins.
Challenge A: A more and more energy efficient railway

For the coasting phase, the speed curve knowing the starting speed (Vtar), the rolling stock characteristics and the profile can also be computed using basic physics principles. Knowing also the braking curve, the ending point of the cruising phase can be computed by finding the point where the braking curve meets the coasting speed curve.

From these observations, one can conclude that the optimization problem is thus reduced to finding the value of the two variables Vtar (the target speed at which the cruising phase will be performed) and P (the point where the engine is stopped, that is to say the limit between cruising and coasting phase) that will define the less energy consuming path within journey time T.

Some works have shown results on this problem, mostly based on evolutionary algorithms: for example, see [FLE2002], [BOC2007] or [CHE2010] who aims at computing the path leading to the best energy consumption within a given time constraint and get interesting results; in [WON2004] only the time objective is considered: the authors compare several search methods to perform the journey respecting the time objective by defining the optimal coasting points.

Here we use an exact method to define the optimal values of Vtar and P, thus leading to the optimal driving strategy: accelerating until speed Vtar, then cruising at the same speed until point P, coasting until meeting the braking curve, and finally braking.

Experimental results
To check the efficiency of our method, we used it to compute train paths on several different profiles, and we compared the path length in time, and the energy consumption.

The four profiles tested are as follows:
- Profile 1: a 20 km long plain profile
- Profile 2: a 20 km long profile with a decelerating slope of 2 kms in the middle
- Profile 3: a 20 km long profile with an accelerating slope of 2 kms in the middle
- Profile 4: a 20 km long profile with two “mounts” (a mount being composed of a decelerating slope of 2 km, a plain section of 2 km, and a decelerating slope of 2 km to get back to the initial altitude)

For each profile we compare 5 driving strategies:
- Strategy 1: the base path with no time slack(at maximum speed)
- Strategy 2: the base path with a time slack of 7% (at a constant speed)
- Strategy 3: the optimal path with a time slack of 7% (with coasting phases, computed with our algorithm)
- Strategy 4: the base path with a time slack of 14% (at a constant speed)
- Strategy 5: the base path for a time slack of 14% (with coasting phases, computed with our algorithm)

NB: in these tests we compute what we call “the base path with a time slack of x%”; this path is computed by calculating an average speed at which the train can stay along the path in order to reach its destination within the time T. This driving strategy is also called “uniform path”.

The results are presented below for 3 different kinds of rolling stocks.

- **TGV**

The TGV is a high speed train with a maximum speed at 320 km/h. It is characterized by good accelerating and braking performances. The results for the TGV are presented in table 1.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Type of profile</th>
<th>Profile 1</th>
<th>Profile 2</th>
<th>Profile 3</th>
<th>Profile 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy 1</strong></td>
<td>Path duration (s)</td>
<td>472</td>
<td>475</td>
<td>470</td>
<td>478</td>
</tr>
<tr>
<td></td>
<td>Energy (GJ)</td>
<td>2,42</td>
<td>2,47</td>
<td>2,37</td>
<td>2,45</td>
</tr>
<tr>
<td><strong>Strategy 2</strong></td>
<td>Path duration (s)</td>
<td>509</td>
<td>513</td>
<td>507</td>
<td>517</td>
</tr>
</tbody>
</table>
We can see here that the gain in energy consumption is consequent: even with a time slack of 7% the energy is reduced by more than 40% (48% with the optimal strategy).
The biggest energy economy is performed on the profile 3, with an accelerating slope (60% economy between the base path and the optimal path with 14% time slack): indeed, this accelerating slope is where the coasting phase takes most advantage. In the contrary, the profile 2, including a decelerating slope, shows less improvement on the energy consumption because there is less opportunities for an interesting coasting phase.

If we compare the driving strategies for a given time slack (i.e. comparing strategies 2 and 3 for 7% time slack or strategies 4 and 5 for 14% time slack) we can see that the improvement provided by the choice of the optimal strategy is smaller with the 14% slack : for a 7% time slack the energy economy ranges from 12 to 31%, when for the 14% time slack the economy is only 2 to 22%. It means that within the imparted time, it is less interesting to add a coasting phase to the driving strategy, since the base path is already performed at a low speed needing less energy.

- **Passenger train**

This train has a maximum speed of 140 km/h and has a tracted weight of 800t. Its accelerating and braking performances are not as good as for the TGV but it is not too heavy. Comparison results for this train are presented in table 2.
Challenge A: A more and more energy efficient railway

For a passenger train the energy economy is less impressive than for the TGV. The maximum energy economy is reached on the profile 3 (with accelerating slope) and is of 50% (instead of 60% for the TGV); however, there is more difference here between two driving strategies with the same time slack (16 to 41% for 7% time slack, 18 to 33% for 14% time slack). It means that the passenger train could still take more advantage of a coasting phase if the time slack was even more important.

**Freight train**

The freight train considered here has a maximum speed of 100km/h and a tracted weight of 1600t. It is a heavy train with low acceleration and braking performances. Comparison resultants for the freight train are presented in table 3.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Type of profile</th>
<th>Profile 1</th>
<th>Profile 2</th>
<th>Profile 3</th>
<th>Profile 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1</td>
<td>Path duration (s)</td>
<td>835</td>
<td>835</td>
<td>835</td>
<td>835</td>
</tr>
<tr>
<td></td>
<td>Energy (GJ)</td>
<td>2,26</td>
<td>2,89</td>
<td>2,14</td>
<td>3,27</td>
</tr>
<tr>
<td>Strategy 2</td>
<td>Path duration (s)</td>
<td>897</td>
<td>897</td>
<td>897</td>
<td>897</td>
</tr>
<tr>
<td></td>
<td>Energy (GJ)</td>
<td>2</td>
<td>2,63</td>
<td>1,89</td>
<td>3,02</td>
</tr>
<tr>
<td>Strategy 3</td>
<td>Path duration (s)</td>
<td>901</td>
<td>901</td>
<td>1020</td>
<td>935</td>
</tr>
<tr>
<td></td>
<td>Energy (GJ)</td>
<td>1,63</td>
<td>2,23</td>
<td>0,96</td>
<td>2,06</td>
</tr>
<tr>
<td>Strategy 4</td>
<td>Path duration (s)</td>
<td>957</td>
<td>957</td>
<td>957</td>
<td>957</td>
</tr>
<tr>
<td></td>
<td>Energy (GJ)</td>
<td>1,82</td>
<td>2,44</td>
<td>1,7</td>
<td>2,85</td>
</tr>
<tr>
<td>Strategy 5</td>
<td>Path duration (s)</td>
<td>961</td>
<td>962</td>
<td>1020</td>
<td>957</td>
</tr>
<tr>
<td></td>
<td>Energy (GJ)</td>
<td>1,44</td>
<td>1,99</td>
<td>0,96</td>
<td>2,46</td>
</tr>
</tbody>
</table>

The results for the freight train are in the same trend as for the other types of train, only the importance of the coasting phase is bigger. Here the addition of a time margin is less profitable if the strategy does not include a coasting phase (strategies 3 and 5) than for the other trains (mean improvement provided by strategy 3 compared with strategy 2 : 22.6% for TGV, 26.4% for passenger train, 28.9% for freight train), when the overall mean improvement is smaller than for other trains (strategy 5 leads to a mean improvement of 36.8% for freight train when compared with strategy 1, 41.8% for passenger train and 56.1% for TGV).

Conclusions and perspectives
About the results presented here, we can see that the coasting strategy leads to higher benefits for high performance trains such as TGV. We can also notice that the further improvement realized by increasing the time slack is negligible, the energy consumed by the strategies with 14% time slack are not much smaller than with the 7% time slack.
Overall, the results show that the energy consumption can be reduced of up to 59% compared with the base path (i.e. the path corresponding to minimum journey time) with a time slack of 7%, and this in very small computational times (less than 1s for the paths tested). Other results found in the literature show an improvement of 31.3% in energy consumption for a time penalty of 12.5% (see [BOC2007]), or 36.8% in energy consumption for a 10% time slack (see [CHE2010]). They apply to a passenger train, where our optimal strategy can lead to an economy of 50% with a 7% time slack. We can thus conclude on the efficiency of our algorithm.

In future works, we will focus on integrating the efficiency of the traction chain, that is to say all the electrical components between the rim of the train and the catenary. Indeed, our algorithm optimizes the energy at the rim, or the effort needed by the train to perform its journey, but not exactly the energy consumed at the catenary. We then need to add a model of the traction chain to our optimization algorithm.

References


